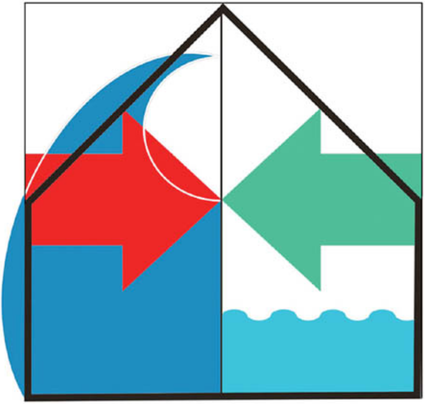
WIND STORM AND STORM SURGE MITIGATION

Edited by Nasim Uddin, Ph.D., P.E.



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Introduction: Wind Storm and Storm Surge Mitigation

US-BANGLADESH WORKSHOP ON INNOVATION
IN WINDSTORM / STORM SURGE MITIGATION

DHAKA, LGED BHABAN, 19 - 22 DECEMBER 2005

This introduction and executive summary covers the following topics:

- the origins of this monograph as a sequel to the three previous monographs generated by ASCE CDRM members and other volunteers;
- brief synopses of the papers included in this monograph; and

The Monograph as a sequel

This monograph, produced by the Council on Disaster Risk management (CDRM), is a sequel to a four previous monographs, *Acceptable Risk Processes: Lifelines and Natural Hazards* (2002) and ASCE CDRM Monograph No. 1 titled *Infrastructure Risk management Processes: Natural, Accidental and Deliberate Hazards* (2006), both edited by Craig Taylor and Erik VanMarcke, *Disaster Risk Assessment and Mitigation* (2008) edited by Nasim Uddin and Alfredo Ang, and *Multihazard Issues in the Central United States (2008)* edited by James Beavers.

The First Monograph

The first monograph contained mainly technical papers that evaluated procedures used in the acceptable risk processes in lifelines against natural hazards. Considering all the advances in probabilistic seismic hazard analysis during more than three decades, David Perkins elaborated a number of remaining issues having the effect that uncertainties may be significantly higher than the well-developed models indicate. Armen der Kiureghian presented a paper explaining how to apply Bayesian methods to obtain seismic fragility models for electric power components. Stuart Werner and Craig Taylor presented issues arising when constructing seismic vulnerability models for transportation system components. Adam Rose dealt with the complex issue of validating models to estimate higher-order economic losses.

A persistent problem is how to develop prescriptive criteria that provides guidance and goals for acceptable risk procedures. In the previous monograph, Keith Porter reviewed and evaluated available life-safety criteria; Daniel Alesch, Robert Nagy, and Craig Taylor addressed available financial criteria.

Because technical procedures do not comprise the full scope of acceptable risk processes, additional papers cover communication, administration and regulation issues. From an owner's and an engineer's perspective, Dick Wittkop and Bo Jensen addressed challenges in communicating risk results. Frank Lobedan, Thomas La Basco, and Kenny Ogunfunmi discussed the administration of the major wharf embankment and strengthening program at the Port of Oakland. And Martin Eskijian, Ronald Heffron, and Thomas Dahlgren discussed the regulatory process for designing and implementing the engineering standards for marine oil terminals in the State of California.

The Second Monograph

The first monograph covered many broad topics pertaining to acceptable risk processes for lifelines and natural hazards. However, in the early stages of developing the second monograph, it became clear that many important topics were not treated. The first monograph's coverage focused on earthquake risks, a field that has shown quantitative sophistication for almost 40 years. In spite of remaining uncertainties in estimating earthquake risks, especially to (spatially distributed) infrastructure systems, the degree of quantitative sophistication for these risks is not matched by number of other natural hazard risks. (see American Lifelines Alliance, 2002). Also, accidental and malicious threats were at best an afterthought to members of CDRM until September 2001. In an effort to fill the apparent gaps, the second monograph covered broad topics including hazard issues, system evaluation issues, risk criteria issues, and systems management issues.

Under the broad topic of hazard issues, only one paper is included. Here Steven Harmsen extends a topic discussed by David Perkins in the previous monograph. Probababilistic seismic hazard analyses (PHSA) based estimates are used in major seismic codes and have a significant bearing on many professional, governmental, engineering, and financial activities. Most importantly, PHSA-based estimates are used in risk studies, but often without sufficient regard to the uncertainty in these estimates. This paper illustrates the quantitative sophistication in developing inputs for estimates of earthquake hazard and risk and resulting uncertainties and presages further quantitative development in seismic risk evaluation of infrastructure systems. For purpose of evaluating and expressing uncertainties resulting from diverse inputs source and attenuation models and assumptions, Harmsen, following USGS (Frankel et al. 2002), has developed a logic tree formulation that represents the broadest features of the input alternative at every phase. Instead of accumulating exceedence probabilities at a fixed ground motion level, however, he computes ground motions at a fixed exceedence probability model. Harmen uses the input models and weights found in the USGS 2002 national hazard mapping work. To supplement this USGS 2002 input information, he adds a preliminary representation of uncertainties in rates of occurrence from known faulting systems and an estimated range of uncertainty for areal source rate and b-values. Results of these logic-tree models are expressed, for instance, in terms of probability density functions of strong ground motion values for a specific return period. These findings can thus be used not only to guide future research but also to express more fully the range of uncertainties in earthquake hazard and risk evaluation as a result of its quantitative sophistication.

In "System Evaluation Issues," Jose Borrero, Sungbin Cho, James E. Moore II, and Costas Synoloakis explore tsunamis and transportation system analysis and discuss a multi-disciplinary project employing expertise in tsunamis generation and run-up analysis, transportation system analysis, and higher order economic analysis. Beverly J. Adams and Charles K. Huyck cover how remote sensing can assist in both pre- and post-disaster planning. Dorothy Reed, Jane Preuss, and Jaewook Park focus on the electric power distribution system affects of four major Pacific Northwest storms and the 2002 Nisqually earthquake. This focus provides initial data for estimating outage times and for assessing local vegetation management polices and practices.

Under "System Management Issues" Mihail Popescu and Manoochehr Zoghi provide a comprehensive account of the state-of-the-art-practice in assessing, evaluating, and managing land slide risks. Yumei Wang and Amar Chaker probe the vulnerability to multiple natural hazards in the Pacific Northwest, a region with diverse geologic settings. The authors examine the complex relations among different modes of transportation (highways, rail lines, and river navigation) and geologic hazards, and assess their importance for the community and the regions. The study results indicate that geologic hazards in the Columbia River Transportation Corridor can have severe, long lasting impacts on the Oregon economy, affect productive capacity, and slow the pace of economic growth and development. Le Val Lund and Craig Davis use a historical approach to explain how the Los Angeles Department of Water and Power Water System has coped with natural hazards as well as with emergency preparedness and homeland security. Balancing these risks reduction activities and resources needed to effect specific risk-reduction objectives requires well defined but flexible plans-of-action.

The Third monograph

The first two monographs covered many broad topics pertaining to acceptable risk processes for lifelines and natural hazards. The board topics addressed were technical issues, risk criteria issues, communication, administration, and regulation issues. In the second monograph, the broad topics covered are hazard issues, system evaluation issues, risk criteria issues, and system management issues.

Some of the papers included in this monograph cover significant technical features of integrated risk evaluations for natural disasters, whereas others deals with the complex personal, organizational, institutional, regulatory, and risk communication features of acceptable risk management.

The recent devastating earthquakes, tsunami, and hurricanes resulted in an international human tragedy affecting over a dozen countries. The white paper "Surviving Nature's Forces: Can Civil Engineers Build Safe Communities?" by Yumei Wang and Erik Vanmarcke, prompted by this human tragedy, considers that civil engineers were much involved in building the infrastructure of the communities that were destroyed.

The fundamentals for the systematic and quantitative assessment of risk, with particular emphasis for hazard mitigation, are summarized. Besides the assessment of the best estimate measure of a pertinent risk, the assessment of the uncertainty underlying the calculated risk is equally important. These are illustrated with a quantitative assessment of the risks (for a 20-year period) associated with the occurrence of a Category 4 hurricane in New Orleans on the assumption that the assessment was performed in 1990 (15 years prior to the occurrence of Katrina in 2005).

Another key feature is administering an acceptable risk evaluation program. In the paper entitled "Port Of Los Angeles Risk Management Strategies," Tony Gioiello, and Richard C. Wittkop outline how a major port has so far administered the very comprehensive acceptable risk evaluation of potential threats for ports.

In light of the port's importance to the local and national economy, the port has risk management strategies already in place. The port will also undertake the completion of a risk reduction plan to identify those facilities and systems that may be vulnerable to seismic or other events and identify ways to mitigate the port's risks in those areas. This approach is based on the premise that, no matter what level of risk reduction is implemented, there is always some residual risk of damage;

it is not possible to achieve zero risk. Even with sound preventive measures, there remain residual risks, which are sometimes extremely large and grave. A natural hazard is an unexpected or uncontrollable natural event that usually results in widespread destruction of property or loss of life. In "Surviving Natural Forces from Taiwanese Civil Engineers Perspective," Edward H. Wang, Hsieh Yuen Chang, and Ming-Hsi Hsu expand this discussion by offering perspectives on life-safety efforts in Taiwan.

The role of civil engineers was written in all phases of activities related to the recent disasters. As unfortunate as these disasters are, they offer tremendous opportunities for civil engineers to learn from the previous short falls and ensure public safety going forward. In the paper titled "Surviving Natural Disasters: Lessons Learned From the December 26, 2004 Sumatra Quake and Tsunami," Yumei Wang, Curt Edwards, Amar Bhogal, and Anat Ruangrassamee review the investigation findings in coastal Thailand and discusses some of the lessons learned from this tragedy. Findings clearly indicate that structures and lifelines require sound engineering design and construction, including tsunami-resistant buildings (at least for more important structures). In addition, tsunami education for communities and regional tsunami warning systems are needed. The paper "Achievements and Challenges of China Construction," by Xila Liu proves the complex relations among construction and natural hazards and assesses their importance for the community and the region. China is beginning an accelerated urbanization process. A great number of infrastructure projects and residences are under construction. This paper briefly introduces construction achievements and discusses construction challenges. Finally, as the key point for further development, it emphasizes construction quality and safety. Finally, there are many features of the acceptable risk processes and mitigation beyond the technically-oriented integrated systems evaluation. One such key feature is risk communication to policymakers. In the paper "Preparing for the Big One," Swaminathan Krishnan discusses the importance of constantly engaging governments in discussion to ensure that the quality of our infrastructure is maintained. Failure to do so could be catastrophic as was witnessed in New Orleans when the storm surge from hurricane Katrina (August 29, 2005) breached or overtopped the aging levees.

The Fourth Monograph

Education, planning, and mitigation are all required to reduce losses from natural and technological hazards in the United States. The U.S. Congress took the right step in establishing the DMA in 2000. However, it is just a first step. As another step in education, planning, and mitigation, ASCE's Council on Disaster Risk Reduction held a symposium in Chicago, IL, on October 18, 2006 in concert with the ASCE's annual meeting. The symposium was titled "Multihazard Hazard Issues in the Central United States." The remaining papers in this monograph highlight some specifics issues of mutihazards related to education, planning, and mitigation. At the symposium held at the Westin Chicago River North Hotel on October 18, 2006, some 12 speakers presented invited papers. These papers, purposely broad in coverage, dealt with various aspects of natural multihazard issues and to a lesser extent with technology (man) generated issues. The papers outlined some of the more important issues that should be addressed in developing comprehensive national and state hazard planning and action scenarios. Following is a brief overview of the principal points addressed in the full papers presented at the symposium and included in this monograph.

W. Hall in his paper titled "Keynote Paper: A Changing Perspective—Major Challenges" focuses briefly on four principal topics: (1) the multihazards (natural and man-made), (2) observations on risk assessment and risk coverage, (3) mitigation measures, and (4) education and training. He presents a brief discussion of issues that must be addressed to make significant improvements in our ability to plan, design, and construct/develop mitigation measures for the noted hazards in the years ahead. In the paper "The Context for Successful Loss Reduction from Natural and Technological Hazards as Applied to the Central and Eastern U.S." by W.P. Graf, the author discusses such issues as (1) incremental improvements in new construction, (2) rehabilitation, (3) loss reduction programs, and (4) risk analysis and the importance to various constituencies, along with imbedded tasks of importance in each case. This paper relates the issue descriptions to current federal guidelines and points to requirements for stakeholders and other constituencies. The paper titled "U.S. Flood Policy 13 Years After the 1993 Flood" by Paul A. Osman briefly describes the 1993 flood of the Mississippi River in the Midwest. Even though the 1968 federal flood control act had been in place for years, few applications within the act's framework had been undertaken. This changed with the serious 1993 flood, and the author points out the great changes in application that arose with that flood. It is interesting reading, indeed, about what can actually take place in flood mitigation measures. N. Uddin in his paper "Thermopastic Composite Structural Insulated Panels (CSIPS) for Building Construction" reported on some of the latest research on structural insulated panels as might be used in special construction. In these studies thermoplastic skins were employed and showed overall significant strength enhancement with three-point loading, although some face sheet components experienced cracking. Clearly more research is needed for this valuable product to meet distortion standards, which might be needed for major disaster protection.

The paper "Proposal for the Tennessee Multihazard Mitigation Consortium (TMMC)"
by James E. Beavers describes the planning and formation of the Tennessee Multihazard Mitigation Consortium (TMMC), a model not only for Tennessee but other states as well. Approved in principle at many levels, the TMMC awaits state legislative authorization and appropriation status. The institute coordinates the activities initially of three institutions but is expected to grow so as to be a major resource and formal action center for disasters of many kinds in the state of Tennessee. This document describes how a fully focused institute that is broad in scope can be developed and serve as the focal point for mitigation action. In the paper "How Communities Implement Successful Mitigation Programs: Insights From the Multihazard Mitigation Council (MMC) Community Study" by Elliott Mittler, Linda Bourque, Michele M. Wood, and Craig Taylor, the authors describe the findings of an ATC congressionally mandated study on successful mitigation efforts by nine U.S. communities of various sizes. For each city the authors describe what mitigation measures were addressed and how leadership factored into the effort. It contains valuable information on subsidizing mitigation measures and the final result. Richard G. Little in his thought-provoking paper "Achieving Risk Reductions in Critical Infrastructure Systems" discusses risk reduction from the broad perspective of the string of critical infrastructure that must be operative to maintain our economy. The theory is simple and expressed in understandable terms, but more importantly, the author discusses of the consequences of non-functional infrastructure.

The Unknown Seismic Hazard in East Tennessee and Potential Losses *by Christine A. Powell and James E. Beavers* presents a mini history of the seismicity in Tennessee (major earthquakes in 900, 1450, and 1811-1812) with particular attention to eastern Tennessee. The authors point out that eastern Tennessee is quite active seismically, and that such seismicity needs more attention by those responsible for national, state and local codes and regulations to mitigate potential damage through economical means. In the paper titled "Frequency of Hailstorms and the Resulting Damage in the Central United States" by *Douglas L. Dewey and Rosemarie G. Grant, a*uthors Douglas Dewey and Rosemarie Grant have prepared a landmark summary contribution on the hazard of hailstorms and the damage potential (risk) associated with it. Among other valuable discussions contained therein is a section on the true impact of hail, which provides interesting insights on current insurance coverage of wind and hailstorm damage. The paper also discusses resistance parameters and case histories.

Genesis of This Monograph and Expansion of Its Objectives

Figure 1: Six Workshop Themes

The Workshop "1st International Workshop on the Windstorm/Storm Surge Mitigation Construction: Issues of Storm, Shelter and Safety" was held at the Agargaon LGED Bhaban, Bangladesh December 19-21, 2005. The Workshop was organized jointly by BRAC/BUET/LGED/the Ministry of Disaster & Relief, Government of the People's Republic of Bangladesh, and National Science Foundation (NSF) and University of Alabama at Birmingham of the United States of America. The inauguration ceremony included Chowdhury Kamal Ibne Yousuf, Minister of Food and Disaster Management, Govt. of Bangladesh; U.S. Ambassador, Japanese Consulate, European Union Representative, USAID Representative, and World Bank Representative.

A key objective of this collaborative workshop was to link U.S. and Bangladeshi scientists and engineers for exploring the long-term issues of wind storm, storm surge, and public safety in the Bay of Bengal regions. This workshop hoped to plant the seed for several interdisciplinary and inter-institutional collaborative partnerships that would center around six thematic areas. The purpose of the workshop was to identify a number of topics related to wind storm, storm surge and public safety of Bangladesh. The workshop focused on the following six thematic areas:

- Windstorm, Hurricane, and Tsunami Characterization
- Effect on Habitat and Infrastructure
- Disaster Reduction Strategy (Affordable Shelters Construction)
- Risk and Loss Estimation
- Socio-economic Aspects of Population Dynamics
- Public Health and Safety Issues

Brief Synopses of the Papers Included in this Monograph

Thematic Area I - Windstorm, Hurricane & Tsunami Characterization

1. Wind Storm Types Affecting Bangladesh by Richard E. Peterson and Kishor C. Mehta

Few locations around the world can compare with Bangladesh in the number of inhabitants who are at peril due to weather-related factors. In the winter months individuals in the northern part of the country succumb to the cold. As the warmer time of the year arrives, melt water from the Himalayas results in flooding of the great rivers that flow north to south through Bangladesh; the capital, Dhaka, is often up to its knees in water. In the warm season powerful thunderstorms can cause local flooding, lightning, and damaging hail; more alarming. However, the storms may spawn tornadoes and thunderstorm outflow winds, both leading to fatalities. In early summer and then again in the fall tropical cyclones can strike, with attendant damaging winds and deadly storm surges. Windstorms then are a major fact of life—and death—in Bangladesh.

2. *Experimental Storm Surge Forecasting In The Bay Of Bengal by Hassan S. Mashriqui, G. Paul Kemp, Ivor Van Heerden, Joannes Westerink, Ahmet Binselam, Young S. Yang' Brian D. Ropers-Huilman, Kate Streva*

The fully parallel Advanced Circulation (ADCIRC) model has been used experimentally since 2002 for storm operations support in the Gulf of Mexico. Improved forecasts of storm surge coupled to more timely and accurate warnings are important prerequisites for saving lives in the heavily populated coastal regions surrounding the Bay of Bengal. Based on the preliminary results presented here, ADCIRC appears to offer great promise if forecast results can be disseminated quickly enough as a storm approaches landfall.

Thematic Area II—Effect on Habitat & Infrastructure

3. *Wind Effects On Cyclone Shelters In The Coastal Regions Of Bangladesh by Mir M. Ali and Puja Mohandas*

Natural disasters are part of our life in one way or another. They cannot be prevented or controlled but can be managed by human societies. With the advancement of science and technology, mitigation measures have been devised to protect human lives and properties from destruction. Tropical cyclones commonly occur in India and Bangladesh whereas hurricanes occur in the United States and typhoons in Japan. Because of these tragic events thousands of lives have been lost in the past. Bangladesh has built many shelters in its coastal region to protect its citizens as part of the mitigation measures. This paper focuses on the wind load effects on shelters during high winds with special reference to Bangladesh. The codes and standards related to wind effects are reviewed. A detailed case study dealing with an existing cyclone shelter in Bangladesh is presented. Conclusions from the investigation are drawn and a few observations and recommendations are made regarding the construction of future shelters.

4. *3D Effects on the Seismic Response of Dam-Reservoir System by M.A Mill'an., Y.L. Young and J.H. Pr'evost*

Conventional seismic analysis of gravity dams assumes that the behavior of the dam-water-soil system can be represented using a 2D model. The assumption is based on the fact that gravity dams are usually built with transversal joints that effectively allow the concrete blocks to behave independently from each other. However, reservoirs usually have a width different from the dam. In this paper, a simplified analytical model and a BEM model are used to investigate the influence of the reservoir geometry on the dam response. The results show that the reservoir shape strongly influences the seismic response of the dam, making it necessary to account for 3D effects in order to obtain accurate results. In particular, the 3D pressure and displacement responses can be quite higher than for the 2D model.

5. *Coasta Land Loss: Hurricanes And New Orleans A Prelude To Hurricane Katrina by Ivor L. Van Heerden, Ph.D.*

Flooding New Orleans is a real threat, a catastrophe that would severely impact the U.S. economy, with ripples felt throughout the world's economy. The problem is exacerbated with global warming. Louisiana would take decades to recover from such a catastrophe. A solution to this problem is the diversion of the Mississippi River into Breton Sound and the creation of a new

Mississippi Delta. Such a project would result in the genesis of significant amounts of new wetlands, improving the buffering of storm surges destined for New Orleans. A large-scale project of this nature will have other benefits. Biological productivity will be enhanced and biological diversity maintained. The expenditure of the billions needed for the Breton Delta project will generate many jobs over time. Additionally, the technology developed and applied by Louisianans will be exportable nationally and internationally, a product of the state's enhanced knowledge and ability in coastal habitat restoration.

Thematic Area III—Disaster Reduction Strategy (Affordable Shelters Construction)

6. *Risk-Based Approach to Shelter Planning for Coastal Areas Exposed to Storm Surge by Jahir Uddin Chowdhury*

Shelters are constructed in the coastal area of Bangladesh to provide refuge to the people during storm surge floods due to tropical cyclones in the Bay of Bengal. According to the National Water Management Plan (NWMP), existing shelters can accommodate only 27 percent of the population at risk, and construction of shelters will be required for 5.9 million people. One of the planning issues is how to allocate shelters among competing areas since the available fund at a given time is a fraction of the requirement. The paper discusses methodology to address this issue. Surge height of 100 years return period at the cost is predicted and corresponding flooded area is simulated. Flooded area is divided into hazard zones based on flood depth and administrative boundary. Shelters are allocated among the zones based on risk and equity considerations. The methodology is illustrated for the eastern part of the Ganges Tidal Plain.

7. *Shelters: More Than a Safe Haven by Ian Rector and Shantana R. Halder*

Bangladesh is exposed to many natural and human-induced events including cyclones, flood, draught, tidal surge, earthquake, riverbank erosion, tsunami, and water-logging. It is not that Bangladesh has more of these events occurring than other countries; however, with a population density of approximately 1,000 persons per square kilometer, Bangladesh is more vulnerable to such events than most countries. Since 1970 more than one million people have lost their lives with the cyclones of 1970 and 1991 claiming in excess of 9000,000 lives. Dollar amounts do not realistically reflect the real cost of such disasters when the broader impacts to the many millions that survived but lost everything are considered. Shelter can be an effective means of providing safe havens during emergencies. There multi-purpose role makes them an important asset to the broader development needs of the community. Bangladesh is the first and single most country in the world with a separate ministry for disaster management. The ministry of food and disaster management is also the first among all other government finalized its corporate and strategic policy frameworks under which a number of policy and planning documents have been published.

8. *Design Criteria for shelters in Coastal areas of Bangladesh under Multipurpose Cyclone Shelter Program by Shamaim Z. Bosunia*

The government of Bangladesh had implemented initiatives to prevent losses by constructing cyclone shelters and kills (earthen mounds) at various locations of the coastal areas of Bangladesh. Between 1972 and 1979 the government and some non-government agencies constructed more than 300 cyclone shelters and hundreds of kills in the coastal areas. This project consequently saved a lot of people and cattle, but over the years these shelters have been deteriorating severely due to poor construction specification and lack of maintenance. Similar problems are also observed in other local concrete infrastructures. Due to the non-availability of proper design and construction specifications, different designers have used different design criteria and material specifications, which have resulted in such poor performance of concrete. The most common problems are random cracking, corrosion of embedded reinforcements, and large-scale spalling of concrete. Such deterioration can be caused by a number of physical, chemical, and environmental factors—acting alone or in combination. It is high time that a serious look is taken into this problem. This paper deals with the appropriate design criteria and material specifications of cyclone shelters to be constructed in future.

Thematic Area IV—Risk & Loss Estimation

9. *Wind Field Statistics: Literature Review and Research Needs by Erik Vanmarcke and Zhaohui Chen*

This paper reviews recent research developments on modeling annual maximum wind speeds as well as wind speed extremes associated with tropical cyclones and tornadoes. Current wind-related structural damage and risk assessment methodologies are also discussed. Based on the preceding account of recent developments in modeling annual maximum wind speeds, we conclude that there is no general consensus on the type of extreme value distribution that best fits the available information about normal wind and best serves to predict long mean return period values of wind speed. The main obstacle is insufficient data to analyze extreme value statistics for wind speed and to discriminate between extreme-value distribution models.

10. *Initial Assessment of the New Orleans' Flooding Event During the Passage of Hurricane Katrina by Ivor L. Van Heerden, Ph.D., G. Paul Kemp, Ph.D., and Hassan Mashriqui, Ph.D.*

Hurricane Katrina made landfall in Louisiana at 6:10 am on Monday August 29, 2005. The storm's track took it north along the eastern edge of New Orleans. After the storm 85 percent of greater New Orleans was flooded, more than 1200 persons had lost their lives, and approximately 100,000 families were homeless, most of whom heeded the evacuation orders. The hurricane protection system that all residents of New Orleans depended upon—their security from surge floods—had failed catastrophically with more than 50 breachings or breaks. A preliminary assessment of the flooding event is given here. The flooding of New Orleans represents two separate flooding events, distinct in time, space, and intensity. In eastern New Orleans the levee failure accompanied a surge overtopping event, flooding surrounding communities; in western New Orleans catastrophic levee failure caused the flooding. Common to both flooding events is that each reflects man's engineering failures.

11. *Improvements in Flood Fatality Estimation Techniques Based on Flood Depths by Ezra Boyd, Marc Levitan, and Ivor van Heerden*

A review of the literature on loss of life models for floods demonstrates that a number of variables are important. In essence, estimating the number of fatalities for a flooding event requires two key numbers—the size of the exposed population and the fatality rate for this population. While measuring the size of the exposed population is relatively straightforward, estimating the fatality rate is very complicated. A number of factors influence this variable. Not only are the physical characteristics important, but the vulnerability characteristics also affect the fatality variable. Of the large list of variables, water depth at a location is identified as the dominant.

Thematic Area V—Socio-Economic Aspects of Population Dynamics

12. Socio-Economic Effects of Tsunamis on Bangladesh by Shah Alam Khan, BUET, Dhaka; Rezaur Rahman, BUET, Dhaka, Haroun er Rashid, IUB, Dhaka; and Salim Rashid, University of Illinois

Bangladesh has been spared any notable tsunami within living memory. As a result, socio-economic effects must be imputed by extrapolation from other countries and other disasters. For effects in Bangladesh, cyclonic storm surges or tidal bores appear to be the closest counterparts. A survey of probable affected areas to assess awareness, preparedness, and concern shows a gap between the worry evoked in foreign circles and the hardy indifference of the local population. The economic damages indicated by the survey are also guesses and suggest that active measures to avoid Tsunami damage will be hard to implement because Tsunamis are seen as low probability events. An examination of the orientation of fault lines in the Bay of Bengal suggests a low probability of Tsunamis in Bangladesh. The paper surveys the historical evidence of Tsunamis in Hawaii, supplemented by evidence from the Tsunami of 2005 in Indonesia, Sri Lanka, and India, to show the specific types of damage and the uncertain faith people have in many warnings. Unlike other countries, if a tsunami wave reaches the Bangladesh coast it may travel far inland because of its extremely flat gradient, a dense network of estuaries, and the long and relatively flat continental shelf. Tsunami preparedness should be folded in with existing disaster mitigation measures and use of current multi-purpose cyclone shelters. For those living within the danger zone, early warning systems and their acceptability is studied, again using Hawaii as a baseline. As all estimates are based on an uncertain induction from the past, the paper concludes by suggesting the implementation of any safety measures that can be included within current disaster mitigation practice. The most important short term measures consist of ways to increase the Lead time of the Tsunami warning system, as well as the effectiveness of such warnings through the training of volunteers. In the long run, such surges can be effectively mitigated by a coastal green belt. Such belts are both cost-effective and environmentally sound.

13. Twenty-five Years of Caribbean Hurricane Disaster Mitigation by D.O. Prevatt, L. Dupigny-Giroux, and F.J. Masters

The damage to buildings and infrastructure during the 2004 (Hurricane Ivan) and 2005 (Hurricane Wilma) hurricane seasons has highlighted the current vulnerability of the populations and socioeconomic fabric of the Caribbean. Annual damage losses continue to accrue despite existing mitigation strategies and the lessons learned from post-disaster assessments. The question now facing Caribbean states is, which of these strategies have succeeded and how can these results be applied to the benefit of other regions susceptible to the hurricane damage? What seems to be missing is a collaborative approach and support for fundamental research to better understand the wind-structure interaction and to better implement this knowledge. Because of the limited implementation and enforcement of building codes around the Caribbean to mitigate hurricane damage, these societies remain dangerously vulnerable to hurricanes despite the recent efforts. Policy changes are needed in addition to engineering improvements to affect lasting changes to the construction. In addition, fundamental research is needed to support policy-making decisions with real data from the region. Linguistic challenges, cultural barriers, and the lack of national resources all serve to hinder a coordinated effort to address the potential annual exposure to hurricane impacts. Conducting research at universities and education can result in lasting and widespread construction improvements.

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Chapter 1: Wind Storm Types Affecting Bangladesh

By Richard E. Peterson and Kishor C. Mehta, Wind Science and Engineering Research Center, Texas Tech University, Lubbock, TX, USA

Introduction

Few locations around the world can compare with Bangladesh in the number of inhabitants at risk due to weather-related factors. In the winter months, individuals in the northern part of the country succumb to the cold. As warmer weather arrives, melt water from the Himalayas floods the great rivers that flow north to south; the capital, Dhaka, is often up to its knees in water. During the warm season, powerful thunderstorms can cause local flooding and damaging hail. More alarming, however, the storms may spawn tornadoes and thunderstorm outflow winds leading to fatalities. In early summer and then again in the fall, tropical cyclones can strike with attendant damaging winds and deadly storm surges. Windstorms are a major fact of life—and death—in Bangladesh.

Since 1970 windstorms and the damage they cause have been a major focus of research at Texas Tech University—first under the auspices of the Institute of Disaster Research (IDR) and Department of Geosciences. Ever increasing collaboration led to the Wind Engineering Research Center (WERC) and now the Wind Science and Engineering Research Center (WISE). While the Lubbock, TX tornado of 1970 motivated the earliest research, other damaging phenomena—tropical cyclones, thunderstorm outflows, and downbursts—have drawn significant attention.

Thunderstorm Outflows

Individual thunderstorms develop within rising air and dissipate with sinking air; the latter is due to the drag of falling precipitation and its evaporation. On occasion the descending air can achieve high speeds and may reach the ground as a downburst capable of producing damage. Clusters of thunderstorms can produce merging of downdrafts, resulting in vigorous outflows near the ground. In the United States, these are sometimes termed "derechos."

At Texas Tech the near-ground characteristics of thunderstorm outflows are continuously studied. Based on data collected from a 2 km linear array of meteorological towers, Orwig and Schroeder (2005) have reported on the horizontal patterns and time variations of several outflow events.

Strong thunderstorm outflows occur in Bangladesh each year. Typically in April and May, afternoon thunderstorm may form in or near western Bangladesh. Hour by hour the storm intensifies. The outflow generates daughter storm cells continuing into the early morning hours. The resulting heavy rains and hail may result in damage or even deaths. Over a much broader area, however, the outflow winds can throw down houses, disrupt communication, and overturn crowded ferries.

Dewan has maintained a database of thunderstorm outflow events for which there have been reports of damage and/or deaths (Dewan and Peterson 2002).

Tornadoes

The 1970 tornado that cut a mile-wide swath across central Lubbock, TX, resulted in 28 deaths and the largest dollar damage of any single tornado until that time. In addition it stimulated a group of structural engineers at Texas Tech, which was grazed by the tornado, to focus on wind/damage relationships. Initially the focus was on sending damage assessment teams to the sites of significant tornadoes; this action plan continues (see, for example, Minor et al. 1977). With the subsequent collaboration of Texas Tech meteorologists, there has been increasing research in the field to document ongoing tornado events (see, for example, Rasmussen et al. 1982).

Each year the Indian Subcontinent experiences tornadoes. Peterson and Mehta (1981) summarized some of the earliest reports (from the 1800s) and outlined the broadest elements of the causative factors and climatology. The greatest frequency stretches from northwest of New Delhi southeastward to Bangladesh. In general the steering currents bring thunderstorms in from the northwest (hence the name nor'westers). Due in large part to the very humid air brought into Bangladesh from the Bay of Bengal and the structure of the winds at different levels in the atmosphere, the storms more likely to produce tornadoes occur over Bangladesh. U.S. National Weather Service forecaster Jonathan Finch has maintained a detailed account of these events. (See *www.bangladeshtornadoes.org.*)

Tropical Cyclones

The same year, 1970, that Texas Tech researchers organized to study wind damage after the Lubbock tornado, Hurricane Celia struck Corpus Christi, TX. In subsequent years their attention was increasingly drawn to the after effects of hurricane events, including international locations such as Cyclone Tracy in Australia and Hurricane Gilbert in Mexico. For the last eight autumns, Schroeder has extended the research to include gathering high-frequency meteorological data from tower arrays placed in the paths of landfalling hurricanes. As summarized by Schroeder (*www.atmo.ttu.edu*), data has been gathered from 23 storms.

Several other areas of tropical cyclone research have been pursued by WISE investigators (see for example, Simmons et al. 2002). A current study (Islam and Peterson 2004) focused on storms affecting Bangladesh. The study extracted the statistical properties of the Bay of Bengal storms to form the database for Monte Carlo simulation of extreme winds and storm surge in Bangladeshi coastal areas.

Practical Issues

The Texas Tech research led to several notable developments regarding wind storms in the United States. For example, early TTU research convinced the U.S. National Weather Service to drop its recommendation to open windows with an approaching tornado. More recently, TTU designs for tornado-resistant house construction have been promoted by the U.S. government.

Mitigation of personal injury/fatality and property damage in Bangladesh depends on numerous factors. With the immediate approach of a storm, observations, forecasts, and communication are critical. It is unclear whether these elements are optimal. In the longer term, education and preparation are essential. This includes adequate construction to protect lives.

Conclusions

Windstorms are a primary factor in the climate of Bangladesh. Hundreds to thousands of inhabitants there die each year from severe weather effects. Researchers at Texas Tech have also focused on windstorms during the last 35 years. Their findings and recommendations should benefit the people of Bangladesh.

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Chapter 2: Experimental Storm Surge Forecasting in the Bay of Bengal

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Abstract

The fully parallel advanced circulation (ADCIRC) model has been used experimentally since 2002 for storm operations support in the Gulf of Mexico. The Louisiana State University (LSU) Hurricane Center generates model output on high-performance computer clusters maintained by the LSU Center for Computation & Technology (CCT). This output is processed through a GIS to the Louisiana Office of Emergency Preparedness within 3- to 6-hour advisory cycles. Hindcasting after the 2002–05 storms revealed good correlation with measured storm surges. The modeling team at LSU demonstrated a capability to provide multiple, near real-time forecast permutations that can improve preparedness and public safety response. Coastal areas of Bangladesh and India adjacent to the Bay of Bengal are vulnerable to storm surges during tropical cyclone passages that can cause more than 300,000 deaths per event (1970 Meghna Estuary super cyclone). Early, detailed, and reliable predictions of storm effects on population centers, levees, and evacuation routes are vital to saving lives. The LSU Hurricane Center will provide similar modeling support for the Bay of Bengal basin and expects to build partnerships with interested agencies. This will be the first modeling program capable of forecasting cyclone surge propagation for a 3- to 5-day period across the entire Bay of Bengal. The model domain includes all of the Bay of Bengal and part of the Northern Indian Ocean, the east coast of India, all of the coasts of Bangladesh, Sri Lanka, and Myanmar (Burma), as well as the islands of Andaman and Nicobar. The finite element mesh includes more than 363,399 elements and 186,981 nodes, particularly along coastlines, in river channels, and around islands. The Bay of Bengal ADCIRC model was calibrated against observations from the April 1991 Chittagong (138,000 deaths) and October 1999 Paradip (10,000 deaths) super cyclones that made landfall in Bangladesh and India.

Introduction

The Bangladesh and East Indian coasts were sculpted by distributaries of the Ganges and Brahmaputra Rivers that join in Bangladesh to form the Meghna. Deltaic lands built by the rivers are low-lying, averaging only 1m to 3 m above sea level, but they are home to millions. They are fronted by a wide and shallow continental shelf. Cyclones making landfall over shallow water can combine with the 2-m to 3-m astronomical tides to produce storm surges in excess of 7 m (As-Salek 1998). Embankments or levees built to protect people are overtopped or seriously damaged with every major storm. This leads to tragedy when thousands are trapped by rising waters. Louisiana, on the north-central coast of the Gulf of Mexico in the United States has a similar deltaic landscape and hurricane threat. There, numerical hurricane surge prediction models are beginning to be used to provide early warning to low-lying areas and guide evacuation and rescue operations (Winer and Naomi 2005).

ADCIRC is a parallel two-dimensional, depth-integrated, finite-element hydrodynamic circulation model (Westerink et al. 1993) that is forced by an atmospheric cyclone model (Cardone et al. 1992) for simulations of circulation and cyclone surge propagation in coastal areas. ADCIRC is ideal for coasts with large inter-tidal zones or occasionally flooded areas because of attention given to the consequences of element wetting and drying (Winer and

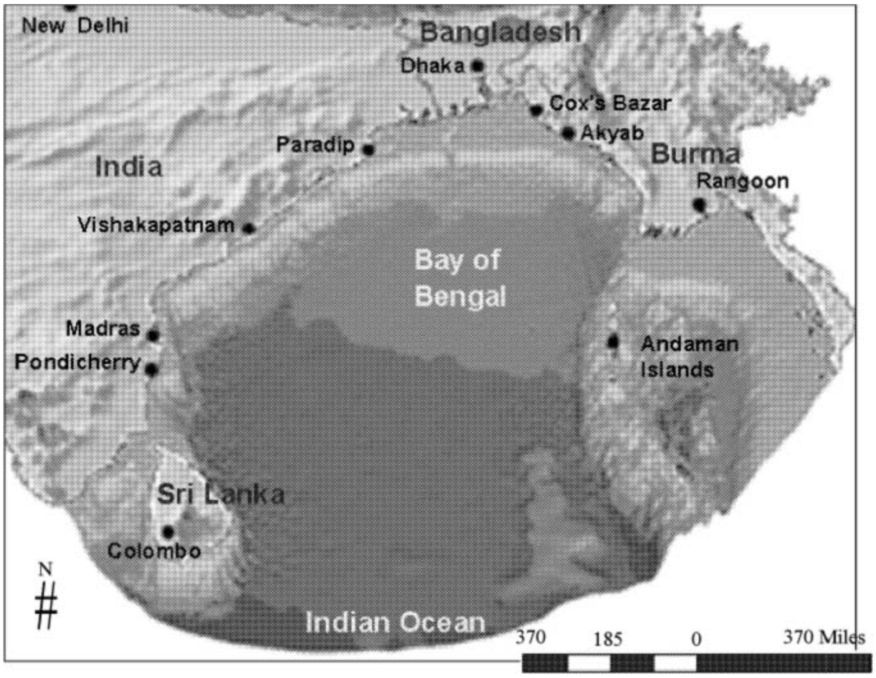


Fig. 2.1. Study area location in the Bay of Bengal basin (Mashriqui et al. 2005).

Naomi 2005). When provided with a relatively small number of storm and storm-track attributes available from the U.S. Navy Joint Typhoon Warning Center (JTWC) in the Bay of Bengal, ADCIRC can produce surge forecasts extending days into the future in a matter of a few hours. Significant experience and insight was gained about how to run the very large ADCIRC/Southern Louisiana model in forecast mode. Based on our experience it appears that the 1-day ramps used for the forcing functions worked quite well. It was noted that the tides needed to be spun up prior to the storm entering the gulf, which requires about 20 days of simulation from a cold start. This year, for the first time, we will apply a version of the ADCIRC model used to forecast storm surge for the east and gulf coasts of the United States to the Bay of Bengal.

Here, we demonstrate the early warning potential of an ADCIRC model for the Bay of Bengal. The model domain introduced here includes the entire Bay of Bengal and part of the Northern Indian Ocean, the east coast of India, all of the coasts of Bangladesh, Sri Lanka, and Myanmar (Burma), as well as the islands of Andaman and Nicobar (Fig. 2.1). The unstructured finite element mesh includes more than 363,399 elements and 186,981 nodes, clustered along coastlines, in river channels, and around islands (Fig. 2.2). In benchmark tests using 64 computer processors, this model has run a 5-day forecast in less than 2 hours of CPU time.

The Bay of Bengal is an underserved area compared to other cyclone-prone parts of the world. United Nations agencies such as World Meteorological Organization (WMO) have yet to implement an advanced near-real-time forecasting model in the Bay of Bengal. Here we describe two methods used to calibrate and validate the Bay of Bengal ADCIRC model. First, we reproduced tidal constituents across the domain and, second, simulated the April 1991 cyclone that caused 138,000 fatalities in Bangladesh (Mashriqui et al. 2005). Finally, we discuss a Web-based procedure for integrating 3- to 5-day cyclone storm surge forecasting across the entire Bay of Bengal into a warning system.

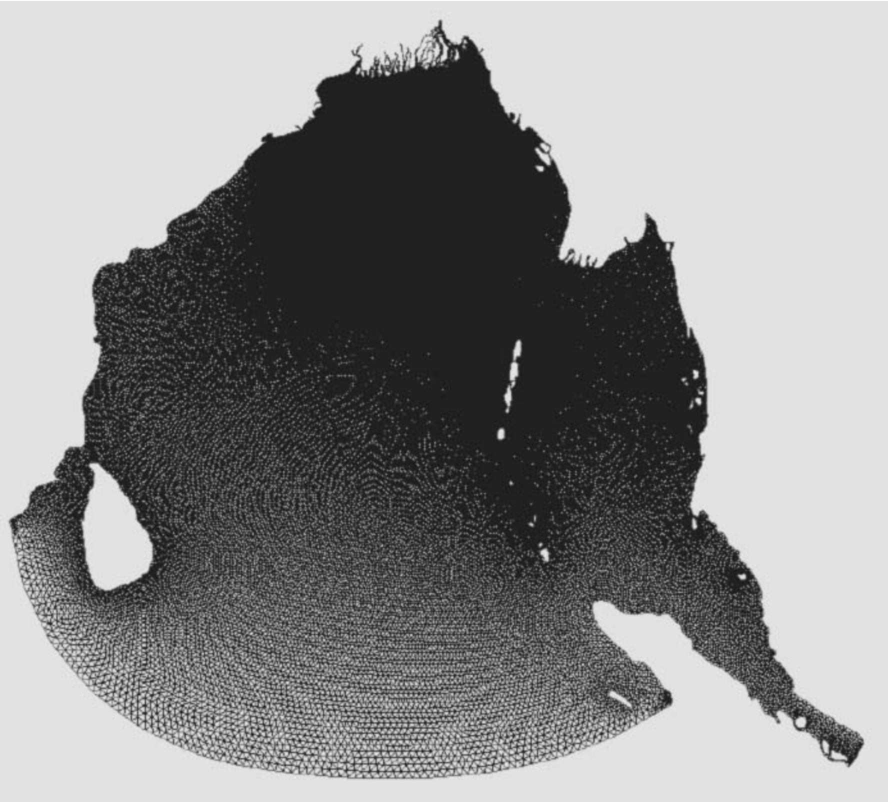


Fig. 2.2. The extended ADCIRC finite elements grid of the model domain.

Earlier Models of the Bay of Bengal

Numerical models have been used to hindcast cyclone storm surge for at least four decades, including efforts to simulate observations from the Bay of Bengal (see Murty et al. 1986 and Flather 1994). Murty et al. (1986) provides a review of earlier Bay of Bengal models used to hindcast past events, typically driven by idealized and symmetric cyclones of constant intensity moving along straight-line tracks. The domains of earlier Bay of Bengal models were confined to the immediate vicinity of the coast (Flather 1994, As-Salek 1998). Regional or local models such as these require ocean and land boundary conditions to be supplied either by *in situ* tide gauges or by reference to basin-scale or global models (Blain et al. 1994). While informative, the hindcasting approach has limited utility for forecasting when the track and storm intensities are changing over time and boundary conditions are not immediately available.

As shown by Blain et al. (1994), a truly predictive capability for elevation and flow in coastal regions requires that all important scales of motion be sufficiently resolved in the numerically discrete form of the governing equations. Blain et al. (1994) clearly showed that storm surge model domains on the continental shelf must be large relative to the size of the storm to avoid significantly underestimating the primary storm surge response. On the other end of the spatial scale, Blain et al. (1994) showed in a grid convergence study that near-coastal resolution is the most critical factor for accuracy of storm surge computations. Typically, a higher degree of grid refinement is required as the landward boundary is approached. The earlier ADCIRC model developed by Mashriqui et al. (2005) extended the model domain to the Northern Indian Ocean. Research reported in this paper is a continuation of that earlier work. Current model domain has been extended to include part of the island of Sumatra to avoid a complex boundary tide when it propagates from the Indian Ocean to the Bay of Bengal. Wetting and drying capabilities were also added to the current model domain.

Methods

The model used by Mashriqui et al. (2005) has a wide, deep open ocean boundary along the south boundary. Depth in the Bay of Bengal decreases south to north, from a maximum of 4,000 m (Fig. 2.1). The Andaman and Nicobar Islands form a discontinuous barrier extending south of Myanmar, which separates a shallow eastern portion from the rest of the bay. The Meghna River enters the model domain from the north at a discharge boundary. We developed the geometry of the model domain from the digital world map (ESRI ArcView sample data). Bathymetry was obtained from the ETOPO2 database from the National Center for Atmospheric Research (NGDC 2004). Near-shore and coastline bathymetry were obtained from U.S. Defense Mapping Agency and British admiralty charts that were hand-digitized and edited. The finite element grid used by Mashriqui et al. (2005) contains 63,407 nodes and 122,822 finite elements. The level of grid refinement is based on grid convergence studies as well as on the response functions obtained from previous computations (Blain et al. 1994, 1995). In general, the deepest waters in the Bay of Bengal are relatively coarsely discretized, while the continental shelf waters and regions of detailed interest, in this case Ganges delta and vicinity, are very finely resolved. The largest finite elements in this grid have a size of 40 km while the finest elements are sized 150 m. The water level along the open boundary is obtained from global tidal information and is represented by the five major constituents (M2, S2, N2, O1, and K1) from LeProvost et al. (1995) FES95.2 database. This database was developed using a global tidal model and has been found to perform very well in deep ocean waters.

For our tidal calibration, we sought to reproduce amplitude and phase of each tidal constituent predicted by the Colorado University (CU) and University of Texas (UT) global models (*www.ssc.erc.msstate.edu/Tides2D*). To do this, the model was spun up from homogeneous initial conditions using a 20-day time ramp (Westerink and Luettich 1991). The very smooth hyperbolic tangent time ramp function was applied both to the boundary conditions and direct forcing functions. A 20-day spin up is more than adequate for all constituents of interest (Westerink and Luettich 1991). Simulations with five s time-steps were run for 90 days, but only the last 60 days were used.

Tidal Calibration Results

An examination of the ADCIRC simulated tides in the Bay of Bengal showed excellent agreement with the CU and UT studies for M2 amplitude and phase (Figs. 2.3 and 2.4). However, the tidal phase that ADCIRC predicts in Bangladesh and Myanmar cannot really be compared to the UT and UC global tides because the ocean models are not meant to predict nearshore conditions. ADCIRC results appear to depict realistic tides in the shallow regions around the basin, such as off the coast of Bangladesh and off Burma and India. The model displays considerable skill in modeling the tides in the Bay of Bengal. Similar agreements were observed for the S2, K1, O1, and N2 tides. Current model domain has been extended to include part of the island of Sumatra to avoid complex boundary tide when it propagates from the Indian Ocean to the Bay of Bengal.

Cyclone Hindcasting

The U.S. Navy Joint Typhoon Warning Center (JTWC) provided an excellent dataset describing the April 1991 cyclone that struck the coast of Bangladesh causing thousands of fatalities (JTWC annual report 1991). This track and central pressure time-series was input into ADCIRC's PBL wind model. The ADCIRC model that had been parameterized against the tidal constituents, as previously described, was not changed for the cyclone hindcast. Flather (1994) provides summaries of field observations of the resulting storm surge.

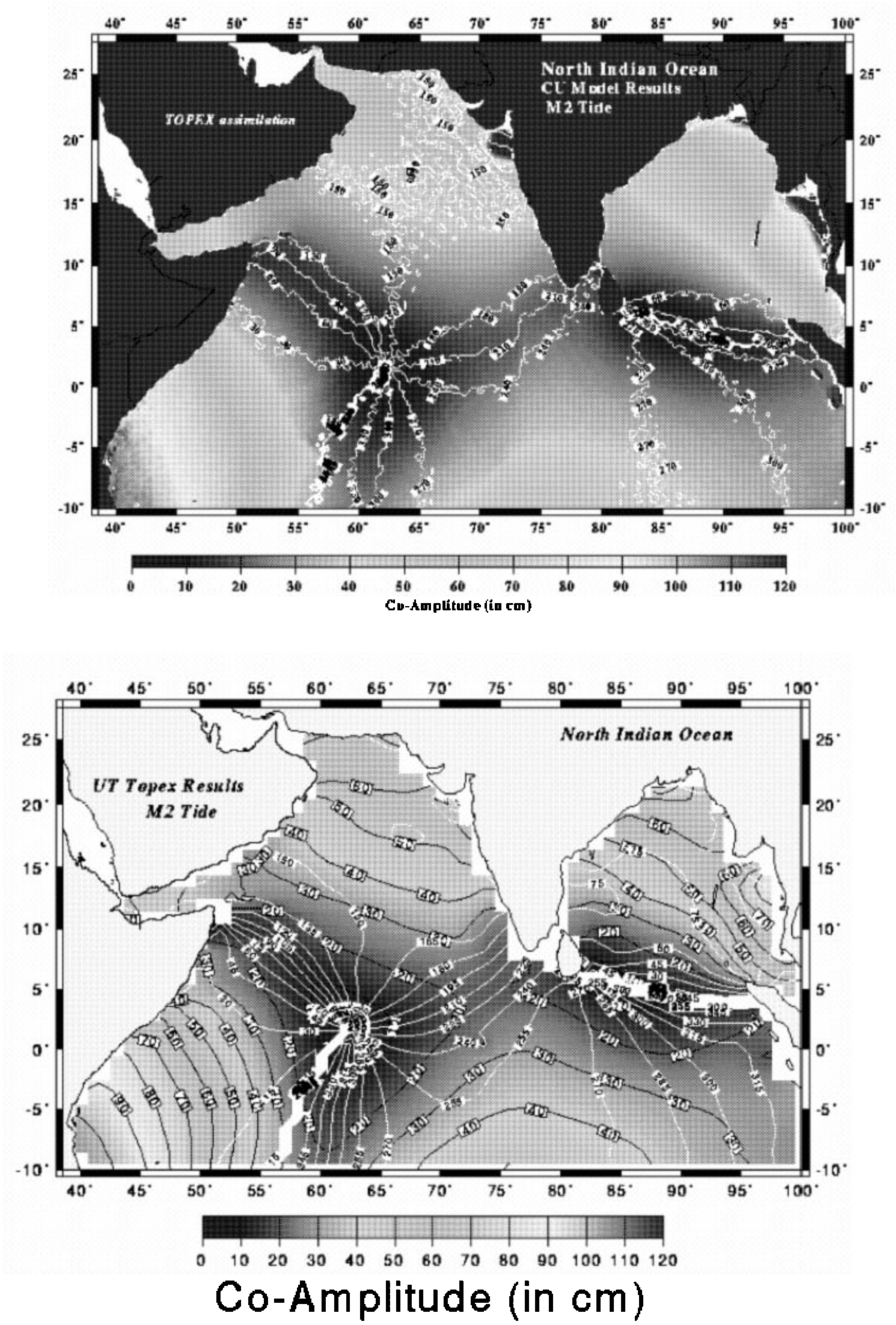


Fig. 2.3. The Indian Ocean and the Bay of Bengal M2 tide derived from the CU/NAVOCEANO (top) and UT model (bottom) (Mashriqui et al. 2005).

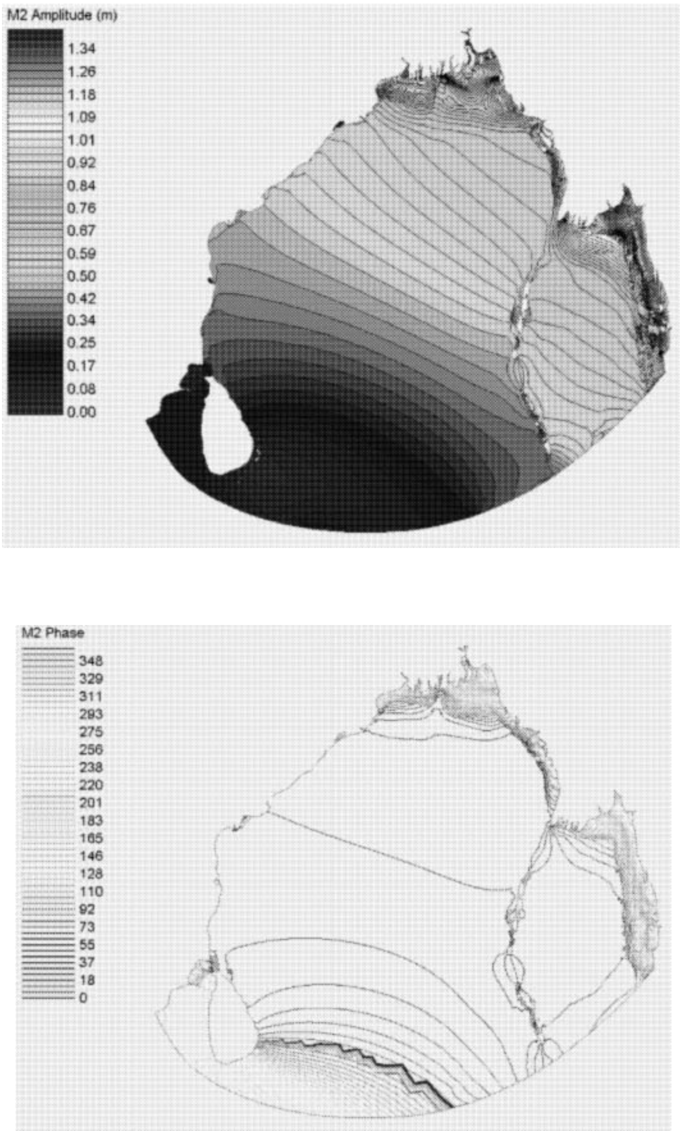


Fig. 2.4. The Bay of Bengal M2 tide derived from the ADCIRC amplitude (top) and phase (bottom) (Mashriqui et al. 2005).

Flather's (1994) distribution and that predicted by ADCIRC both show that maximum elevation was reached in the strait between Kutubdia Island and the Bangladesh mainland south of Chittagong (Fig. 2.5). ADCIRC predicted the highest surge to be 4.23 m above mean sea level (MSL). Flather (1994) gives a 4-m contour for storm surge residual elevation that includes all of Kutubdia Island, suggesting very reasonable agreement with ADCIRC. Again, the April 1991 cyclone was simulated using the new extended model domain with wetting and drying capabilities. Patterns and sequences of flooding of the east coast of Bangladesh near Chittagong are shown in Figure 2.6.

Forecasting of Future Cyclones

The fully parallel ADCIRC model has been used experimentally since 2002 for storm operation support in the Gulf of Mexico. The ADCIRC model was calibrated using two different hurricanes that made landfall in Louisiana—Hurricanes Betsy (1965) and Andrew (1992). The ADCIRC model showed a very good correlation with the actual storm surges measured during these storms. The ADCIRC Southern Louisiana storm surge flood model is the most sophisticated, detailed, and accurate model of coastal flooding in the world.

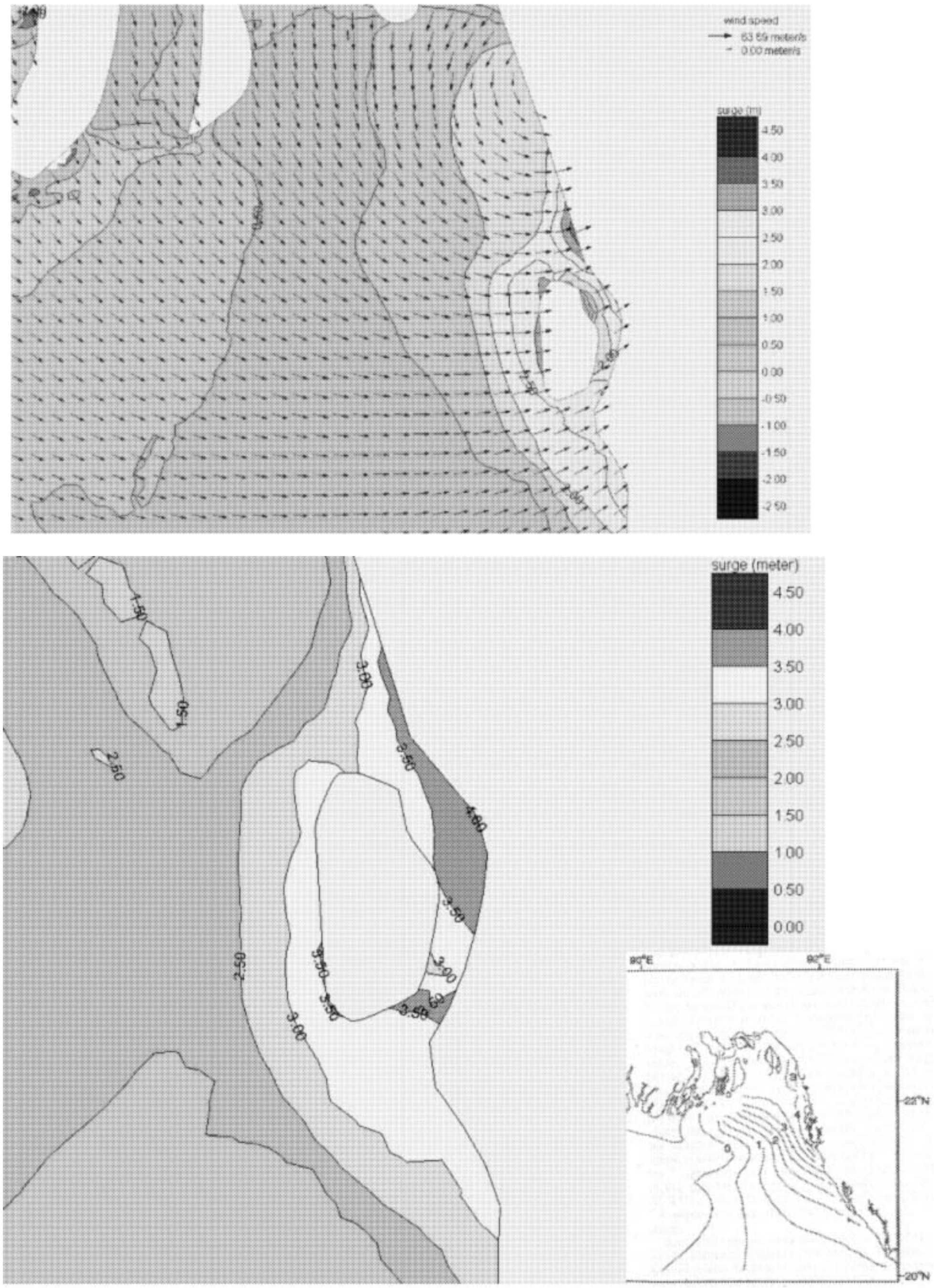
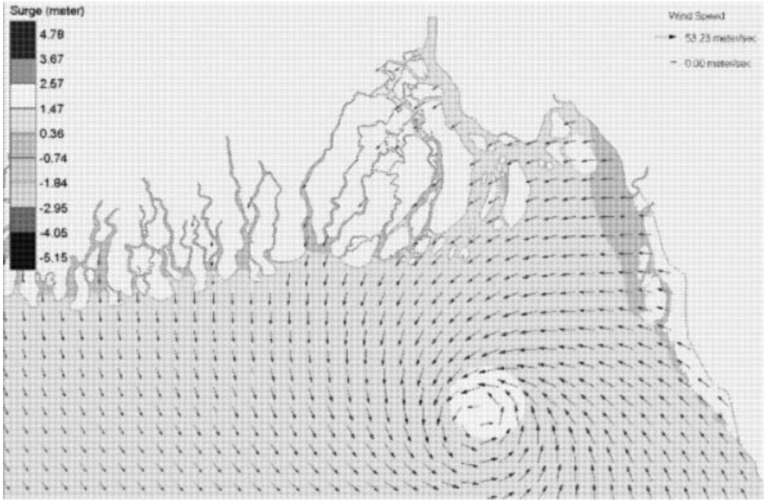
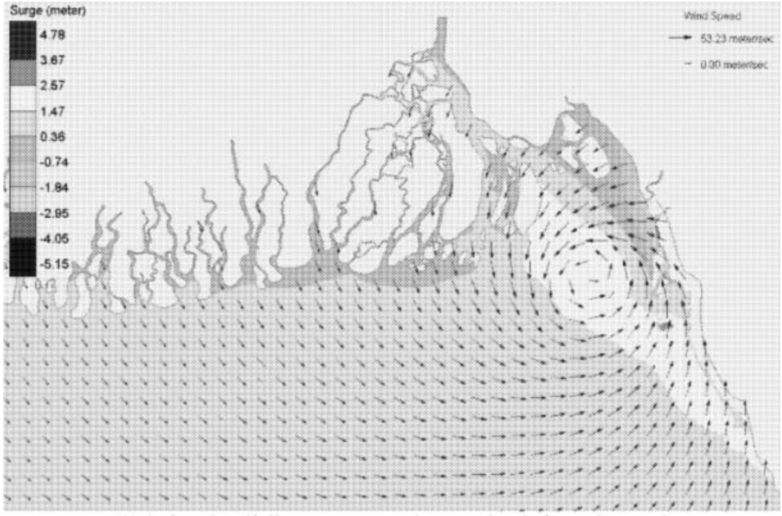


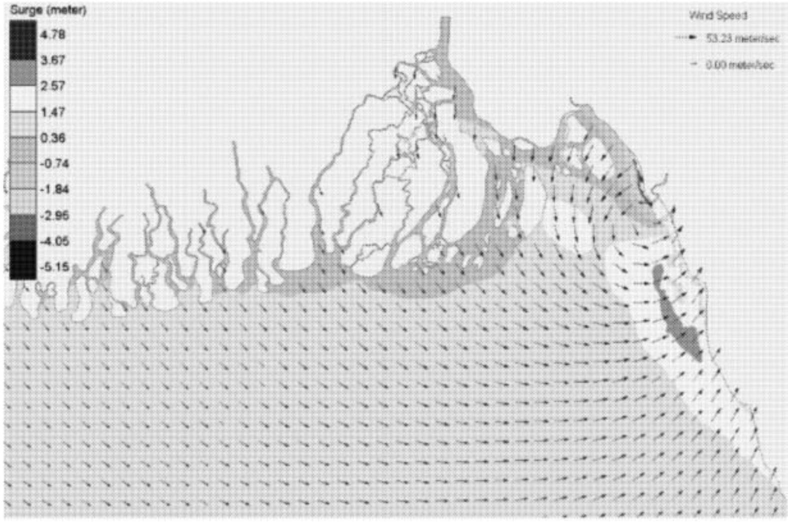
Fig. 2.5. ADCIRC simulated storm surge before landfall. The arrows indicate wind vectors; the colors indicate water levels (top). ADCIRC maximum surge height near Kutubdia Island compared to Flather (1994) (bottom, inset).



(a) long before the landfall



(b) before landfall, surge is inundating islands from the south



(c) during landfall, surge is inundating islands from the south and the west

Fig. 2.6. ADCIRC simulated storm surge before and during landfall. The arrows indicate wind vectors; the colors indicate water levels (top).

The modeling team at LSU has demonstrated a capability to provide multiple, near real-time forecast permutations that can meet decision-makers' needs to improve preparedness and public safety response. The LSU Hurricane Center will process JWTC forecast data and provide similar experimental modeling support for the Bay of Bengal basin, beginning with the 2005 cyclone season, to improve and demonstrate model capabilities. The objectives of this modeling program are to provide 3- to 5-day forecasts of storm surge height and propagation and to illustrate them on a Web-accessible, high-resolution coastal map of the Bay of Bengal (Fig. 2.7) (*www.stormsurg.lsu.edu*). Storm surge computations will be made on a new LSU CCT supercomputer, a Beowulf-class supercomputer with 1,024 processors, which is among the fastest academic clusters in the world. Use of the supercomputer technology and GIS makes this modeling program unique and the first model ever to simulate storm surge in the Bay of Bengal in a forecast mode.

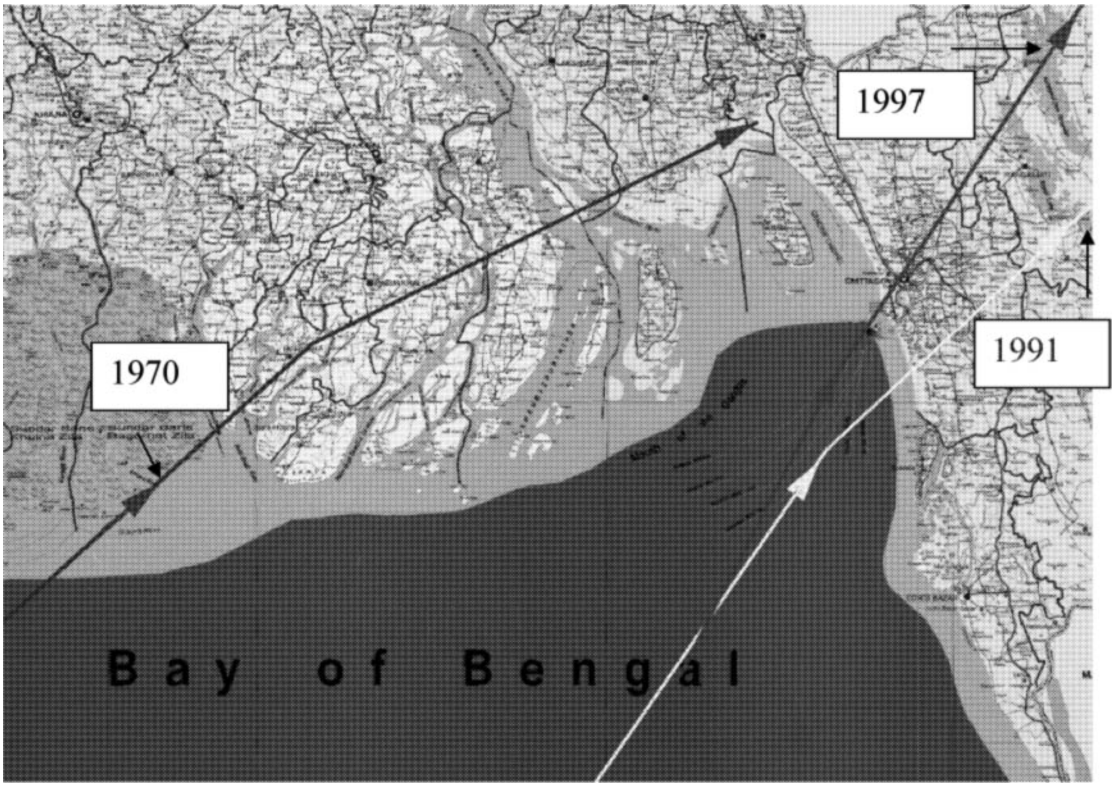


Fig. 2.7. November 1970, April 1991 and 1997 cyclone landfall location from the best track data of JTWC super imposed on a local high-resolution map. Note the path of the eye over local cites.

Conclusions and Recommendation

Improved forecasts of storm surge coupled with more timely and accurate warnings are important prerequisites for saving lives in the heavily populated coastal regions surrounding the Bay of Bengal. Based on the preliminary results presented here, ADCIRC appears to offer great promise if forecast results can be disseminated quickly enough as a storm approaches landfall. More detailed information on bathymetry and land elevations in the vulnerable areas would improve the simulation of inundation. The Bay of Bengal is an underserved area in contrast to other cyclone prone parts of the world. We strongly recommend that United Nations agencies such as WMO implement an advanced near real-time forecasting model in the Bay of Bengal. Twenty years ago Murty and Henry (1983) recommended that an international effort be organized to collect and publish complete dossiers of relevant data on major surges in the bay. Approximately four large surges occur each year within the Bay of Bengal ADCIRC domain, but since each affects only a small portion of coastline, Murty and Henry (1983) concluded that this data-gathering scheme would have to be pursued for up to two decades to accumulate an adequate body of verification data. We believe that a tool like ADCIRC could greatly reduce the time necessary because it would be possible to generalize more efficiently from fewer storm dossiers.

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Chapter 3: Wind Effects on Cyclone Shelters in the Coastal Regions of Bangladesh

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Abstract

Natural disasters are part of life. They cannot be prevented or controlled, but they can be managed. With the advancement of science and technology, mitigation measures have been devised to protect human lives and properties from destruction. Tropical cyclones commonly occur in India and Bangladesh, hurricanes occur in the United States, and typhoons develop in Japan. These tragic events have cost thousands of lives. Bangladesh has built many shelters in its coastal region to protect its citizens. This paper focuses on the wind load effects on shelters during high winds with special reference to Bangladesh and reviews codes and standards related to wind effects. It also presents a detailed case study on an existing cyclone shelter in Bangladesh, draws conclusions from the investigation, and presents a few observations and recommendations about the construction of future shelters.

Introduction

The coastal region of Bangladesh is frequently hit by tropical cyclones. In 1970 a severe cyclone reportedly took more than 300,000 lives. Perceived apathy towards Bangladeshis by the Pakistani central government at the time of the disaster contributed to their list of grievances in seeking independence. Two cyclones in 1991 took about 270,000 lives. The disastrous cyclone that hit the coast on April 29-30, 1991 was the impetus for undertaking a study to prepare a master plan for cyclone shelters in the vulnerable areas of the Bangladesh coastal belt. The study was completed in 1992 (BUET and BIDS 1992).

A principal goal of the 1992 study was to develop a definitive program for building multi-purpose shelters. To accomplish this, a methodology was developed to determine the number of new shelters required and possible locations (Nishat 1998). This methodology was then evaluated through a pilot project conducted in Char Fasson of Bhola District. Discussions were held with the local residents to objectively assess the need for new shelters and their locations. The study team thoroughly investigated all facets of the proposed shelters and developed a methodology to determine the number and location of new shelters.

This study determined that about one-third of the total population in the high-risk area could be sheltered in buildings capable of resisting the extreme winds during a cyclone with floors raised above the maximum surge levels. The remaining two-thirds could be protected by building 2,500 multi-purpose shelters, almost all of which would be used as schools. Some of these shelters would be set on top of *killas* or earthen mounds raised above the surge level so the livestock could be protected as well. The probable movement of the population to different types of shelters is shown in Figure 3.1 (Nishat 1998).

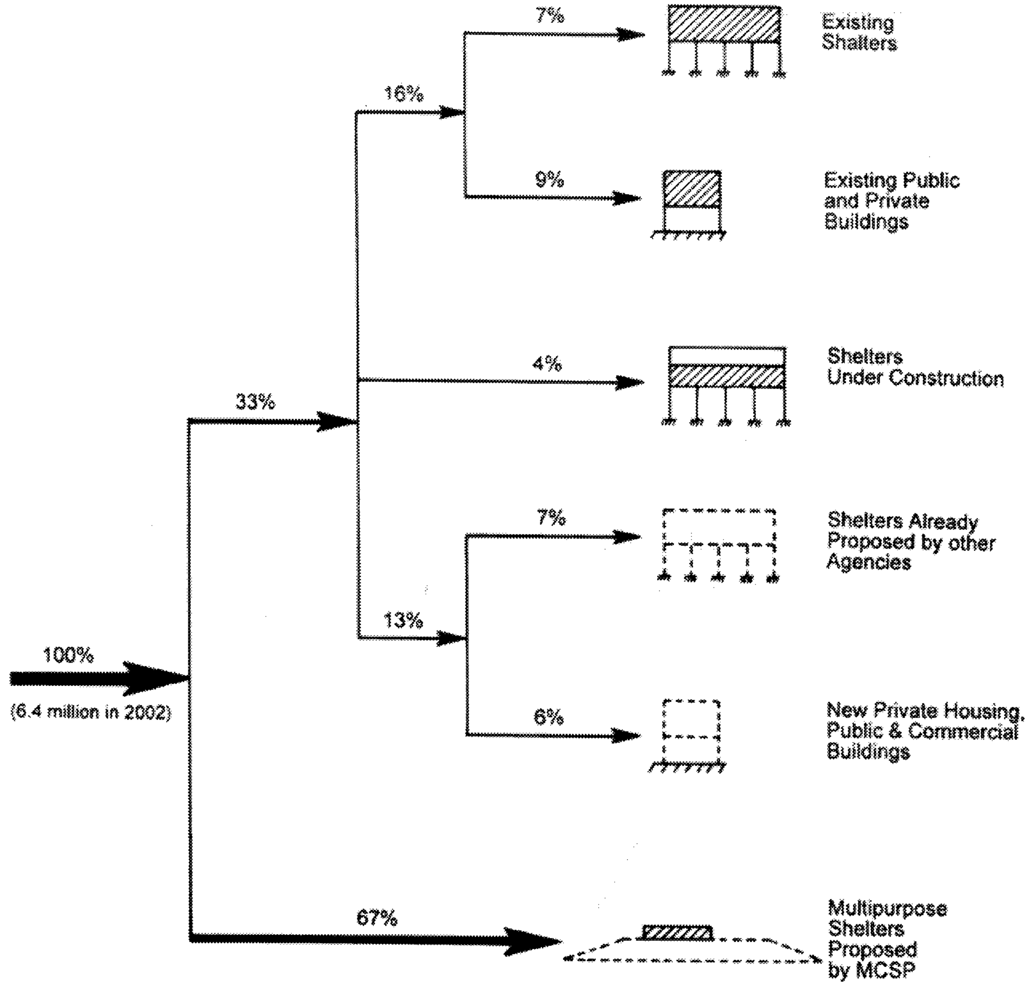


Fig. 3.1. Distribution of probable movement of the population in high risk areas to different types of shelter accommodation (Nishat 1998)

A number of shelters have been constructed in the coastal belt of Bangladesh. Simultaneously, Bangladesh has been improving its forecasting and early warning services. The Bangladesh government has built concrete shelters on columns and atop *killas* that are higher than surge levels, but these are still inadequate considering the large coastal population. This paper presents an overview of the government's shelter program and investigates the adequacy of an existing shelter in withstanding wind load effects on it.

The Big Picture

Unlike developed countries, which have effective agencies to forecast, prepare, and mitigate natural disaster, developing countries are caught in the midst of development. Agencies in countries such as India and Bangladesh struggle to assist people during times of disasters. Their ineffectiveness is due in large measure to population size and poor/ineffective modes of communicating with the people. The Red Crescent Society is reported to now have about 33,000 volunteers who travel on foot around villages with relaying microphones to warn people of the impending storms. Transportation problems also make evacuation difficult. These problems are exacerbated by the rapidly increasing population, the vast majority of whom are impoverished and lack the means to build protective homes to withstand disastrous tropical storms.

The primary solution in Bangladesh is to build more cyclone shelters within vulnerable areas. The government and a few Non Governmental agencies (NGO) have built reinforced concrete shelters. Unfortunately these are small and poorly maintained, and most who seek shelter in them must stand through the storm due to the lack of space. Many shelters are chaotic with rooms originally intended for storage being used to shelter people. Architectural planning is a low priority and cultural sensitivities are not taken into account. For example, Bangladeshi women in many cases are unwilling or unable to take refuge in cyclone shelters because it means staying in the same place with men outside their family, which is not culturally accepted. In addition, the main economic assets at risk from cyclones are household possessions and livestock. As a result, residents place high priority on sequestering their cattle, goats, and poultry on *killas* before taking refuge in cyclone shelters. While not the topic of this paper, some of these shelters might have been built to comply with out-of-date building codes and as a result are unsuitable for occupancy during a storm.

More effort and research need to be directed to developing countries like Bangladesh in the design and planning of cyclone shelters. These countries need storm shelters that:

- provide a safe and secure temporary refuge for people within a reasonable distance of their homes;
- are planned with cultural and social sensitivities in mind;
- provide enough space for the community's population;
- provide good hygiene and sanitary conditions; and
- are durable and economical.

The most crucial aspects of shelters are proper architectural planning and structural design because the shelters must ensure that the population's needs are met in a healthy and safe manner during the temporary stay.

Factors Influencing the Design of Multi-Purpose Shelters

Multi-purpose shelters are economically viable because they can be used for other purposes during normal times. Planning for these shelters involves an accurate assessment of many factors, including site location, building shape, materials used, planning and programming, structure, and construction techniques, to name a few.

Site Location: Site location is crucial to keep the shelter safe from flooding. It should include determining the elevation of the shelter floor needed to avoid flooding. The buildings should not be located on exposed hillcrests or in open-ended valleys that act like funnels for the wind. In addition, the shelter should be located within a critical distance of the people it serves for ready access during an emergency.

Shape: Configuration is the most important factor in determining a building's performance during a cyclone. Simple, compact, symmetrical shapes are the best way to avoid torsion caused by wind

forces on the structure. Another important consideration is the roof geometry. This is less important in Bangladesh, however, because flat roofs are traditionally used.
Material: The most important step in building a shelter is evaluating building materials and each component's rating to carry large wind forces. As in many developing countries, concrete is the favored material in Bangladesh because of its local availability and tradition. However, the durability of concrete is important, especially in the corrosive environments prevalent in coastal areas.

Planning and Programming: Evaluating the need for a shelter and all needs of its occupants is essential in the planning effort. The program requirement should clearly meet and exceed requirements for space and resources. The architecture should lift its occupants' spirits during a disaster and maintain healthy living conditions to encourage communal harmony and interaction. Special attention should be given to the design of spaces for handicapped, old, and feeble people.

Structure: Structural requirements must be satisfied to ensure that the components of the shelter —foundation, walls, columns, roof, and such—will withstand wind speeds and water surges specified in the local building code and employ higher safety factors while designing them.

Construction Technique: Shelters are fast emerging as special building types. They should be built using specialized construction techniques and strong materials.

Building Codes and Standards

The Bangladesh National Building Code (BNBC) was developed and released in 1993 by the Housing and Building Research Institute and the Bangladesh Standards and Testing Institution (BNBC 1993). Part 6, Chapter 2 of the code, specifies wind loads (Section 2.4) and loads due to flood and surge (Section 2.6.4). It appears that this code has not been updated since 1993. In the United States, ASCE 7-02 forms the basis of wind load calculations (ASCE 7-02, 2002). This code is rigorous and represents the state-of-the-art in wind load as well as flood and surge research in the United States. The flood-level and wind-load effects are presented in Sections 5 and 6. The latest International Building Code (IBC) refers to the ASCE 7-02 for wind load effects in its Section 1609 and to ASCE 7-02 for dry flood-proofing, but it is silent on surges or hydrodynamic loads (IBC 2003). The Federal Emergency Management Agency (FEMA) has guidelines for shelters in its report FEMA 361 (FEMA 2000). The U.S. National Research Council has published several reports in this area including *Facing the Challenge: The U.S. National Report to the IDNDR World Conference on Natural Disaster Reduction* in 1994.

The International Code Council (ICC) formed the ICC Consensus Committee (CC) to develop the "Standard on Design, Construction, and Performance of Storm Shelters." This standard will provide technical design and performance criteria to facilitate and promote the design, construction, and erection of safe, reliable, and cost-effective storm shelters to protect the public. This standard is being developed jointly by the ICC and the National Storm Shelter Association to augment FEMA guidelines for protecting the public from extreme environmental effects such as hurricanes.

Assessment of Wind Loads on a Structure

The ASCE 7-02 standard stipulates three methods for determining wind loads:

1. Simplified procedure
2. Analytical procedure
3. Wind tunnel procedure

To qualify for the simplified procedure, an enclosed/partially enclosed building whose design wind loads are determined in accordance with this procedure must meet a number of conditions. These include the mean roof height of the building is less than or equal to 9 m; the building has a regular shape or structure, and the structure is not flexible (dynamically sensitive). For the analytical procedure, the building or structure must be regularly shaped; must not be vulnerable to a cross-wind loading, vortex shedding, and galloping or flutter; and must not have a site location for which channeling effects or buffeting in the wake of upwind obstructions warrant special conditions. Buildings that do not meet these requirements or have unusual shapes or response characteristics must be designed using the wind-tunnel procedure.

The focus of this paper is to investigate the kind of external wind forces that act on a typical shelter located in the cyclone-prone areas of Bangladesh. The study analyzes wind forces using the ASCE 7-02 standard acting on a representative cyclone shelter in the coastal belt. The wind pressure values are then compared to those obtained using the Bangladesh Code to analyze the same building. The building's stability was also checked for overturning and sliding based on the highest wind force values obtained. A preliminary structural analysis was performed for the calculated wind loads using computer software RAM-Advanse 5.1 to check the structural integrity of the shelter.

Case Study

The building chosen for the case study is an existing reinforced concrete shelter at Moheshkhali, an island off the coast of Cox's Bazar in Bangladesh. Cox's Bazar is the tourist capital of Bangladesh and has the world's longest natural beach (75 mi./hr. [120 km/hr.]), which slopes down gently to the Bay of Bengal. Through the center of the island and along the eastern coastline, lies a range of low hills about 300 ft. (91 m) high, but the coast to the west and the north is low lying, fringed by mangrove jungles. The island has an area of 25 sq. mi. (268 km^2). The multi-purpose shelter is located in this area, within a few kilometers of the coastline. Several views of the shelter are shown in Figures 3.2, 3.3, 3.4, and 3.5. Its windows are louvered instead of glazed. Hence the structure was taken as enclosed for the wind load effects.

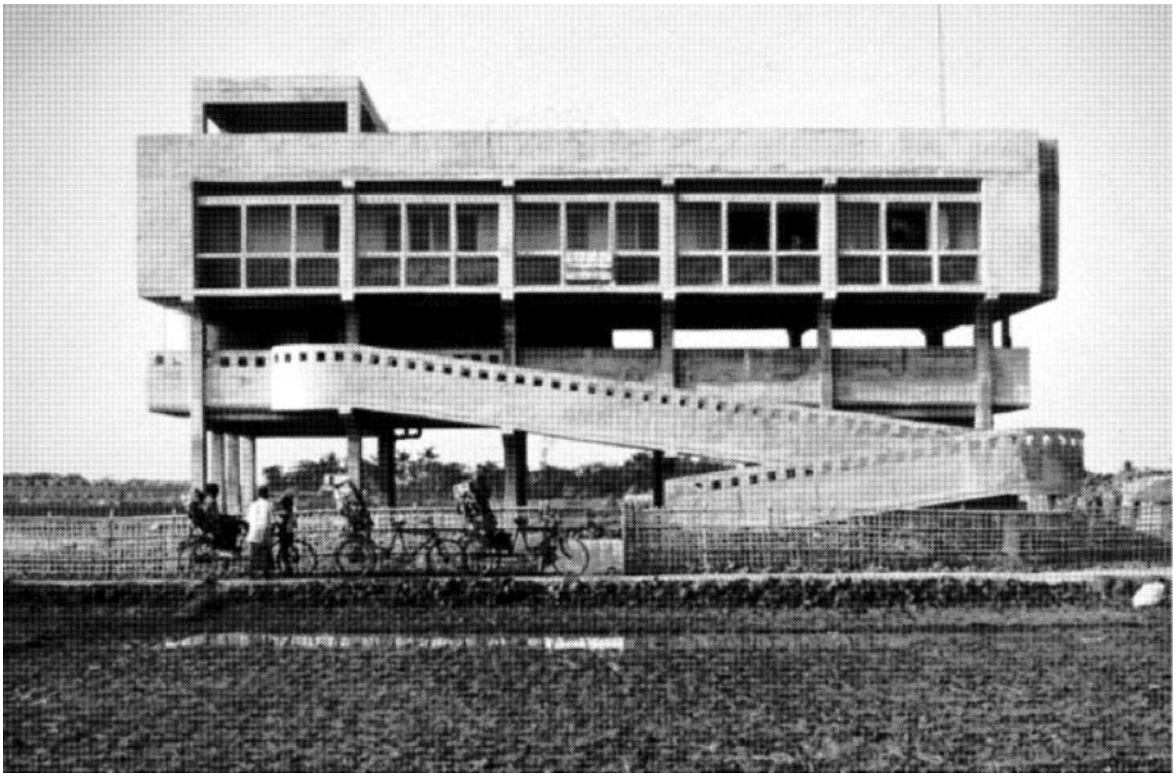


Fig. 3.2. Front elevation of Moheshkhali Shelter

Fig. 3.3. Isometric view of the shelter

Fig. 3.4. Interior view of the shelter

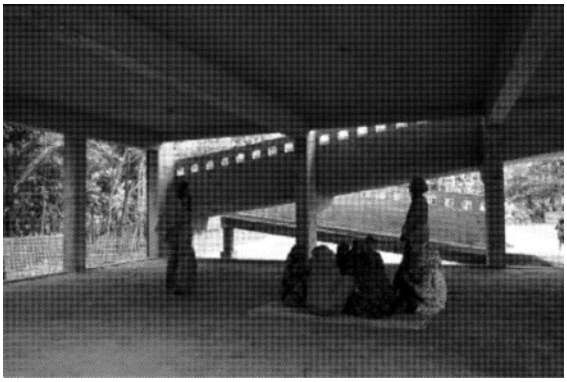


Fig. 3.5. View of the first floor

Because sufficiently detailed data were not available, the following approximate building dimensions were assumed on the basis of best possible information and judgment:

Horizontal dimensions of the shelter:	110 ft. H 30 ft. (33.5 m H 9 m)
Column dimensions:	
Perimeter columns	24 in. H 16 in. (610 mm H 406 mm)
Interior columns	16 in. H 16 in. (406 mm H 406 mm)
Column spacing:	21 ft. (6.33 m) o.c. along the long side and 9.8 ft. (3 m) o.c. along the short side
Column height:	
First or lowest story (open)	14 ft. (4.25 m)
Second story	12 ft. (3.7 m)
Third story	12 ft. (3.7 m)
Height of building:	38 ft. (11.6 m)
Penthouse dimensions:	22 ft. H 13 ft. H 8 ft. (6.7 m H 4 m H 2.4 m)
Parapet dimensions:	3 ft. (0.9 m) high H 8 in. (203 mm) wide
Ramp dimensions:	165 ft. (50.3 m) total length H 3.5 ft. (1.1 m) wide H 5 in. (127 mm) thick
Ramp railing dimensions:	3.5 ft. (1.1 m) high H 6 in. (152 mm) thick

The structure was designed following the ACI Code prevailing at the time. For the superstructure, rigid moment-resisting frames were employed. For such shelters in general, mat and pile foundations were used with spread or combined footings for low column loads in some locations. The foundation detail for this particular building was not available. Clear covers of 3 in. (75 mm) for columns, 2 in. (50 mm) for beams, and a minimum of 1 in. (25 mm) for slabs were specified. Concrete of 3.6 ksi (25 MPa) strength and grade 60 steel were used. The structure was designed for a wind speed of 162 mi./hr. (260 km/hr.). Information on reinforcement quantities was not available, but it may be inferred that the structural design was conservative for the assumed loads because past ACI codes are generally more conservative than the current ACI 318-05 Code due to reduced load factors, albeit with a decrease in the strength reduction factors for shear, axial compression, and bearing.

Dynamic Sensitivity of Structure

Because the shelter is supported entirely on columns resulting in an irregular structure with an extremely soft-story condition, the dynamic sensitivity of the structure subjected to wind loads was investigated. According to ASCE 7-02, a building is flexible or dynamically sensitive if the fundamental frequency is less than 1 Hz. For such a condition, the gust effect factor G_f is specified differently from the same factor G of rigid structure and is based on a long-wind buffeting response. A commonly adopted rule is that if the height is less than four times the least horizontal dimension, the fundamental frequency is judged to be greater than 1 Hz. However, due to the irregular nature of the structure, this rule is not applicable in this case. An approximate yet rigorous procedure was followed to find the frequency of the structure and determine whether the structure is rigid or flexible. The fundamental period of the structure was calculated from

$$T = 2\Pi\,(m/K)^{1/2}$$

in which m is the mass and K is the stiffness of the structure.

For simplicity and practical considerations, the structure was assumed as a single-degree-of-freedom system. The total effective mass of the building was calculated as 97,550.44 lb. sec^2/ft. (1,423,261 kg). To find the stiffnesses, two column base conditions were considered: (1) fixed for mat foundation and (2) hinged for pile foundation. This assumption of the column support conditions is based on practical experience and the fact that large rigid mats are highly stiff compared to column stiffness, whereas pile caps are relatively less rigid and are vulnerable to unpredictable rotations on soft soils. The end conditions for columns at the top are assumed to be fixed where the floor plate meets the columns at 14 ft. (4.25m) above grade. This assumption is based on the fact that (1) the structure above is top-heavy with great mass and very large built-in stiffness due to the presence of the walls and other non-structural elements and that (2) the top of the columns are restrained from rotation. The stiffness of the fixed-fixed column (Condition 1) is given by

$$k = \frac{12\,EI}{L^3} \tag{3.1}$$

where EI is the rigidity modulus and L is the height of the column. For the fixed-pinned column (Condition 2) the stiffness is given by

$$k = \frac{3\,EI}{L^3} \tag{3.2}$$

The structure's stiffness was calculated in both the short and long directions by adding all element stiffnesses. The column length was taken as 18 ft. (5.5 m) measured to the top of the foundation. For Condition 1, the fundamental periods in the short and long directions were found to be 0.55 sec. and 0.86 sec. Thus, the corresponding fundamental frequencies in these two directions are 1.82 Hz and 1.18 Hz (the building is rigid in both directions). For Condition 2, the fundamental periods in the short and long directions were found to be 1.1 sec. and 1.69 sec. Thus, the corresponding fundamental frequencies in these two directions are 0.91 Hz and 0.59 Hz (the building is flexible in both directions). Note that the structure is dynamically more sensitive in the long direction than the short direction because the orientation of most columns offers lower stiffness values of individual columns in the long direction. This suggests that such shelters built on pile foundations in anticipated soft soil conditions in the coastal belt may be dynamically sensitive.

Wind Pressure Determination: ASCE 7-02

For calculating the wind pressure on the shelter, both cases of rigid and flexible structure were considered. Wind speed was taken as 162 mi./hr. (260 km/hr.). This can also be seen in Figure 3.6, which shows the location of Cox's Bazar (BNBC 1993). The analytical procedure is applicable for the shelter.

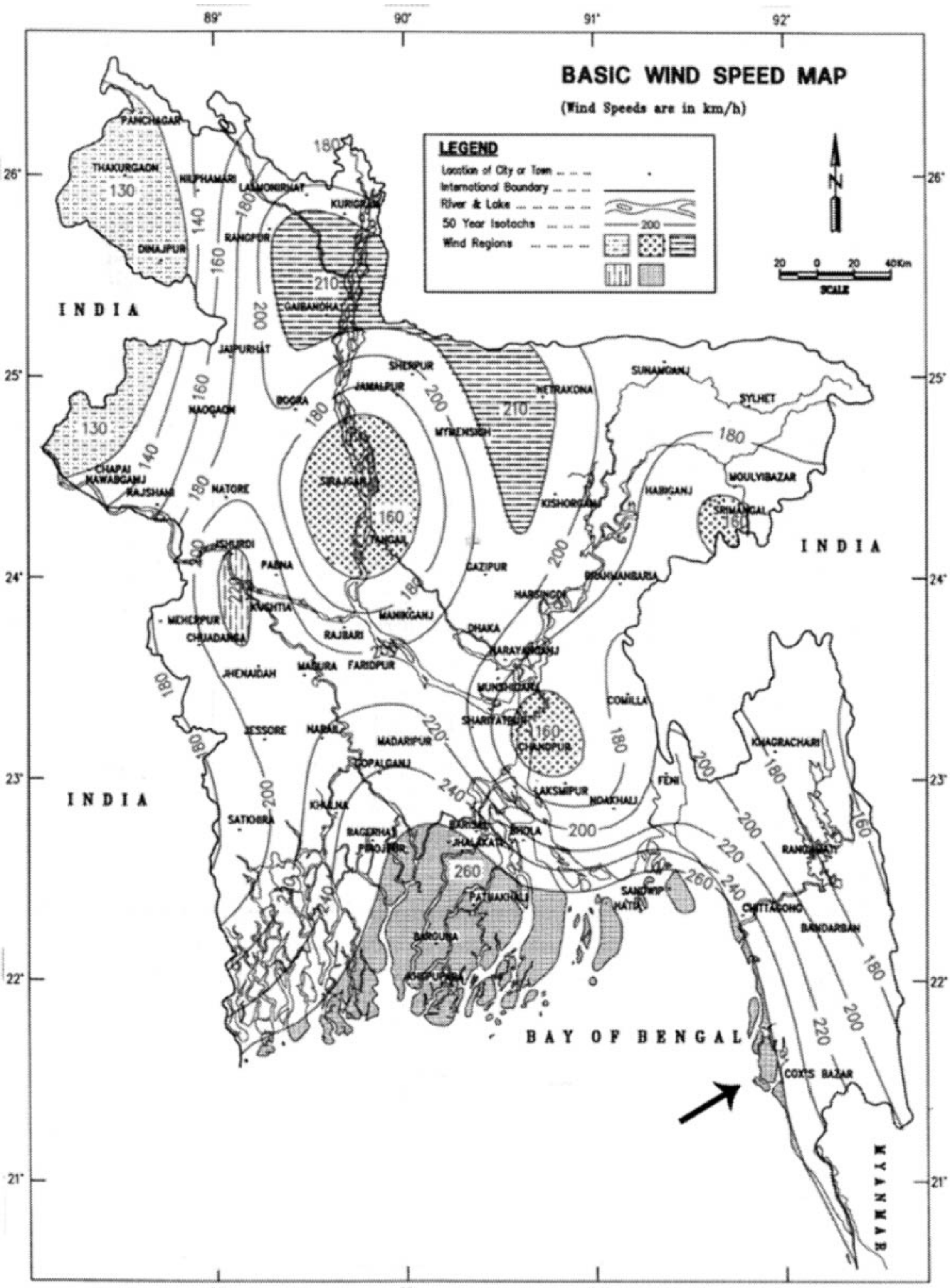


Fig. 3.6. Basic Wind Speeds of Bangladesh (BNBC-93)

The velocity pressure, q_z in N/m^2, was calculated by the following equation:

$$q_z = 0.00256\, K_z\, K_{zt} K_d V^2 I \text{ (lb/ft}^2\text{)} \tag{3.3}$$

$$[\text{In SI: } q_z = 0.613\, K_z\, K_{zt} K_d V^2 I \text{ (N/m}^2\text{)}]$$

where
K_z = velocity pressure exposure coefficient evaluated at height Z
K_{zt} = topographical factor
K_d = wind directionality factor
V = basic wind speed in m/sec
I = importance factor

Taking K_{zt} = 1 (due to homogenous terrain), k_d = 0.85 (for buildings) and I = 1.15 (for designated hurricane center) and assuming Exposure Category C (flat and open terrain), q_z is calculated as 65.67 K_z lb/ft^2 (3144.28 K_z N/m^2). K_z was calculated from Table 6-3 of ASCE 7-02. K_z depends upon the height Z above ground and thus defines the vertical wind pressure distribution.

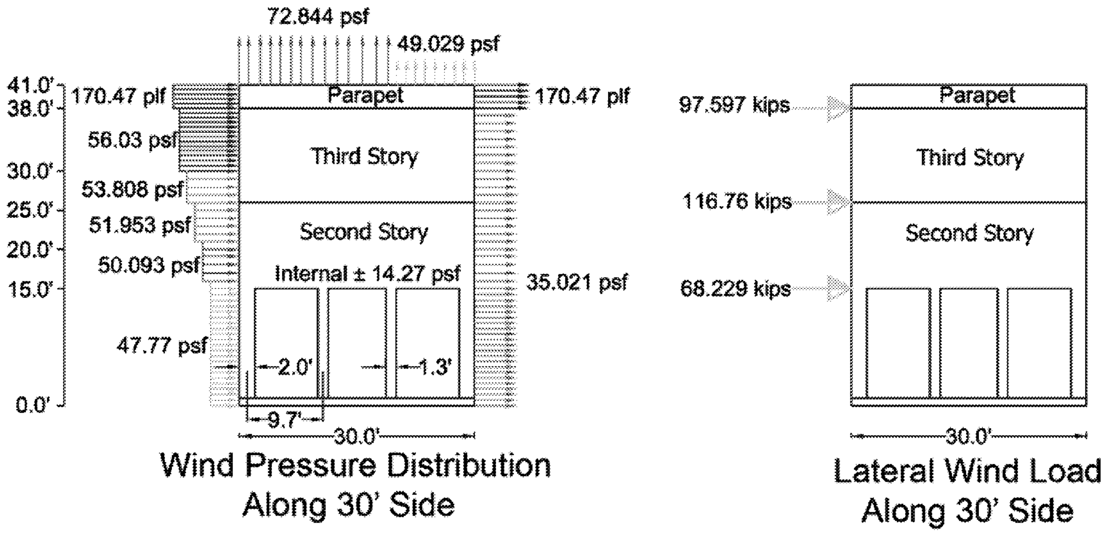
Design wind pressures for rigid main wind force resisting system (MWFRS) are given by

$$p = qGC_p - q_i (GC_{pi}) \tag{3.4}$$

where
q = q_z for windward wall evaluated at height Z
q = q_h for leeward walls evaluated at height h
q_i = q_h or q_z defining internal pressure coefficient depending upon certain specific conditions
G = gust effect factor
C_p = external pressure coefficient
(GC_{pi}) = internal pressure coefficient

The factor G can be simply taken as 0.85 or calculated from a detailed formula (Eq. 6-4 of ASCE 7-02). Using the detailed formula, G was found to be equal to 0.894. Selecting the appropriate values from the ASCE 7-02 tables and figures, the wind pressures are shown in Tables 3.1 and 3.2.

Since roof and sidewall pressures are not critical for structural behavior in any one principal orthogonal direction, these are not considered in this research. Design pressures on the Main Wind Force Resisting System (MWFRS) for the two principal directions are presented in Figures 3.7, 3.8, and 3.9, where the lateral wind loads at floor levels are also presented.

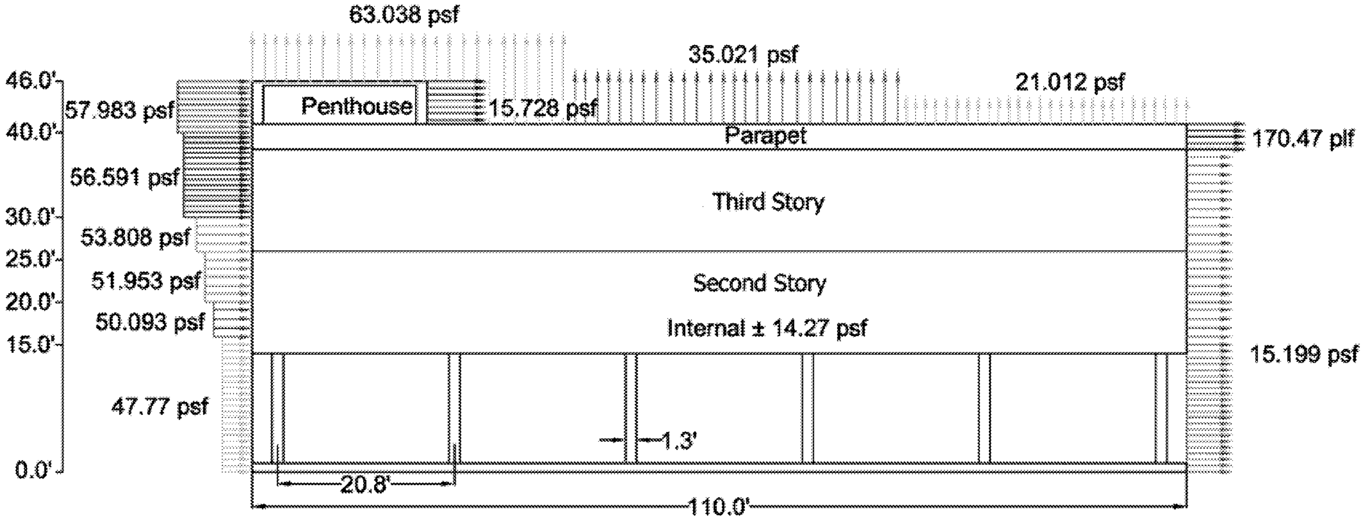


Wind Pressure Distribution Along 30' Side

Lateral Wind Load Along 30' Side

Note: 1 psf = 47.88 N/m² 1 kip = 4.448 kN
1 plf = 14.593 N/m 1 ft = 0.3048 m

Fig. 3.7. ASCE 7-02 Code—Rigid Structure



Wind Pressure Distribution Along 110' Side

Note: 1 psf = 47.88 N/m²
1 ft = 0.3048 m

Fig. 3.8. ASCE 7-02 Code—Rigid Structure

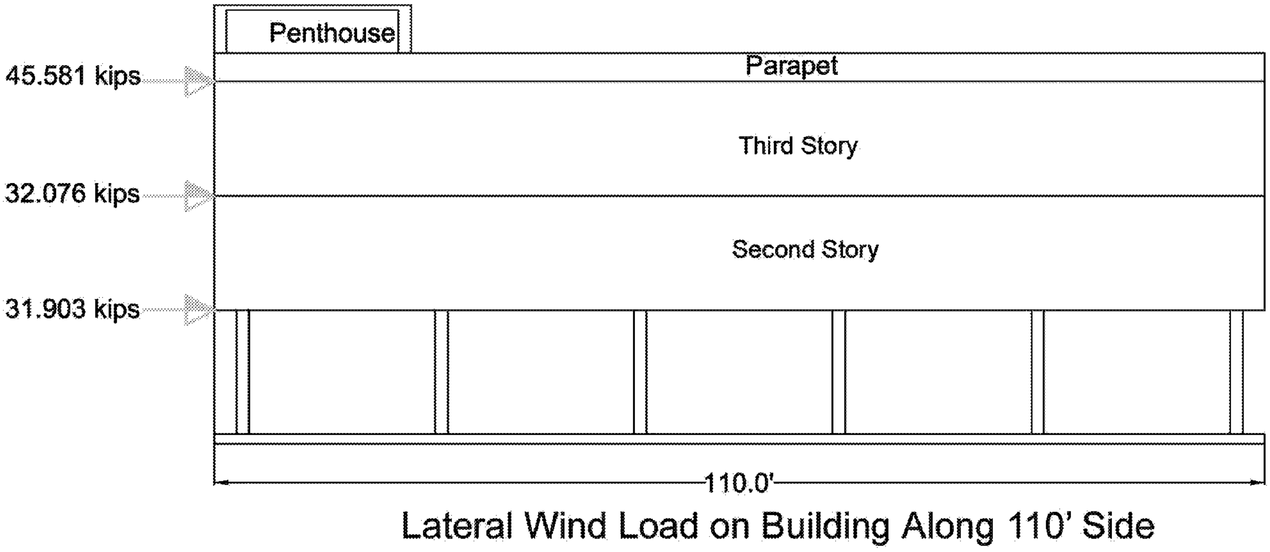


Fig. 3.9. ASCE 7-02 Code—Rigid Structure

Table 3.1. Wind Along the 30′ Side—Rigid Structure

Surface	z (ft.)	k_z	q (psf)	C_p	MWFRS Pressure (psf)
Windward Wall	0-15	1.030	67.64	0.8	47.77
	20	1.080	70.92	0.8	50.093
	25	1.120	73.552	0.8	51.953
	30	1.160	76.179	0.8	53.808
	38	1.208	79.33	0.8	56.03
	41	1.225	80.448	0.8	56.82
Leeward Wall	All	1.208	79.33	-0.5	-35.021
Side Walls	All	1.208	79.33	-0.7	-49.029
Roof	0-19	1.208	79.33	-1.04	-72.844
	> 19	1.208	79.33	-0.7	-49.029

Note: 1 ft. = 0.3084 m; 1 psf = 47.88 N/m^2

For flexible buildings, design wind pressures for the MWFRS are given by

$$p = qG_fC_p - q_i\,(GC_{pi}) \tag{3.5}$$

in which all terms are as previously defined. ASCE 7-02 defines the factor G_f for flexible structure by its Eq. (6-8). G_f was calculated for both directions using this formula. It was found to be 0.98 and 1.13 in the short and long directions. The calculated wind pressures are shown in Tables 3.3 and 3.4. Also, the wind pressures and the lateral loads at floor levels are shown in Figures 3.10, 3.11, and 3.12.

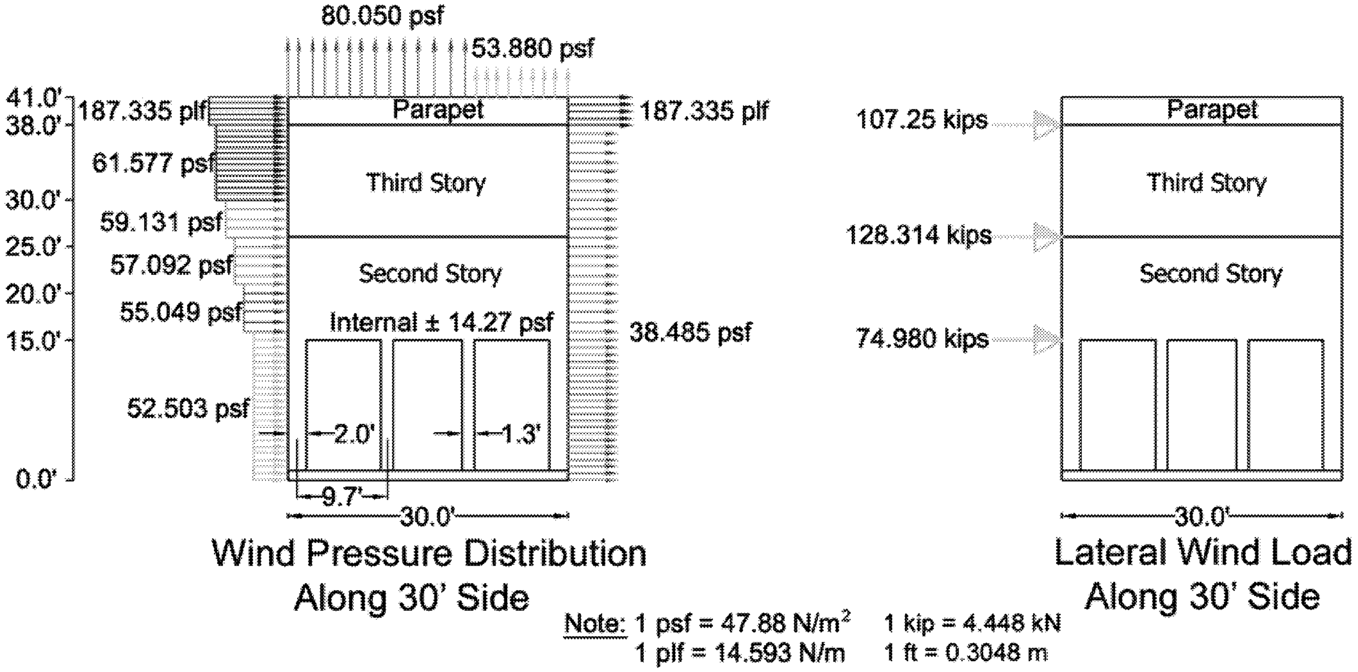


Fig. 3.10. ASCE 7-02 Code—Flexible Structure

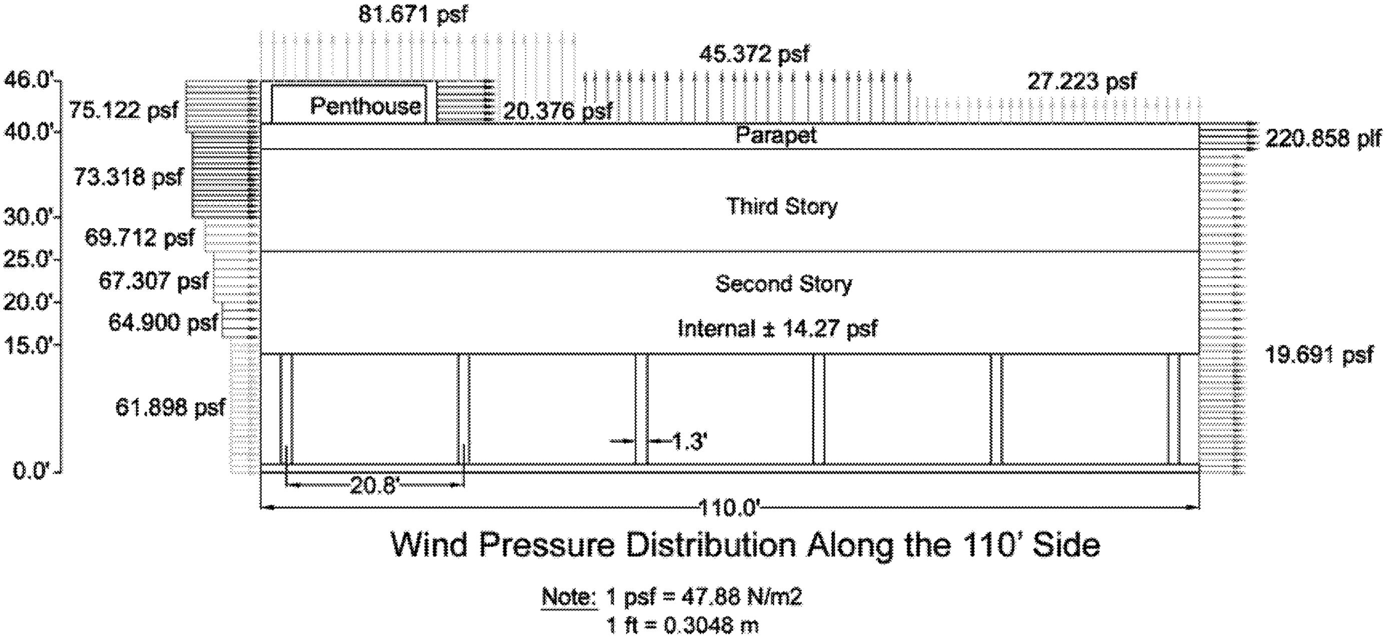


Fig. 3.11. ASCE 7-02 Code—Flexible Structure

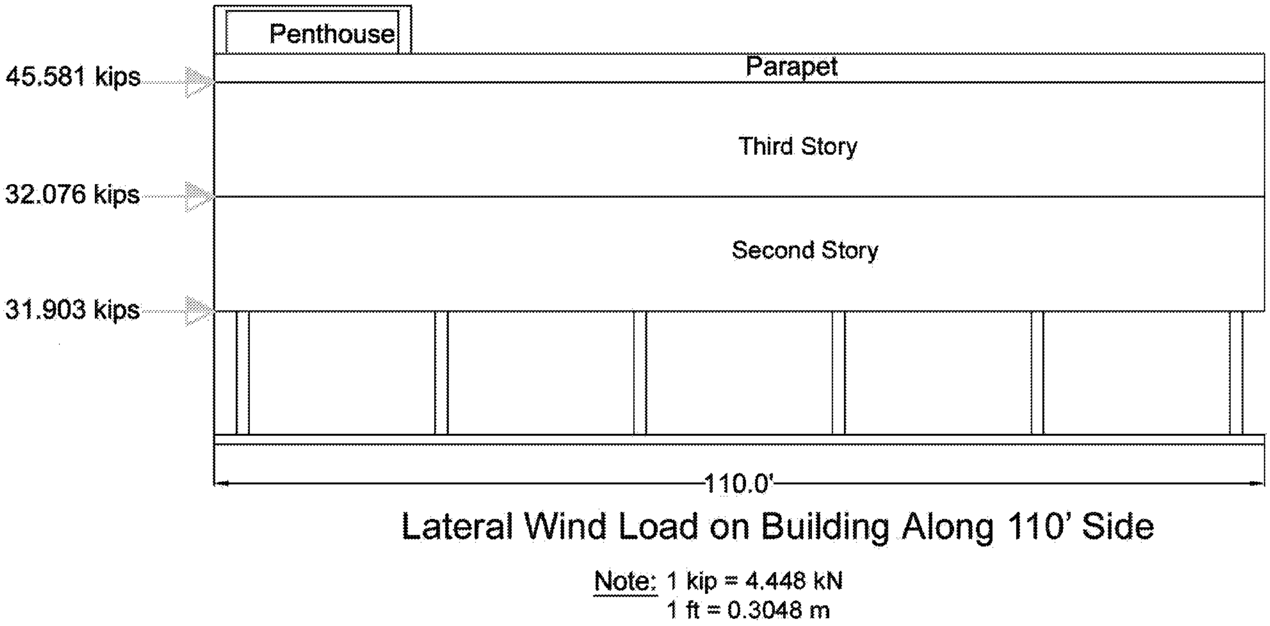


Fig. 3.12. ASCE 7-02 Code—Flexible Structure

Table 3.2. Wind Along the 110′ Side—Rigid Structure

Surface	z (ft.)	k_z	q (psf)	C_p	MWFRS Pressure (psf)
Windward Wall	0-15	1.030	67.64	0.8	47.77
	20	1.080	70.92	0.8	50.093
	25	1.120	73.55	0.8	51.953
	30	1.160	76.178	0.8	53.808
	40	1.220	80.119	0.8	56.591
	46	1.25	82.09	0.8	57.983
Leeward Wall	38	1.208	79.33	-0.2170	-15.199
	46	1.25	82.09	-0.2170	-15.728
Side Walls	All	1.208	79.33	-0.7	-49.029
Roof	0-38	1.208	79.33	-0.9	-63.038
	38-76	1.208	79.33	-0.5	-35.021
	> 76	1.208	79.33	-0.3	-21.012

Note: 1 ft. = 0.3084 m; 1 psf = 47.88 N/m^2

Table 3.3. Wind Along the 110′ Side—Flexible Structure

Surface	z (ft.)	k_z	q (psf)	C_p	MWFRS Pressure (psf)
Windward Wall	0-15	1.030	67.64	0.8	61.898
	20	1.080	70.92	0.8	64.900
	25	1.120	73.55	0.8	67.307
	30	1.160	76.178	0.8	69.712
	40	1.220	80.119	0.8	73.318
	46	1.25	82.09	0.8	75.122
Leeward Wall	38	1.208	79.33	-0.2170	-19.691
	46	1.25	82.09	-0.2170	-20.376
Side Walls	All	1.208	79.33	-0.7	-63.521
Roof	0-38	1.208	79.33	-0.9	-81.671
	38-76	1.208	79.33	-0.5	-45.372
	> 76	1.208	79.33	-0.3	-27.223

Note: 1 ft. = 0.3084 m; 1 psf = 47.88 N/m^2.

Table 3.4. Wind Along the 30′ Side—Flexible Structure

Surface	z (ft.)	k_z	q (psf)	C_p	MWFRS (psf)
Windward Wall	0-15	1.030	67.64	0.8	52.503
	20	1.080	70.92	0.8	55.049
	25	1.120	73.552	0.8	57.092
	30	1.160	76.179	0.8	59.131
	38	1.208	79.33	0.8	61.577
	41	1.225	80.448	0.8	62.445
Leeward Wall	All	1.208	79.33	-0.5	-38.485
Side Walls	All	1.208	79.33	-0.7	-53.880
Roof	0-19	1.208	79.33	-1.04	-80.050
	> 19	1.208	79.33	-0.7	-53.880

Note: 1 ft. = 0.3084 m; 1 psf = 47.88 N/m^2. Wind Pressure Determination: BNBC-93

BNBC-93 also considers both rigid and slender structures for wind load calculations. However, the formulas are different from those of ASCE 7-02. Due to lack of complete information necessary to calculate wind pressures for slender (flexible) structures, this was not pursued. Only rigid structures are considered.

The sustained wind pressure, q_z, is given by

$$q_z = C_c C_I C_z V_b^2 \text{ (kN/m}^2\text{)} \tag{3.5}$$

where

C_c = conversion coefficient takes as 47.2 x 10^{-6}
C_I = importance coefficient
C_z = combined height and exposure coefficient
V_b = basic wind speed (km/hr)

The design wind pressure, p_z, is given by

$$p_z = C_G C_P q_z \ (\mathrm{kN/m^2}) \tag{3.6}$$

where
C_z = gust coefficient
C_p = pressure coefficient

Assuming Exposure C and selecting applicable values from the tables and figures in the code, the wind pressure values in the short and long directions were calculated. These and the lateral loads are shown in Tables 3.5 and 3.6 as well as Figures 3.13, 3.14, and 3.15.

Table 3.5. Wind Along the 9.14 m Side—Rigid Structure

Surface	z (meters)	q_z ($\mathrm{kN/m^2}$)	Gust coefficient C_G	Pressure coefficient C_p	p_z in ($\mathrm{kN/m^2}$)
Windward Wall	0-4.5	4.770	1.1054	1.4216	7.495
	6	5.037	1.1054	1.4216	7.915
	9	5.464	1.1054	1.4216	8.187
	12	5.787	1.1054	1.4216	9.093
	12.49	5.829	1.1054	1.4216	9.159
Roof	12	5.787	1.1054	0.70	4.477

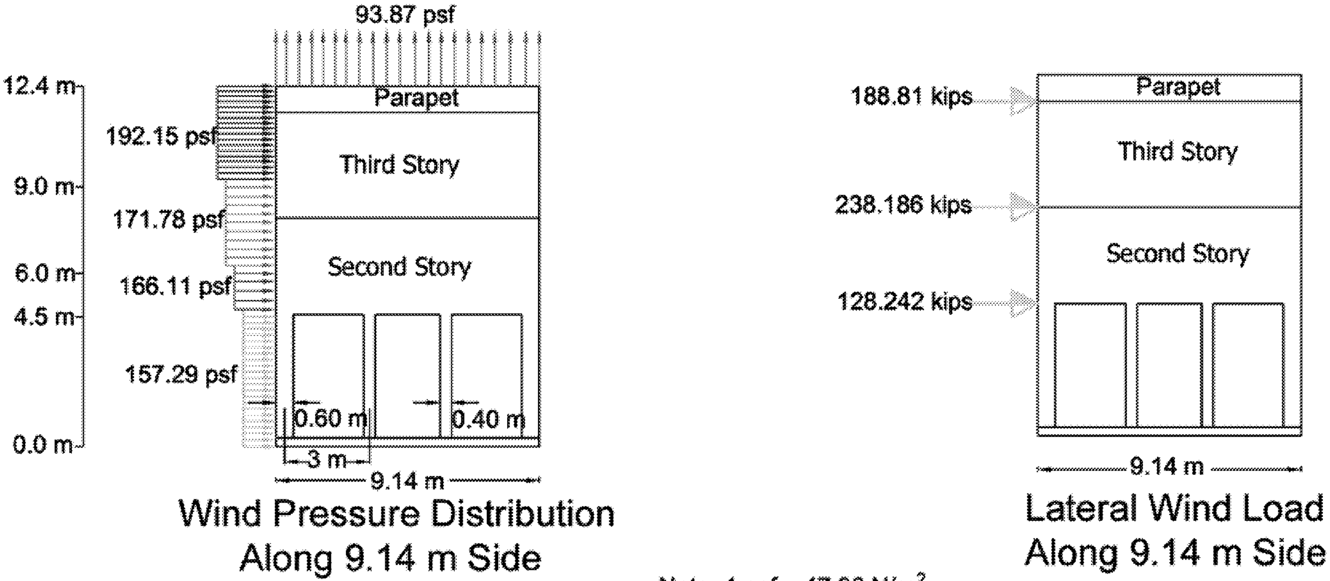
Note: 1 ft. = 0.3084 m; 1 psf = 47.88 $\mathrm{N/m^2}$

Table 3.6. Wind Along the 33.5 m Side—Rigid Structure

Surface	z (meters)	q_z in ($\mathrm{kN/m^2}$)	Gust coefficient C_G	Pressure coefficient C_p	p_z ($\mathrm{kN/m^2}$)
Windward Wall	0-4.5	4.770	1.100	1.1054	5.800
	6	5.037	1.100	1.1054	6.124
	9	5.464	1.100	1.1054	6.643
	12	5.787	1.100	1.1054	7.036
	12.49	5.829	1.100	1.1054	7.087
	14.0	5.962	1.100	1.1054	7.249
Roof	12	5.787	1.100	0.70	4.455

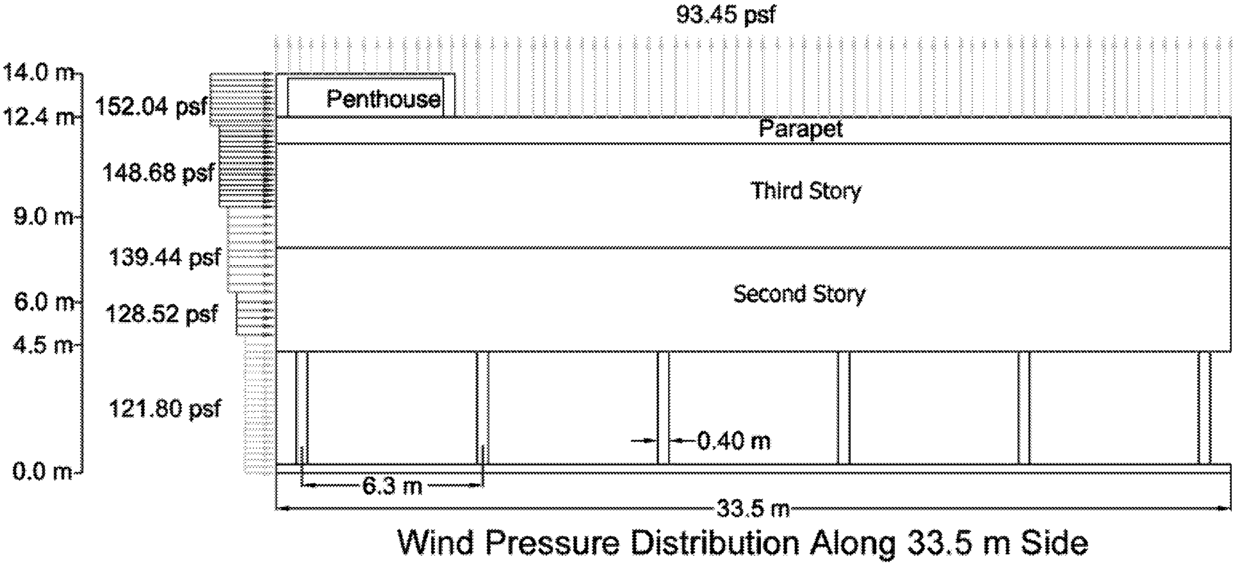
Note: 1 ft. = 0.3084 m; 1 psf = 47.88 $\mathrm{N/m^2}$

It can be concluded that the wind pressures by BNBC-93 are much greater than those of ASCE 7-02 and hence are conservative.



Note: 1 psf = 47.88 N/m^2
1 kip = 4.448 kN
1 ft = 0.3048 m

Fig. 3.13. BNBC 93—Rigid Structure



Note: 1 psf = 47.88 N/m^2
1 ft = 0.3048 m

Fig. 3.14. BNBC 93—Rigid Structure

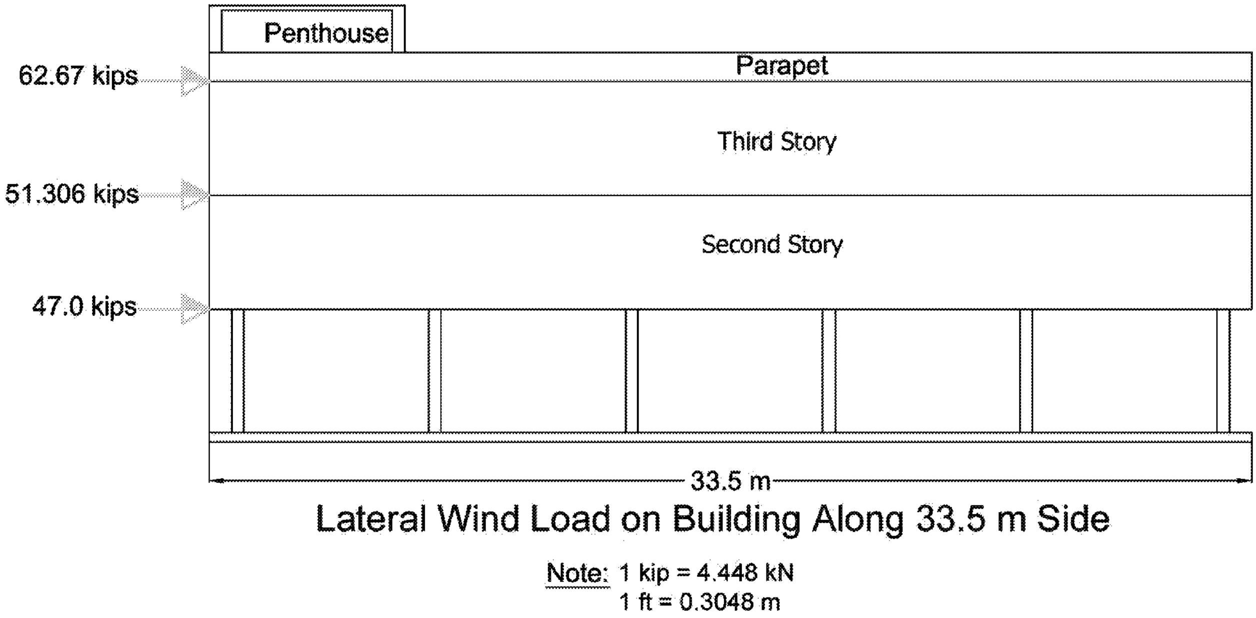


Fig. 3.15. BNBC 93—Rigid Structure

Structural Analysis

As stated earlier, full details of reinforcement were not available to the authors, but they are assumed to be adequate because the structural members were designed using the ACI Code. However, a structural analysis was conducted using the RAM-Advanse 5.1 computer program. This analysis was conducted to gain a better understanding of the structure's global behavior. The frame stiffnesses were determined for both directions using the program. The total wind loads at floor levels were then distributed to the frames based on their relative stiffnesses assuming rigid floor and roof diaphragms, as is usually done for reinforced concrete slabs. Tables 3.7 and 3.8 summarize the interstory deflections for ASCE 7-02 and BNBC-93 Codes. It is noted that the lowest story is very soft if the drift index, δ/h, is compared against 1/400, where δ is the interstory draft and h is the story height, which is conventionally taken as the maximum permissible value for hurricane forces. This value could be taken as much as 1/350 for such structures intended for emergency shelters. However, unlike for seismic loads, the code does not specify a definitive deflection limit for wind. Moreover, there is no non-structural element in the bottom story, which is open, and thus there is no serviceability problem. However, such large deflection may cause discomfort and sea-sickness due to the building's motion during a cyclone. For this analysis, the bases of columns were conservatively assumed to be pinned. If the columns are on rigid mats or the foundations are connected by grade beams, this soft story problem may be alleviated. Also, additional columns in the lowest story will improve the frame stiffnesses there.

Table 3.7: Deflections Along the 9.14 m Side

Story	Interstory Deflection (inches)			
	ASCE 7-02		BNBC -93	
	Rigid	Flexible	Rigid	Flexible
3	0.1161	0.1302	0.2321	–
2	0.2760	0.3051	0.5492	–
1	1.7021	1.8720	4.1336	–

Note: 1 in. = 25.4 mm.

Table 3.8: Deflections Along the 33.5 m Side

Story	Interstory Deflection (inches)			
	ASCE 7-02		BNBC -93	
	Rigid	Flexible	Rigid	Flexible
3	0.1304	0.1737	0.2476	–
2	0.2577	0.3568	0.5232	–
1	1.0785	1.4865	2.1838	–

Note: 1 in. = 25.4 mm.

Building Stability Against Overturning and Sliding

The structure was checked for overturning and sliding to determine how stable it is for the large forces and to establish the optimum foundation depth for required stability. For pile foundations, the stability cannot be checked without knowing the details. Assuming the foundation to be a mat with a thickness of 24 in (610mm) and top 4 ft. (1.22m) below grade, an investigative analysis was carried out using the BNBC wind forces, which are the most conservative and represent the worst-case scenario. The unit weight of the soil was estimated at 110 lb./ft.^{3} (16 kg/m^3). It is also assumed that during tidal surge, no erosion or scouring of this soil will take place. Calculations show that the safety factors against overturning and sliding are 7.2 and 3.7, which are quite satisfactory.

Conclusions

This investigation on wind load effects on an existing shelter structure in the coastal belt of Bangladesh shows that the values of wind pressures by BNBC-93 are more conservative than those by ASCE 7-02. If the design of the shelter was based on the BNBC-93 Code or values of similar order of magnitude, then the structures are inferred to be designed with adequate margin of safety.

The building is found to have a soft bottom story. Although this may not pose serious serviceability problems, it may cause motion sensitivity for the occupants. Stiffening the base by using rigid mat foundations or a pile foundation with grade beams linking the pile caps will improve the performance of the structure. This will minimize differential settlement problems. Also, the frames should be more closely spaced to increase the structure's overall stiffness. Additional intermediate columns at the lowest story will substantially alleviate or overcome the soft story problem.

Although the shelter's lowest occupiable floor is placed above the surge height, the tidal waves and flood water will impact the columns and introduce additional forces on the structure. The effect of tidal surge that causes hydro-dynamic loads is important. The combined effect of tidal and wind loads need to be considered. Analysis for tidal surges was not included in this study. Such investigation will provide a better idea of what force intensities the structure and its elements have to be designed for.

Assuming that the soil overburden over the foundation will remain generally intact without erosion or scouring, the shelter is found to be safe against overturning and sliding. At any rate, adequate protection of soil at the grade level under the shelter with geosynthetic membranes is desirable.

Additional issues to consider are the protection of concrete in a corrosive coastal environment. The extra cover on the reinforcement seems to be adequate. Additional insights about the durability of concrete can be gained by observing existing shelters for a period of time. Shelters must be periodically inspected and maintained so they do not deteriorate and eventually fall into disrepair.

Consideration should also be given to using admixtures that reduce the tendency for reinforcing steel to corrode in concrete. Corrosion inhibitors are classified according to how they interfere with the corrosion process. Anodic inhibitors are the most widely used (Mindess et al. 2003).

Finally, quality control during construction of reinforced concrete shelters is another important consideration. This is particularly crucial for shelter construction in remote, rural areas. Continuous supervision of construction by competent professionals cannot be overemphasized.

Acknowledgement

The authors wish to thank Mr. Mahbubur Rahman, P.Eng., Project Director of Design & Development Consultants (DDC) in Dhaka, Bangladesh, for his help in providing some valuable data on cyclone shelters.

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Chapter 4: 3D Effects on the Seismic Response of Dam-Reservoir Systems

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Abstract

Conventional seismic analysis of gravity dams assumes that the behavior of the dam-water-soil system can be represented using a 2D model. The assumption is based on the fact that gravity dams are usually built with transversal joints that effectively allow the concrete blocks to behave independently from each other. However, reservoirs usually have a different width than the dam. In this paper, a simplified analytical model and a BEM model are used to investigate the influence of the reservoir geometry on the dam response. The results show that the reservoir shape strongly influences the seismic response of the dam, making it necessary to account for 3D effects in order to obtain accurate results. In particular, the 3D pressure and displacement responses can be quite higher than for the 2D model.

Introduction

Understanding the dynamic behavior of the dam-reservoir system is extremely important considering the serious potential consequences of seismic failure. Over the years, many analytical models have been developed to advance the state of knowledge of the seismic response of gravity dams. However, there are still some aspects that require additional research. The classical assumptions for gravity dam analysis are that the dams are located in wide valleys, have uniform geometry along the transversal direction, and have vertical contraction joints that allow the monolith to slip and vibrate independently during strong ground motion. Thus, plane stress behavior can be assumed for the dam. In previous models, this 2D idealization has been used for the dam-reservoir system. However, a real system does not always match this idealization, and it may have additional 3D effects that cannot be captured by a 2D model. One example is when the dam is located in a valley with a different width than the dam, and this difference is relatively important related to the dam width.

For analytical models developed for the dam-reservoir system, the most important contributions were made early in 1933 by Westergaard (1933) and later by Chakrabarti and Chopra (1973 a and b) in the 1970s. Later, dam-foundation interaction effects were also taken into account because the rock and concrete may have comparative properties and its effect may be significant. The reservoir foundation interaction and the effect of reservoir bottom sediments revealed to be important and were introduced in Chopra and Gupta (1981, 1982), which made the method far more complex than the simply added mass procedure.

This paper investigates the influence of the reservoir-width on the seismic response of gravity dams using simplified analytic models and a 3D boundary element model (BEM). A simple triangular-shape model and other simple reservoir shapes are considered. To focus on the influence of 3D effects, the foundation and reservoir bottom are assumed to be rigid.

The model is based on analyzing pressures in a potential fluid. The general wave propagation equation is obtained and the particular boundary conditions corresponding to a reservoir wider than the dam are applied. The equation's solution for a horizontal earthquake excitation is obtained considering two different models for the dam: The dam is assumed to have a triangular shape, and its dynamic response is represented by its fundamental mode of vibration.

To validate the numerical solution and to accommodate more complex 3D geometries, a 3D BEM is also applied. The method was first applied to the analysis of arch dams, considering the effects of dam-water-soil-sediments interaction (Maeso, et al. 2002, 2004).

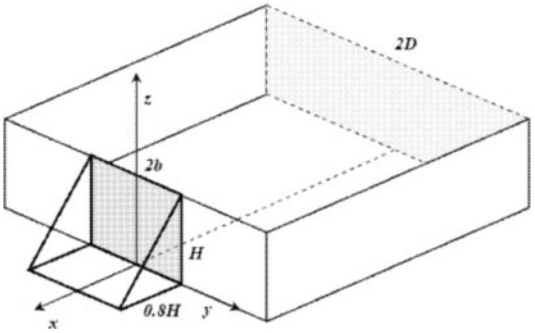


Fig.4.1. 3D representation of the reservoir-dam model

Analytical Model Considering the Effects of Reservoir Geometry

Basic Equation

The differential equation for the pressure in a potential fluid can be expressed as:

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{4.1}$$

where p denotes the hydrodynamic pressure and c denotes the wave velocity.

For harmonic excitation, with circular frequency ω, the pressure is:

$$p(x, y, z, t) = p(x, y, z, \omega)\, e^{i\omega t} \tag{4.2}$$

where p(x, y, z, ω) is the complex response function. Hence, the Eq. 4.1 can be expressed as:

$$\nabla^2 p + \frac{\omega^2}{c^2} p = 0 \tag{4.3}$$

which is valid for the study of an inviscid compressible fluid with small displacements.

The general solution of the differential equation is

$$p(x,y,z,\omega) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} A_{nm}\, e^{K_{nm}\,x}\, cos(\lambda_z^n\, z)\, cos(\lambda_y^m\, y) \qquad (4.4)$$

Simplified Triangular-Shaped Model of the Dam

A triangular-shaped model has been defined for the dam (see Fig. 4.1). The dam height is H, and the base is 0.8H. Considering the symmetry of the system, the dam half width is b and the reservoir half width is D. The dam material is viscoelastic, the dam is considered to be rigid in the transversal direction, and the reservoir boundaries are assumed to be rigid. The earthquake is idealized in the same way as in the previous model. As shown in Figure 4.2, two cases are examined:

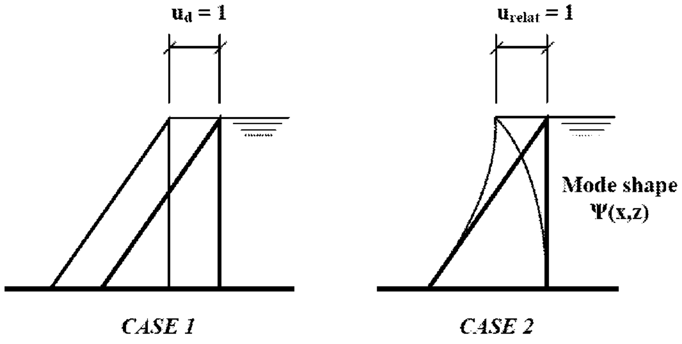


Fig. 4.2. Displacement model decomposition, Cases 1 and 2

- Case 1: Uniform unit excitation of the dam (considered rigid) and boundaries along the x direction.

$$u_d = 1;\ u_b = 1 \qquad (4.5)$$

where subscripts d and b denote dam and boundaries, respectively.

- Case 2: Excitation of the dam with relative displacement between dam and reservoir boundaries along the x direction, defined by the fundamental mode shape Ψ(x, z), calculated using the Ritz method. This mode shape is considered constant in the transversal direction (y).

$$u_d(x, z) = u_{relat}.\Psi(x, z);\ u_b = 0 \qquad (4.6)$$

Using superposition, the total horizontal displacement uT_d of the dam is

$$u_d^T(x, z) = 1 + u_{relat}.\Psi(x, z) \qquad (4.7)$$

Considering the two cases examined in the solution, the final pressure p^T is

$$p^T(y, z) = p_1(y, z) + u_{relat} \cdot p_2(y, z) \tag{4.8}$$

where p_1 and p_2 denote the pressures for Case 1 and Case 2 respectively.

In this paper, the free vibration of the dam is studied using the Ritz method. The dam is considered to be a right cantilevered 2D triangle, with height H (z direction) and width b (x direction).

Coupled System Solution

The equation of motion for the system can be obtained by applying the virtual work principle. Expressing the displacement in terms of the mode shape (Eq. 4.7), the dam becomes a single-DOF system (see, for example, Chakrabarti and Chopra1973 b). Considering that both internal and external work should be equal and dividing by the virtual displacement, the generalized equation of motion in frequency domain is obtained

$$(K^*(1 + i2\xi) - \omega^2 M^* - P2^*)u_{relat} = P1^* + \omega^2 F^* \tag{4.9}$$

where

$$K^* = 2b \int\int [(1/2)\lambda[U_{,x} + V_{,z}]^2 + G[U_{,x}^2 + V_{,z}^2] + (G/2)[U_{,z} + V_{,x}]^2][\Psi(x,z)]^2 \, dx \, dz \tag{4.10}$$

$$M^* = \rho b \int\int [U^2 + V^2][\Psi(x,z)]^2 \, dx \, dz \qquad F^* = \rho b \int\int [U^2 + V^2] \, \Psi(x,z) \, dx \, dz \tag{4.11}$$

$$P1^* = \int\int p_1(y,z) \, \Psi(0,z) \, dy \, dz \qquad P2^* = \int\int p_2(y,z) \, \Psi(0,z) \, dy \, dz \tag{4.12}$$

where U and V are the horizontal and vertical components, respectively, of the displacement in the frequency domain. ρ is the constant mass per unit of surface, and λ and G are the Lame constants for a homogeneous and isotropic material. The integration is done over the dam, which yields

$$u_{relat} = \frac{P1^* + \omega^2 F^*}{(K^*(1 + i2\xi) - \omega^2 M^* - P2^*)} \tag{4.13}$$

Examples

System Properties

The assumed parameter values for the dam-reservoir system are the following: dam modulus of elasticity $E = 3.44738 \times 10^{10}$ N/m2; dam Poisson's ratio $\nu = 0.17$; dam density $\rho = 2480.0$ Kg/m3; dam damping ratio $\xi = 0.05$; water wave velocity c = 1440 m/s; water density $\rho_w = 1000$ Kg/m3, and reservoir depth H = 100 m.

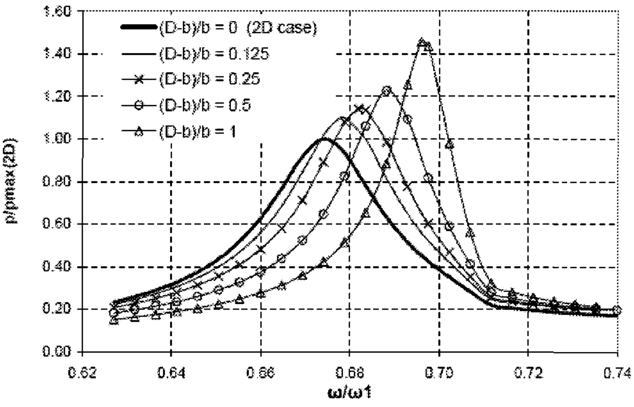


Fig. 4.3. Dam pressure response for different values of (D − b)/b (D = reservoir width, b= dam width) and normalized circular frequency of the excitation = ω/ω$_1$.

Analysis of the Influence of the Reservoir Width

The validity of the 2D model assumptions are analyzed with simplified geometric model. First, maintaining D − b (reservoir width − dam width) constant, the response is obtained for different values of b and the excitation circular frequency ω. Second, maintaining b (dam width) constant, the response is obtained for different values of D/b and ω.

For the first case, the response of the dam is presented in Figure 4.3. The 3D solution approaches the 2D solution when the relation (D − b)/b decreases, that is, when the difference between the dam width and the reservoir with tends to zero. An important difference in the peak value and the natural frequency can be seen when (D − b)/b increases. As shown in Figure 4.4, the maximum pressures at the bottom and the maximum displacements at the top of the dam (both normalized by the maximum values for the 2D case) increase with increasing (D − b)/b. This figure allows designers to determine the significance of the 3D effect of the reservoir width with respect to the 2D behavior.

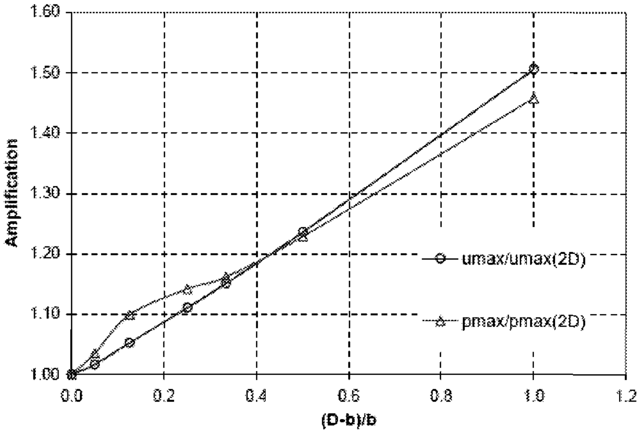


Fig. 4.4. Maximum displacement and pressure amplification respect to the 2D maximum value for different values of (D − b)/b (D = reservoir width, b = dam width).

For the second case, the response of the dam is analyzed for different values of relative width D/b by keeping b constant. The results are shown in the Figure 4.5, where the ratio of the 3D pressure over the 2D pressure is shown with respect to the normalized circular frequency ω/ω_1in the region around the natural frequency of the coupled system. The system response varies with the excitation frequency. Below the natural frequency for the 2D dam-reservoir system ($\omega/\omega_1 \cong 0.7$), the response decreases, slightly increasing D. This behavior changes for frequencies near and above ω_{nat} of the coupled system, where the response increases with increasing D. This presents an important peak for D/b= 3.5 at ω/ω_1= 0.7. The response amplification for this point is a 1.89 times the amplification presented by the 2D model, at the same frequency. At slightly higher frequencies, the amplification increases with D/b monotonically.

In Figure 4.6 the displacement and pressure frequency responses are presented for different values of D/b. The displacement of the natural frequency towards higher values of ω/ω_{nat} and the increase of the peak value are clearly shown.

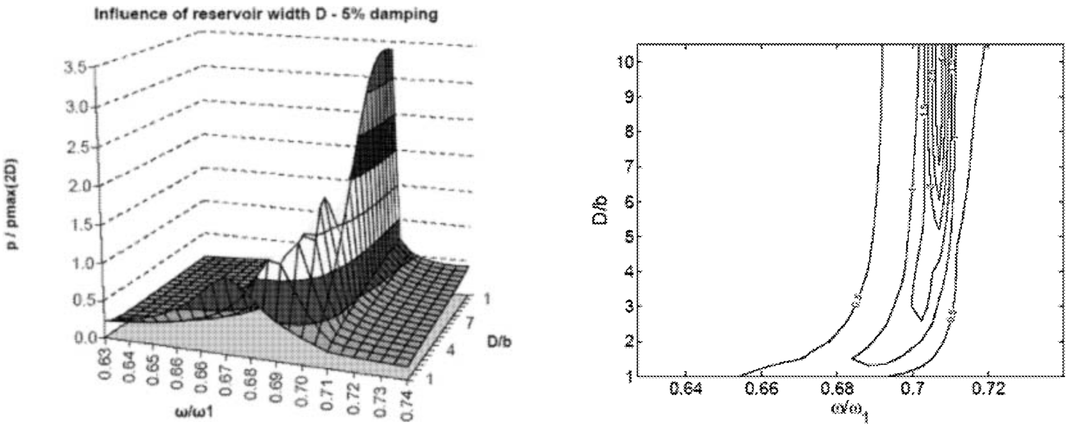


Fig. 4.5. 3D representation and contour graphic of dam pressures response for different values of D/b (reservoir width D/dam width) and normalized circular frequency ω/ω_1.

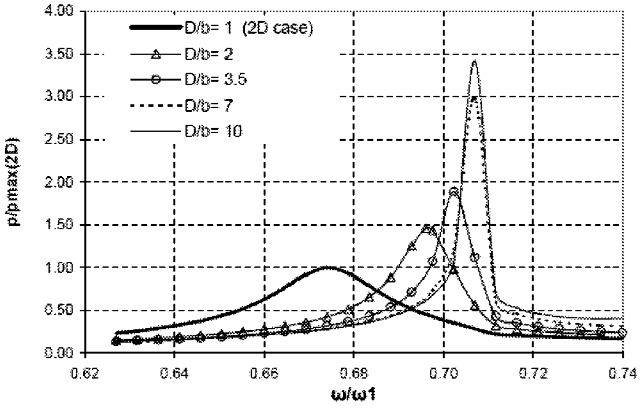


Fig. 4.6. Dam pressure response for different values of (D – b)/b (D = reservoir width, b = dam width) and normalized circular frequency of the excitation ω/ω_1.

A detailed figure showing the dependency on the D/b ratio is presented in Figure 4.7 for the normalized frequencies ω/ω_{nat}= 0.677, 0.696, 0.702, and 0.708.

A variation of the maximum pressures (calculated over the considered range of frequencies) obtained for different values of D/b, considering different damping coefficients ξ, is presented in Figure 4.8, where the pressures are normalized with the maximum value obtained for the 2D case (for the same damping coefficient).

All these results show that the pressures and displacements obtained with the 2D model of the dam with uniform reservoir could be substantially lower than the 3D behavior of the actual system because the influence of the reservoir shape is not captured.

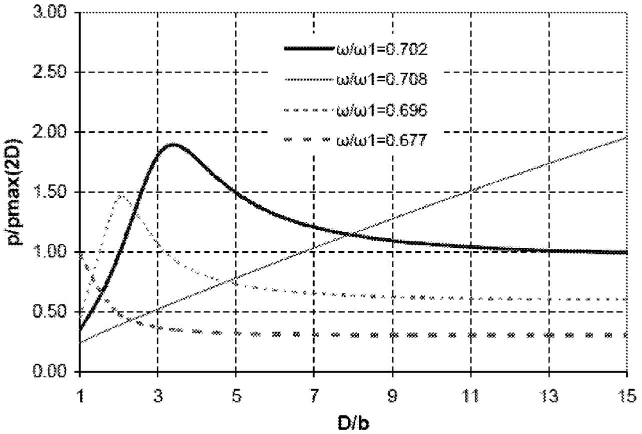


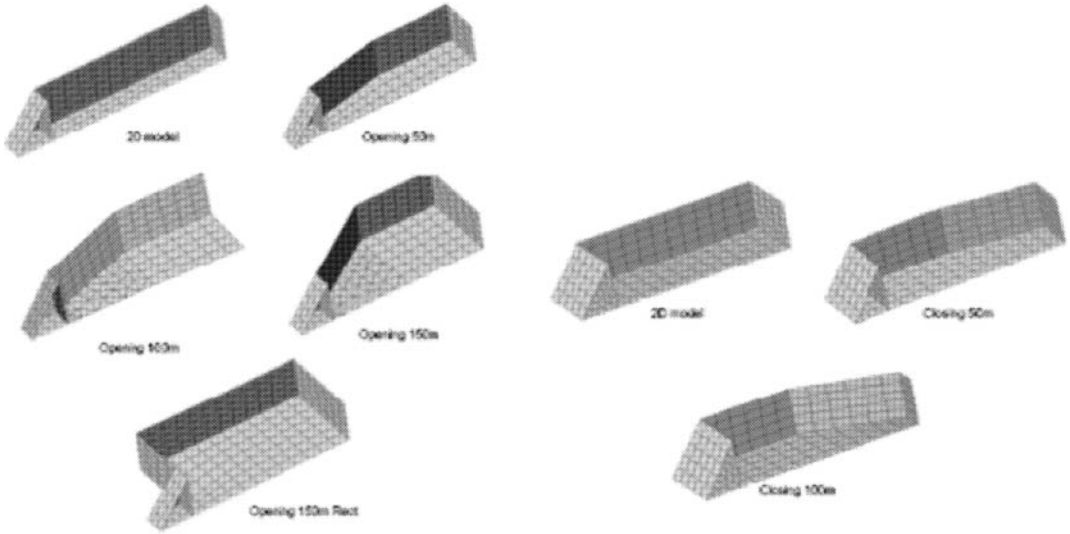
Fig. 4.7. Normalized dam pressure response for different values of reservoir width D and circular frequency of the excitation, 5 percent damping.

Fig. 4.8. Normalized maximum pressure response for different values D/b, normalized frequencies and damping coefficients.

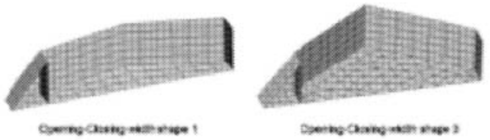
Numerical Model Considering the Effects of Reservoir Geometry

The dam geometry and properties from the analytical model are adopted here. To study 3D effects of the reservoir geometry, different simple models have been defined. In all cases, a symmetric model is applied and the width is varied. Models with opening-width shapes are shown in Figure 4.9(a) and models with closing-width shapes are shown in Figure 4.9(b). Models with opening-closing-width shapes are shown in Figure 4.9(c). The width of the dam is 100 m for the opening-width shape reservoir cases and 200 m for the closing-width shape reservoir cases.

The earthquake is idealized as a uniform horizontal or vertical harmonic acceleration of unit amplitude in the pressure analysis. A harmonic (horizontal or vertical) displacement of unit amplitude is assessed in analyzing the influence of the reservoir shape. In all the cases, the reservoir boundaries are assumed to be rigid.



(a) Opening-width shapes (b) Closing-width shapes



(c) Opening-closing-width shapes

Fig. 4.9. BEM dam-reservoir models with different shapes

Analysis of the Influence of the Reservoir Shape

Results for the different models with opening width reservoir and horizontal seismic excitation (in longitudinal direction) are shown in Figure 4.10 where the pressures are normalized by those corresponding to the 2D case. The circular frequency is normalized with the first natural frequency of the 2D reservoir. Results show that a wider reservoir (continuing to the infinite) results in a natural frequency closer to that of the infinite reservoir, and the resonance amplitudes for both the displacements at the top of the dam and for the pressures at the bottom of the central upstream face of the dam increases with increasing width. On the contrary, a closing-width reservoir results in decreasing values for the pressures and displacements as well as a slight reduction of the resonance frequencies. In this case, one model with a closed reservoir has also been included in the comparison.

For an opening-closing-width reservoir intermediate results are obtained. The pressures for the two of the reservoir cases depicted in Figure 4.9 (c) are shown in Figure 4.11. Similar results corresponding to vertical seismic excitation are shown in Figure 4.12. An opening width reservoir amplifies the dynamic response due to increase in added mass, and a closing-width reservoir weakens the dynamic response due to decrease in added mass.

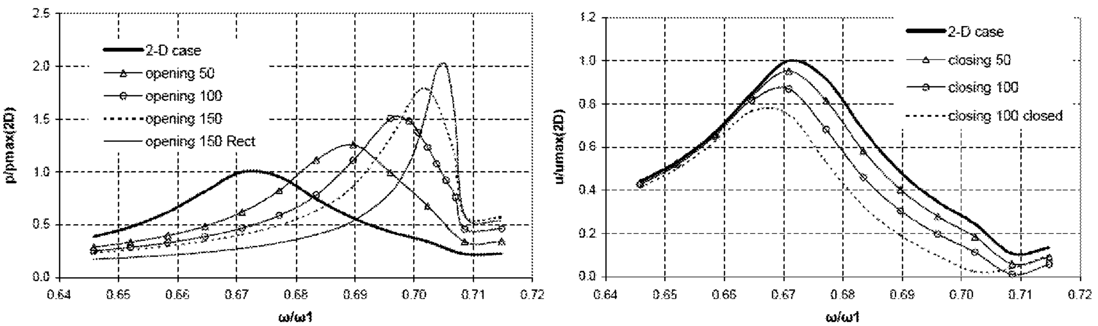


Fig. 4.10. Pressures for reservoir models with opening-width and closing-width shapes; horizontal seismic excitation.

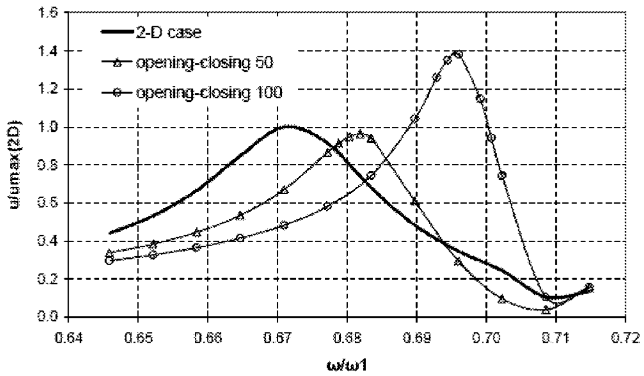


Fig. 4.11. Pressures for reservoir models with opening-closing-width shapes; horizontal seismic excitation.

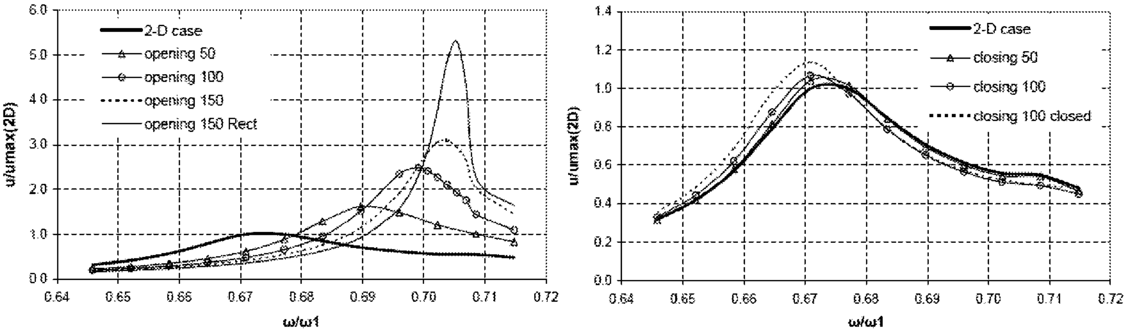


Fig. 4.12. Pressures for reservoir models with opening-width and closing-width shapes; vertical seismic excitation

Taking into account the dimensions represented in Figure 4.13, a parametric representation of the maximum pressures for the opening-width shape cases are shown in Figures 4.14 and 4.15 for the models previously investigated. The maximum pressures obtained at the bottom of the upstream face of the dam are normalized with the maximum pressure obtained for the 2D case. These normalized pressures are represented versus the relation D/b (width of the reservoir related with the 2D width case) for the cases where L is constant, and versus (D – b)/L (tangent of the inclined boundary) for cases where D is constant.

Nevertheless, the following conclusions can be made: The conventional 2D model should be applied with caution because it assumes the reservoir to be of constant width; for canyon geometries with opening-width, the 2D method tends to underpredict the maximum displacement, pressure, and natural frequency of the system. In addition, the 2D behavior of the dam depends not only on the width but also on the type of vertical contraction joints, the relative dimension of the dam to the valley, and the shape of the valley itself. This means that for uniform-shape straight valleys, where the dam has the same width as the valley, the 2D system model produces good results. For other cases, such as those presented in this paper, a 3D model should be applied.

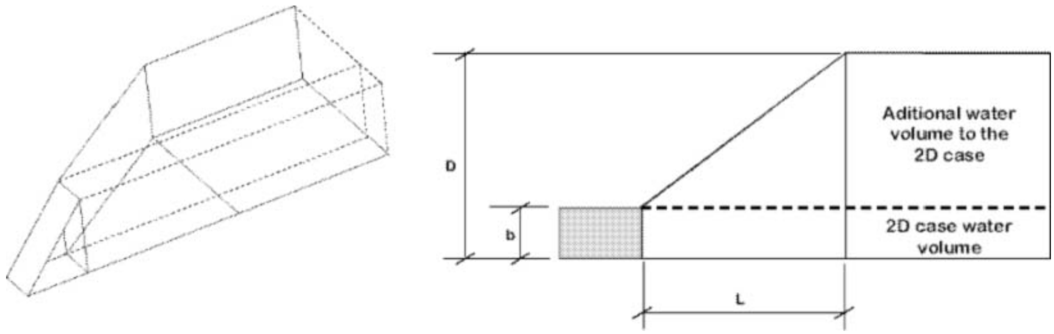


Fig. 4.13. Dam-reservoir scheme with opening-width shape and plan with related dimensions.

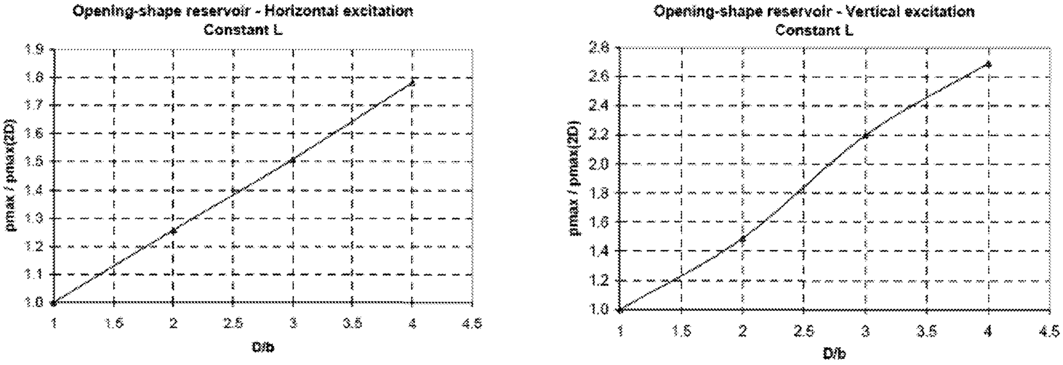


Fig. 4.14. Normalized pressures for different D/b ratios and constant L; horizontal and vertical seismic excitation

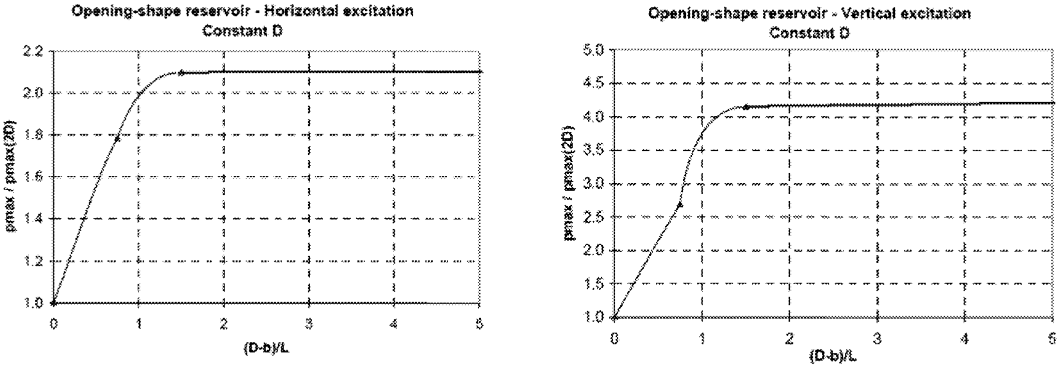


Fig. 4.15. Normalized pressures for different (D − b)/b ratios and constant D; horizontal and vertical seismic excitation.

Conclusions

This paper presents an analytical and a numerical three-dimensional approach to investigate the seismic behavior of a reservoir-dam system to account for the influence of the reservoir geometry. The dam is modeled as a cantilevered triangle where the dynamic response is represented by the fundamental mode of vibration. The water in the reservoir is assumed to be compressible, and the reservoir is assumed to be infinite in the upstream direction. To study 3D effects of the reservoir geometry, different simple models have been defined.

Despite the simplifications, important conclusions can be obtained from the model:

- The response is highly dependent on width D of the reservoir and on the excitation frequency ω. The pressure decreases when D increases if ω is under the natural frequency of the system; on the contrary, the pressure increases when D increases if ω is around or greater than the natural frequency.

- The resonance peak in the response moves with D/b towards higher values of ω. This peak is higher than the maximum response corresponding to the 2D case for most of the values of D/d.

- A 3D model should be applied to analyze a dam system when the reservoir width is different from the dam width.

- More research is needed to analyze the influence of other important parameters in the response, for example, flexibility of the dam, reservoir shape, bottom flexibility, and such.

Acknowledgements

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Chapter 5: Coastal Land Loss: Hurricanes and New Orleans—A Prelude to Hurricane Katrina

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Historic Note

This paper summarizes our pre-Katrina understanding of what would happen to New Orleans if a major hurricane struck the area. As Hurricane Katrina revealed, the science was correct, and the U.S. federal government's marginalization of science in the last few years cost lives and billions of dollars in property damage. The moral of the story is if you ignore the science, you will suffer the consequences.

Abstract

Recent tropical cyclone-induced floods in the United States and elsewhere have demonstrated the complexity of public health impacts including trauma and fires, along with chemical, sewerage, and corpse contamination of air and water. Disease risk in Louisiana during hurricanes/major floods is very high because 70 percent of the population lives in the 40 percent of the state that is in the coastal zone. Ninety percent of this zone is near/below sea level. Densely populated areas, such as New Orleans, rank among the highest in the United States for potential societal, mortality, and economic impacts.

Louisiana's coastal wetlands and barrier islands are its outer buffer to storm surges. Since 1930, 1 million acres have been lost—400,000 acres seawards of New Orleans. In 1990 the state and federal governments initiated a coastal restoration program with total expenditures to date of $400 million. However, even with these efforts land loss still exceeds 28,000 acres annually.

New Orleans was built on wetlands. Leveeing and draining has resulted in substantial subsidence. As a result, most of the city is now below sea level, with a maximum deflation of 13 feet. Approximately 600,000 people reside within this bowl. The West Bank, south of New Orleans and across the Mississippi River, has a population of about 500,000, who live within levee protected bowls. Recent research reveals that a slow moving Category 3 hurricane, or stronger, could cause levee overtopping and complete flooding of New Orleans, with the West Bank even more susceptible. Floodwaters would have residence times of weeks. The resultant mix of sewage, corpses, and chemicals in these standing flood waters would set the stage for massive disease outbreaks and prolonged chemical exposure. Estimates are that 300,000 people would be trapped and 700,000 would be homeless; thousands could perish.

There is a need to develop and implement a long-term coastal restoration plan to ensure New Orleans' survival. A project that appears to have the greatest potential to reduce hurricane storm surges in New Orleans requires the Mississippi River to be diverted into Breton and Chandeleur Sounds through the Bohemia Wildlife Management area (van Heerden 1994). If implemented, approximately 5,000 acres of new wetland would be created in this stable basin every year. Large-scale coastal restoration efforts would positively affect New Orleans' future.

Environmental Setting

Coastal Land Loss in Louisiana

The coastal wetlands and estuaries of Louisiana are one of the world's great ecosystems. For millennia, the Mississippi River has supplied the coast with an immense resource of freshwater, nutrients, and sediment to build a vast expanse of marsh and swampland. These lands have been altered by natural erosional processes. The dynamic interplay of land and water in which new lands are continuously built and old lands changed and lost has produced an environment rich in natural habitats, with an unsurpassed diversity in vegetation, wildlife, fisheries, and an extraordinary biological productivity. Louisiana's marshes and swamps, which encompass 4 million acres, represent more than 40 percent of the coastal wetlands in the United States and provide 30 percent of the country's annual commercial harvest of fish and shellfish (van Heerden 1994). Millions of people rely directly or indirectly on the marshes for their livelihood and for protection against hurricanes and storms. Natural habitats benefit from the wetland's ability to improve water quality. The delta is the heart of Cajun culture, which combines natural beauty, abundant wildlife, and rich sport fisheries to provide a unique tourist attraction. The delta's wetlands are also of enormous economic importance because they produce some 15 to 20 percent of the nation's oil and almost 30 percent of its natural gas. Additionally, the Mississippi River ranks as the country's most important inland navigational waterway (van Heerden 1994).

In the last several decades, however, people have affected this ecosystem in many ways, especially by controlling rivers so that natural floods are no longer a part of wetland maintenance and creation and by building channels that expose freshwater marshes to salt water at an unnatural rate. Levee systems and control structures confine sediment that once nourished the wetlands adjacent to the river channel. Ultimately, this sediment has deposited in the deep waters off the Louisiana coast. The lack of sediment input in the interdistributary wetlands results in an accretion deficit. Natural and human-induced subsidence exceeds accretion, so the wetlands sink below sea level and convert to water. Statistics only begin to suggest the importance of the ecosystem and the extent of modern damage.

As the 20th century progressed, the Louisiana coast lost its incredibly fruitful wetlands at an increasing rate to reach about 40 square miles per year in the 1970s. Louisiana's loss represents 80 percent of all coastal wetland loss in the United States. The lost land has been conservatively valued at $4,000 per acre in natural services (recreation, aesthetics, and water purification) and productivity (fish, shellfish, and fur) (Costanza and Farber 1985, Houck 1983). Assuming a real estate value of $400 per acre and a similar value for coastal communities in protecting the coastal wetlands from major tropical storms, that means that the annual loss to Louisiana and the nation exceeds $150 million every year (van Heerden 1994). Since the 1950s the total loss exceeds $7.6 billion. Recently, the rate has slowed slightly, but tens of square miles are still lost each year (approximately 100 acres per day). Total wetland loss since the turn of the century exceeds 1 million acres, an area 1.5 times that of Rhode Island (Templet and Meyer-Arendt 1988).

The loss of wetlands is more than a loss of the prevailing resource base. Life and property are increasingly threatened as the populated, low-elevation natural levee lands become more exposed to the Gulf of Mexico. The loss of storm-buffering protection by wetlands and barrier islands not only jeopardizes the safety of isolated bayou communities but also the New Orleans metropolitan area. The potential impact of a hurricane directly striking the city is much more serious today than in decades past because of the increased storm surge levels expected with adjacent open-water conditions (Templet and Meyer-Arendt 1988).

Much of the physical cause of the wetland loss lies in attempts to control the Mississippi River's flooding, while enhancing navigation and mineral extraction. Many signs indicate that if nothing is done, large rates of loss will continue—and in some areas perhaps increase—far into the future. The ultimate economic cost will be tens of billions of dollars and beyond that, immeasurable environmental damage.

Hurricane Public Health Issues and Threats

The Hurricane Threat

The world is at ever-increasing risk from hurricanes, tropical cyclones, and major flooding events. Population growth and global migration patterns toward at-risk coastal areas, increased development and urbanization of the coastal zone, long-term climactic trends, and other factors combine to expose growing numbers of people to hurricane and flood threats. These threats include storm surge flooding, extreme winds and tornadoes, rainfall-induced flooding and landslides, and coastal erosion.

Storm phenomena, damage, and direct casualties are generally investigated and documented by the engineering and scientific communities. Less well investigated, understood, and accounted for in future planning are the public health issues that arise immediately in the wake of hurricanes, tropical storms, other severe flooding events, and thereafter. Disease outbreaks can occur, and trauma-related mental health problems are common (Noji 1997). People are often exposed to high levels of biological and chemical contaminants in floodwaters, which can have immediate and/or long-term health consequences. Additionally, the transport and fate of these contaminants is largely unknown. Many remain in the environment, contaminating soil, houses, and other buildings and water supplies and leading to potential long-term health problems (Noji 1997).

The past few years have witnessed several massive storms. Hurricane Mitch in 1998 devastated much of Honduras. Direct casualties were estimated at 9,000, but the full impact will not be known for many years. India and southern Africa have experienced major cyclone-induced flooding in which thousands perished. Hurricanes Floyd and Irene—and more recently Isabel—pounded North Carolina and the rest of the East Coast, causing some of the most severe flooding on record. Animal wastes, carcasses, and other sources contributed to extremely high levels of contamination of the floodwaters, posing immediate and long-term health threats. Tropical storm (TS) Allison dropped in excess of 2 ft. of rain in a few days over portions of Texas and Louisiana, causing a major concern about disease due to an explosion of mosquitoes.

On a national scale, 45 million Americans live in coastal counties alone stretching from Texas to Maine (Jarrell et al 1992). These coastal counties have the highest population growth rates in the United States (FEMA 1997). While their residents are generally at the highest risk, severe flooding can threaten residents much farther inland as well. Louisiana has as much if not more risk from hurricanes and other flooding events than any other state. During the past century, south central Louisiana has experienced what appears to be the highest number (six) of landfalls of major hurricanes (Category 3 to 5 storms) (see Fig. 5.1). Louisiana and Texas typically rank numbers 1 and 2 in annual flood insurance claims. New Orleans is the most vulnerable major city on the Gulf Coast and perhaps in the entire United States. Had Hurricane Georges not taken a last minute turn to the east in 1998, major portions of New Orleans would have flooded. It would likely have been one of the worst disasters of the century in loss of life and damage.

The catastrophic flooding in coastal North Carolina as a result of Hurricane Floyd serves as a frightening example of potential future threats to public health caused by high water. Public health risks during potential massive flooding events in Louisiana are at least as high as those experienced in North Carolina. However, the major differences are that Louisiana, lacking the topographic slopes of North Carolina would drain much more slowly and standing water could be a problem for many weeks. Additionally, Louisiana has extensive infrastructure of oil and gas facilities, chemical plants, and hazardous, industrial, and residential landfills. Most of these facilities are in flood prone areas and within the confines of levee systems protecting housing and other structures from flooding. Even in areas where mitigation strategies have been engineered (levee, drainage, and pumping systems), such designs are unable to capture and control all stormwater runoff from the occasional extreme rain event. Further, hazards associated with these events can be prolonged over periods of days to weeks, as the region's generally low-lying and flat terrain can extend residence times of floodwaters. As a result, the array of potential health risks associated with large-scale flooding may be exacerbated by the persistence of standing water within affected areas.

Hurricane Public Health Research Initiative

There is a need to develop and implement a long-term coastal restoration plan that rapidly rebuilds the coastal wetlands. In the interim, the range of severity of public health effects are being researched and plans are being developed for mitigation, preparedness, response, and recovery to minimize both the long- and short-term health impacts. Toward this end, the Center for the Study of Public Health Impacts of Hurricanes was created at Louisiana State University in 2002. The center consists of a multi-disciplinary, multi-campus team comprising natural and social scientists, engineers, and the mental health and medical communities. Using computer models, storm surges and rainfall flooding scenarios are being determined. Computer models are being used to simulate the air and water movement of chemical contaminants. GIS technologies allow documentation of at-risk areas. Epidemiologists, toxicologists, social scientists, and public health experts will then determine the effects on public health. These will be assessed against with a realization that the Pacific Decadal, which began in late 2000, is expected to last for 10 to 30 years and cause harsher weather patterns with an increased incidence of hurricanes. This phenomenon, against a backdrop in Louisiana of shrinking wetlands and rising sea-surface temperatures, increases the urgency.

Facts to consider in developing the medical response include global temperature increases that would extend the domain for malaria and dengue fever (including other forms of these diseases from Central and South America). A 4° F rise would extend the domain from the current 42 percent to 60 percent of the earth's landmass. In this scenario, tropical diseases would become endemic to many temperate areas such as the United States and Europe. Global warming is expected to contribute to an increased incidence of food and waterborne diseases.

Some common short-term public health effects noted following recent flooding events (Hurricane Andrew and TS Allison) include increased risk of disease due to crowding (or being housed with homeless), water contamination and resulting gastrointestinal disease, increased arthropod and animal vector diseases, snake and animal bites, and injuries (for example, jumping off roofs, motor-vehicle accidents). Some of the chronic health impacts include upper respiratory infections, headache, chronic illness, and stress.

Louisiana, like other Gulf and Atlantic coastal states, needs to prepare and develop plans to deal with public health risks during major floods. During a disaster, citizens may be exposed to environmental sources of disease from a variety of hazardous material sources. Public health outcomes that can result from such complex disasters include contamination of drinking water, buildings (such as toxic mold), agriculture production areas, wetlands, and bodies of water that are both habitat and sources of food (such as fish and wildlife). This, in turn, creates the potential for immediate disease epidemics and for long-term genetic abnormalities and health problems. All of these potential public health outcomes must be identified; preparedness, mitigation, remediation, and recovery techniques must be developed now, before a major flooding disaster occurs in Louisiana.

Hurricane Public Health Research

The objective of the LSU Public Health Research Center is to develop the science, technology, and medical know-how to assess the public health impacts resulting from hurricanes and major flooding events. This objective also includes the development of remediation approaches. A flowchart summarizing the major research activities and interrelationships is provided in Figure 5.2.

There are two levels of data collection and modeling of the physical phenomena and community response. These tasks provide the inputs necessary to adequately understand and model the public health threats. The outputs will be used to develop suitable mitigation, preparedness, response, and recovery plans and procedures. Most of the data and modeling will be within a GIS framework.

The focus of the physical systems modeling tasks was to provide the inputs needed to model the effects on public health. Physical modeling tasks began with identifying and selecting the most appropriate existing models, followed by applying the chosen models to the specific problems defined by the study area. The real research challenges were coordinating and integrating all of the other disciplines that provide and use the model outputs. This is a crucial component for such a multi-disciplinary research project because formulating all models to work within a consistent GIS framework requires extensive coordination and cross-disciplinary teamwork.

Initial Research Results

Will New Orleans Flood?

New Orleans was built on wetlands. As a result of leveeing and draining, most of New Orleans is now below sea level, with a maximum deflation of 13 ft. Today 600,000 people reside within this bowl. The West Bank, south of New Orleans across the Mississippi River, has a population of 500,000 who also live within levee protected bowls. Computer simulations using both the sea, lake and overland surges from hurricanes (SLOSH) computerized storm surge model run by the National Hurricane Center, as well as the parallel advanced circulation (ADCIRC) model for oceanic, coastal, and estuarine waters show that a slow moving Category 3 storm, on any number of tracks, could flood New Orleans from levee to levee completely filling the bowl. For Category 4 and 5 storms the situation is even bleaker.

The Gulf of Mexico is a favorable environment for the formation of intense hurricanes. Unlike other hurricane prone areas that do not provide enough retention time for storms to build, the water in the Gulf of Mexico is extremely warm in the late summer/early fall with a potential to support Category 5 storms (>155 mph wind speeds). In this region intense hurricanes not only form but intensify rapidly due to favorable conditions. Additionally, storms can be intense and form quickly, and they are numerous. In the last 50 years, six major storms (Category 3 or above) (see Fig. 5.1) have made landfall in Louisiana. These included Audrey (1957, Cat 4), Hilda (1964, Cat 3), Betsy (1965, Cat 3), Camille (1969, Cat 5), Carmen (1974, Cat 3), and Andrew (1992, Cat 3). As evidenced from the tracks of these storms, New Orleans had not sustained a direct hit, but had had quite a few narrow misses. Such storms often do not provide much lead time for evacuation.

On the positive side, Louisiana's population centers are located further inland (as opposed on the coast, such as Miami, FL) because storms tend to dissipate as they move inland. It generally takes 4 to 6 hours for a rapidly moving hurricane to move inland over New Orleans, and in that time, a 25 to 35 percent reduction in hurricane force may be realized.

Hard and firm rules do not apply to rainfall. Looking historically at rainfalls associated with tropical storms and hurricanes in the area, one of the largest events occurred in 1940 in southern Louisiana, where more than 30 inches of rainfall was recorded (Robbins 2003). More recently, when TS Isidore tracked over New Orleans, winds were not much of a problem; however, 26 inches of rainfall pouring into the city was. Historical data on tropical storms and hurricanes demonstrate that 15 to 20 inches of rainfall is not uncommon.

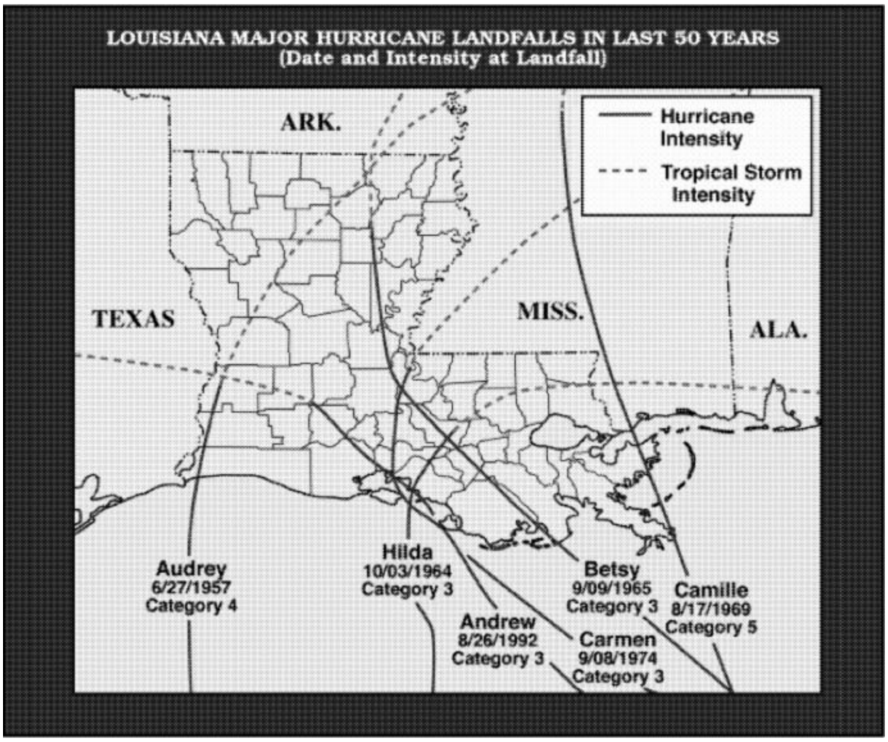

Fig. 5.1. Major hurricanes (with track and intensity) that have made landfall in Louisiana in the past 50 years (Source: NOAA, courtesy of Kevin Robbins, SRCC)

The New Orleans storm of May 1995 with 26 inches of rain affected 37 hospitals. During the flooding access routes to 68 percent of these hospitals were blocked by flood waters and debris; 44 percent cancelled all elective and surgical procedures; 32 percent had nursing shortages; 25 percent had doctor shortages; 18 percent had no sewage; 11 percent had no potable water; 7 percent had medical supply shortages; and 4 percent had food supply shortages.

How Many People Will Stay in a Major Storm?

A baseline survey was conducted from a random sample of 1,000 New Orleans residents. The data was primarily collected by telephone, with the sample selected via random-digit dialing. However, New Orleans contains many areas where substantial portions of the population live either below the poverty line or in extreme poverty. Representing the social and economic resources and the potential health needs of that segment of the population is both critical and difficult, because this segment of the population is least likely to evacuate. With the aid of social workers, these individuals were sampled using a door-to door survey.

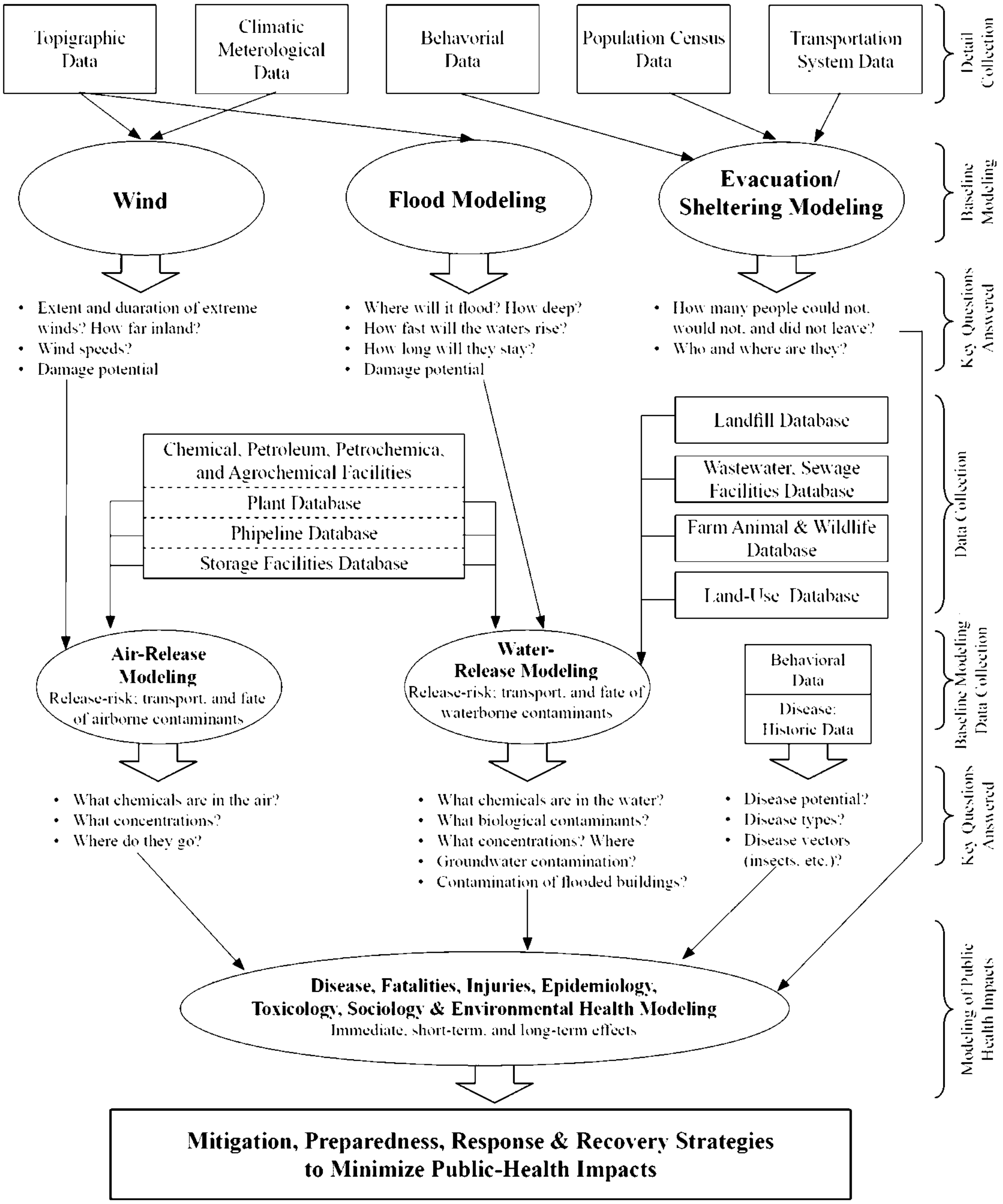

Fig. 5.2. Comprehensive flow chart of research activities

The primary focus of the survey was to understand how New Orleans area residents would prepare for and respond to a major hurricane. The study first assessed network structures and resources available and the extent to which these individuals would use formal and informal sources of help. Second, it asked residents about their past hurricane experience and how participants would respond if a storm as dangerous as Andrew approached the New Orleans area. It included questions on past hurricane experiences, the availability of transportation, and how, under what circumstances, and in what direction they would evacuate if a hurricane approached the area in the future. These questions included asking residents whether they knew someone they could go to and whether they would go to a motel/hotel, a shelter, a house, or other if they evacuated. The questions also included a third expanded section on hurricane evacuation. The section gained vital information on how the direction and severity of an approaching hurricane would affect the decision to evacuate and the timing of the evacuation. The answers will provide a better understanding of the social and economic resources of New Orleans area residents. They will also provide more detailed information on evacuation response (Hurlbert 2003).

Preliminary data from the survey are now available. Overall, 68.8 percent of respondents would leave the area. Another 9.8 percent would leave their homes but remain in the area. The remaining 21.4 percent would remain in their homes—a startling and important statistic. It indicates that nearly one in four New Orleans residents would refuse to leave their homes as a possibly deadly major hurricane approaches the city.

Evacuation Issue—Can They All Get Out?

Important research objectives about evacuation include the following:

- Assessing the effectiveness of the planned evacuation strategy for New Orleans and, by default, other similar strategies around the United States;
- Using these results to develop alternative strategies that may be more effective than those currently planned; and
- Testing these alternative strategies to determine if they would be more effective in moving evacuees than those currently planned.

A traffic model to simulate the evacuation of traffic from New Orleans, with specific emphasis on the I-10 westbound contraflow segment from the vicinity of Loyola Avenue to the I-10/I-55 interchange has been developed, beginning with a base model using the corridor simulation software package, CORSIM (Wohlson 2003). An additional project centered on the traffic and congestion characteristics associated with various planned contraflow termination point configurations, including the one in New Orleans.

While it has been widely suggested that the use of two contraflow lanes would increase the capacity of a four-lane freeway by about 70 percent, there has been insufficient data and analyses to support this claim. Experiments have now shown, however, that the total exiting evacuation volume on I-10 increases by about 53 percent over a standard two-lane configuration with contraflow (Wohlson 2001, 2003). The most significant finding, however, is the critical role played by the entry point and the plan to load vehicles into the contraflow lanes. Since the inception of contraflow evacuation, emphasis has been placed on the location and control of the segments because it has been assumed that the segment length and termination design would dictate the effectiveness of the operations. However, new research suggests that the segment itself does little good if adequate capacity is not provided at the point where vehicles enter the segment. These results further suggest that the contraflow segment planned for westbound I-10 out of New Orleans will likely create a bottleneck. This would lead to the typical three-state flow condition in which traffic conditions upstream of the restriction would be heavily congested, then flow at near capacity rates through the restriction, before flowing in a near free-flow state downstream. Under an evacuation scenario this condition can potentially have both positive and negative aspects. Most critically, the entry congestion would be a significant problem because it would slow the departure of vehicles from the threat area. In New Orleans, where in excess of 120,000 vehicles are expected to use this segment within a short period (24 to 72 hours), monumental traffic congestion would likely occur. However, the use of downstream entry points after the restriction could at least partially offset this problem by helping to fill the underutilized contraflow segment (Wohlson 2003).

CORSIM simulation results show that when there is no available ramp for traffic to exit along the evacuation route, merging conflicts and traffic congestion are expected to occur before the one-lane closure. Although it might not always be possible to exit 50 percent of the total traffic, these results showed that increasing the exiting vehicles using more available exit ramps improved the efficiency of the contraflow operations.

The models also showed that traffic flows tended to drop dramatically with speeds less than about 30 mph. On both the contraflow and normal flow roadways, the critical density and critical speed were around 40 vehicles per mile per lane (vpmpl) and 30 mph, respectively. Maintaining densities on the freeway below critical density and above critical speed can ensure higher traffic flow (Wohlson 2003).

Public Health Outcomes, Phase One—Immediate Impacts

The Corps of Engineers currently predicts that if the New Orleans bowl fills, it would take nine weeks to pump out all of the water, assuming the necessary permits are obtained. There would likely be a strong push by commercial fishing interests to restrict the pumping for fears the contaminated water would severely affect the harvestable marine and estuarine species. Air evacuations by helicopter would ensure the evacuation of thousands a day, but at the same time, a mechanism to get food, water, and medicines to those trapped is needed. An "Operation Dunkirk" effort would have to be launched from the north shore of Lake Pontchartrain, using sport fishing and recreational boats to collect stranded New Orleans residents from the levees on the north side. On the south side, barges and commercial vessels would do their own river evacuations to centers such as Baton Rouge. Within the flooded city, where water levels in many areas would reach the eaves of houses, another small craft operation would have to be set up to move people and supplies to and from their places of refuge to the levees (high ground) and vice versa. This "Operation Dunkirk" evacuation and supply operation, using mostly volunteers, would require significant planning. Each crew would need emergency supplies and radio/cellular phone communications, a stock of medicines, and medical experts to communicate with. Insurance issues and waivers would have to be negotiated.

There would be trauma cases from projectiles as well as collapsing structures and the concomitant risk of tetanus among the survivors who rode out the storm in New Orleans. Their immediate health problems would certainly include high incidences of diarrhea and other gastroenteric problems due to contaminated water, stress, worsening personal hygiene, and toxic chemicals. In addition, evacuation centers would have to deal with people who left home without adequate supplies of their prescribed medications. Although most people are helpful and altruistic during disasters, security issues nonetheless pose another risk.

Despite the widespread flooding, there also would be a significantly increased risk of fires in New Orleans from barbecues, portable stoves, open cooking fires, candles, and lanterns. Remaining occupied structures, abandoned warehouses, high-rise office buildings, and all unflooded upper stories—many serving as commandeered shelters—would also face increased fire risks from downed power lines, disrupted floating gas lines, and gas pockets trapped in roofs and upper stories. Unfortunately, these fire risks would be met by understaffed and inadequately equipped firefighting and EMS personnel. Local fire departments would be denied ground access, would have inadequate airborne and marine firefighting equipment, and would lack water pressure except that supplied by siphon pumps.

Many storm and flood refugees would have been inadequately vaccinated for measles and influenza, and unvaccinated for pneumococcal pneumonia and bacterial meningitis. These highly communicable, yet preventable, diseases cause frequent epidemics among military recruits crowded in base camps, as well as refugees crowded in temporary shelters. Public health personnel would require adequate supplies from the strategic national stockpile of the appropriate vaccines to offer timely vaccinations to large numbers of displaced persons in crowded conditions (Diaz 2003). The homeless pose communicable disease threats (STDs, especially HIV/AIDS, and multi-drug resistant tuberculosis [TB]) and infectious disease threats, such as typhus and hemorrhagic scabies, if crowded in shelters with susceptibles. Evacuating survivors from the flooded city, ensuring adequate flood and water supplies, and gaining rapid access to medical support are essential elements of phase one.

Phase Two—Initial Recovery

From the end of the first week to the second month (initial recovery) there would be complex human population fluxes—people allowed home, others kept in evacuation centers, movement from one center to another, further evacuations, and possibly a floating uncontrolled criminal population. The health consequences of this period would be characterized by continued stress and the appearance of mental health problems. There would be an increasing incidence of stress-related infections, asthma, and other respiratory diseases and lethal pneumonias, such as Legionella and pneumococcal pneumonia, especially in the elderly, the very young, and the immunosuppressed. Various parasitic infections could emerge as additional communicable disease threats following weeks of outdoor living, inadequate sewage treatment, inadequate personal hygiene and hand washing, and defecation. There would be a potential for encephalitis, dengue, and other arboviral infections. Food delivery problems would result in contaminated food outbreaks and, because this state is fond of seafood, there is also the potential for various rotavirus, calicivirus, hepatitis A, paralytic shellfish poisoning, and *Vibrio spp.* outbreaks, including cholera. Chemical toxic conditions should decrease during this time. However, toward the end of this phase, there would be a surge in infectious disease diagnoses by inadequate diagnostic laboratory capabilities (Diaz 2003). During this period there would be an urgent need for aggressive mental health programs and getting children back into structured lives and school to prevent longer-term juvenile problems. There would be faster and slower components of recovery. Noji (2001) stresses the need for better epidemiologic knowledge of disasters to better facilitate relief efforts.

Communicable vs. Non-Communicable Disease and Conditions

Of the communicable diseases, waterborne diseases would likely be the most common, followed by food borne, vector borne, and airborne-respiratory, in that order. Waterborne diseases and conditions would result primarily from human feces (*E. coli, Shigella, Salmonella*, HAV, caliciviruses, and amebic) but also from animal feces (Cryptosporidium, Cyclosporidium, and Giardia). Food borne illnesses would result from food spoiled in refrigerators from loss of power or from eating raw shellfish and would include exposures to the *Staph aureus* enterotoxin, Salmonella, Shigella, Campylobacter, non-cholera Vibrios, and caliciviruses. Vector-borne disease would be primarily caused by mosquitoes (for example, West Nile, in which most cases are asymptomatic), zoonotic vectors, which can cause more serious problems (for example, St. Louis encephalitis [SLE]), rodent vectors (which can cause leptospirosis), fleas, and ticks (for example, which can be vectors for Lymes disease and related conditions). Airborne-respiratory diseases would include upper respiratory infections (URIs), the flu, and measles (Diaz 2003).

Non-communicable conditions likely to follow hurricanes and floods, include psychological, musculoskeletal (primarily falls), chronic diseases (or exacerbation of current conditions), and physical and toxic exposures, in that order. Physical conditions include drowning, near-drowning, submersion, hypothermia, electrocution, and burns. Toxic conditions include carbon monoxide and nitrogen oxide poisoning at the top of the list (most commonly resulting from operating a generator indoors), chlorine and phosgene gas exposure (ubiquitously available on tank farms in neighborhoods), and exposure to volatile organic chemicals, such as benzene, MTBE, TCE, and perchloroethylene. Possible psychological conditions include anxiety, aggression, anger, insomnia, estrangement, depression, post-traumatic stress syndrome, and disaster shock. Musculoskeletal conditions also include strains, sprains, dislocations, and fractures. Exacerbated and chronic conditions include myocardial infarction/heart attack, cerebrovascular accidents/ stroke, and diabetic conditions/diabetic ketoacidosis (Diaz 2003).

A stockpile of measles vaccine is critically important for primary prevention. MMR (two to three sets of vaccinations), a current annual flu shot, and a tetanus shot within at least the last 10 years should be priorities for any citizen who decides they will not leave or who cannot leave a potential disaster zone. There is a high probability of a measles outbreak, particularly in shelters or conditions of close living quarters for extended periods of time. Measles has long incubation phase (around 21 days) after which it becomes highly infectious. If an individual with measles enters a shelter where many have incomplete or no measles immunizations, an outbreak could rapidly spread with high morbidity and mortality in both children and adults. Measles is the most common killer in refugee camps.

In summary, the primary vaccines to stockpile in preparation for flood disaster in New Orleans include influenza, pneumococcal pneumonia, measles, rubella, and pertussis. Contrary to past recommendations, vaccines for cholera or typhoid are unnecessary. Cholera is an ineffective vaccine, and typhoid vaccines should be reserved for travelers (Diaz 2003).

A Coastal Restoration Plan to Save New Orleans

The New Orleans catastrophe is real, and extensive coastal restoration is needed. The most viable proposed restoration plan to protect New Orleans from hurricane risks has been guided by the following principles (van Heerden 1994):

- Restoration projects must benefit the local communities of Louisiana's coastal zone and not reduce long-term economic viability. Specifically, restoration projects must be designed at a minimum to maintain the current level of flood protection and transportation infrastructure. Projects that will unavoidably result in displacement of facilities and natural resource harvesting areas should be implemented gradually and include funding to offset unavoidable short-term economic dislocations.
- Restoration projects must maintain and enhance the long-term biological productivity and biodiversity of Louisiana's estuarine systems, which are the primary impetus for restoration.

- An effective long-term restoration strategy must re-establish large-scale, natural deltaic wetland creation and maintenance processes using seasonally pulsed sedimentation and freshwater input from the rivers to counter the sediment accretion deficit.

Creation of Productive, Sustainable Wetlands Through Major Freshwater Diversions from the Mississippi River

Two approaches must guide our thinking: (1) initiating a new locus of deposition for Mississippi River sediments that will result in significant wetland creation in the long-term, and (2) creating new distributaries or revitalizing existing distributary channels to once again deliver sediments to areas some distant from the river.

Breton-Chandeleur Sound encompasses 1,200 square miles, dominated by shallow bays. These water bodies are protected from the direct impact of Gulf of Mexico's wave energy by the Breton-Chandeleur Barrier Island chain. The region's shallow bays, coupled with subsidence rates of about 0.5 ft. per century, can serve as an excellent containment reservoir for Mississippi River discharge and sediment (NMFS 1993, van Heerden 1993b).

Creating a major Mississippi River diversion into Breton Sound, south of Bohemia opposite the village of Nairn, would begin a new delta cycle reversing wetland loss rates in eastern Plaquemines and St. Bernard parishes. It is proposed that an average discharge of 200,000 cubic feet per second (cfs) would pass through this diversion to create in excess of 5,000 acres (8 sq. mi.) of wetlands each year (van Heerden 1994). In 20 years, new wetlands totaling more than 140 sq. mi. would be created. Moreover, water movements caused by tides, southerly winds in spring and summer, and coastal water level set-up proceeding cold-front passage in the winter would drive resuspended sediment into the St. Bernard marshes. Wetland loss in these marshes would be reduced considerably.

Diverting most of the Mississippi River flow into Breton-Chandeleur Sound implies abandoning the Mississippi bird-foot delta. Wetland loss in this area is characterized by two problems: high subsidence rates (3 ft. per century) and most of the Mississippi sediment being discharged into relatively deep water. Consequently, as the bird-foot delta is abandoned, it will be slowly reworked into barrier islands. These islands will coalesce with the Breton-Chandeleur islands to the east, and the shell/sand shoals/islands that form the seaward edge of western Plaquemines Parish. As a result, an almost continuous barrier island arc will extend from Grand Isle in the west to the northeastern tip of the Chandeleur Islands. These barrier islands will greatly aid in hurricane protection for the eastern half of coastal Louisiana, especially the greater New Orleans' metropolitan area (Van Heerden 1993a, b).

Without question, this new diversion will have some impact on navigation along the Mississippi River and the Mississippi River-Gulf Outlet (MRGO). After all diversions presently proposed by state and federal agencies are constructed, the Mississippi River's annual discharge would equal 200,000 cfs. If this flow was directed through Southwest Pass—the river's main navigation channel—the route could be maintained for deep-draft vessels. Ultimately, a set of locks may have to be constructed from a point upstream of the town of Empire, connecting through Adams and Bastian Bays to the open waters of the Louisiana Bight. In the locks, flocculation and accumulation of fluid mud could require the development of a vacuuming system using, for example, fluid-mud-jet pumps installed in the floor of the locks. The Scripps Institute of Oceanography in California has investigated siltation in slips and how to deal with it for the U. S. Navy. Thus, technology to address siltation problems in locks does exist.

In the first 10 years, the Breton delta's impact on MRGO would be minimal, but after 20 years the delta front would reach the channel. Thereafter, either MRGO would have to be closed and the necessary navigation infrastructure made, or the diversion and/or MRGO would have to be modified.

Over time, introducing fresh water into Breton Sound would change the landscape of the region's commercial fisheries. Some existing oyster beds, for example, would have to be abandoned in favor of new ones being created in the bird-foot delta or in eastern St. Bernard Parish. In 20 years, however, the Breton delta would create approximately 100,000 acres of new wetlands and significantly alter the character of the St. Bernard marshes, pushing them towards the fresher end of the spectrum and expanding the marsh landscape. Further, the extended barrier island arc would have the ability to absorb a significant portion of any hurricane's energy, with positive consequences for New Orleans and adjacent communities. Navigation practices and channel maintenance within the Mississippi River, downstream of the diversion, may have to be changed, and ultimately, a lock may have to be built connecting the river to the Louisiana Bight. If the delta were allowed to expand beyond MRGO, infrastructure changes would be needed to accommodate closure of this channel. Assuming eventual closure of MRGO, this project could have a $ 3.0 billion price tag. Van Heerden (1994) has shown that the Mississippi River still carries enough sediment for restoration needs, even though its suspended load has decreased by at least 70 percent since 1850 (Kesel 1989).

Conclusions

Flooding New Orleans is a real threat, a catastrophe that would severely impact the U.S. economy, with ripples felt throughout the world's economy. The problem is exacerbated with global warming. Louisiana would take decades to recover from such a catastrophe.

A solution is diverting the Mississippi River into Breton Sound and creating a new Mississippi Delta. Such a project would generate significant amounts of new wetlands, improving the buffering of storm surges destined for New Orleans.

A large-scale project of this nature would have other benefits. Biological productivity would be enhanced and biological diversity maintained. The expenditure of the billions of dollars needed for the Breton Delta project would generate large number of jobs over time. Additionally, the technology developed and applied could be exported nationally and internationally, a product of the state's enhanced knowledge and capability in coastal habitat restoration.

The Breton Delta project would also result in improving the harvest potential of natural resources, thus expanding the job base. In many coastal parishes, natural resource harvesting is the main employer, or runs a close second to the oil industry. Enhancing the biological productivity of our coastal wetlands would create new opportunities in fishing, tourism, and other areas. This is important because oil industry jobs are expected to continue to shrink. Visitors could be shown the restoration projects, which would be some of the largest ever attempted. Although New Orleans already attracts millions of visitors annually, the right infrastructure could entice them to spend some time in the coastal wetlands, injecting new money into local economies.

Not to act on Louisiana's coastal land loss with all the facilities of government exposes New Orleans to greater threats than necessary.

Acknowledgements

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Chapter 6: Risk-Based Approach to Shelter Planning for Coastal Area Exposed to Storm Surge

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Abstract

Shelters were constructed in the coastal area of Bangladesh to provide refuge for people during storm surge floods from tropical cyclones in the Bay of Bengal. According to the National Water Management Plan (NWMP), existing shelters accommodate only 27 percent of the population at risk; additional shelters are needed for 5.9 million people. This paper addresses one of the key planning issues: how to allocate shelters equitably among competing areas as available funds cover only a fraction of those needed. It predicts the100-year surge height at the coast and simulates the corresponding flooded area. The flooded area is divided into hazard zones based on flood depth and administrative boundary. Shelters are allocated among the zones based on risk and equity considerations. The methodology is illustrated for the eastern part of the Ganges Tidal Plain.

Introduction

The coastal region of Bangladesh is exposed to occasional devastating storm surge floods from the formation of tropical cyclones in the Bay of Bengal. Shelters are constructed to provide refuge to the exposed population during floods. Existing shelters accommodate only 27 percent of the population at risk, and 6.3 million will be at risk in 2025 according to the NWMP (WARPO 2001). The plan includes a disaster management program to construct 775 additional multi-purpose shelters in 25 years for 3.74 million people at a cost of 7,221 million Taka. One of the planning issues is how to allocate shelters among competing areas in the intermediate years. Another issue is the equitable distribution of community facilities in the storm surge prone coastal region. Bangladesh's Coastal Zone Policy emphasizes the right of neglected and disadvantaged groups, and gives priority to the poorest and the remote rural areas in the distribution of national economic benefits (Ministry of Water Resources 2005). This paper discusses a risk-based, decision-support methodology for shelter allocation that takes into consideration the equity concern. It is an improvement in the work reported by Chowdhury and Rahman (1998).

Generation of Flood Data

Prediction of Surge Height at the Coast

The Bay of Bengal's long and shallow continental shelf and the configuration of the Bangladesh coastline are important factors in the amplification of storm surges generated by tropical cyclones. Based on an approximate solution for the slope of water surface due to wind stress during a cyclonic storm over a uniformly rising continental shelf and shallow water correction suggested by Bretschneider (1966), Chowdhury derived a formula to predict the maximum surge height at the Bangladesh coast. To obtain design surge heights, the coast of was divided into segments. Then the surge heights were predicted for a segment using representative values of the length of continental shelf. The formula can be expressed as follows:

$$s_P = \frac{13\times10^{-6} lw^2{}_{2P}}{(5\times10^6 + lw^2{}_{2P})^{0.2}} \tag{6.1a}$$

$$w_{2P} = 104.53 - 40.10\ln[-\ln[1-2P]] \tag{6.1b}$$

where s is the maximum surge height at the coast in m, w the maximum wind velocity in km/hr., l the average distance in km between the 200 m depth contour of the continental shelf and the coastline, P the exceedance probability, and the subscripts of s and w indicate the exceedance probability for them. It is noted that the exceedance probability for w in Eq. 6-1a is twice that for s. Details are given in Chowdhury (1994).

Flood Simulation Model

Flat topography and presence of wide estuaries allow the storm surge from the Bay of Bengal to intrude as far as 60 km. As a result, areas adjacent to rivers are flooded. The propagation of tides and storm surges along the estuaries was simulated using the numerical hydrodynamic model developed by Chowdhury (1986). It is based on an implicit finite difference solution of the gradually varied unsteady flow equations given below:

$$b\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \tag{6.2a}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{a}\right) + ga\frac{\partial h}{\partial x} + ga\frac{Q|Q|}{C^2a^2r} = 0 \tag{6.2b}$$

where x is the distance along the river in m, t the time in s, b the water surface width in m, h the elevation of water surface in m with respect to a common datum, Q the flow rate along the river in m^3/s, q the lateral inflow per unit length along the river in $m^3/s/m$, a the cross sectional area of flow in m^2, r the hydraulic radius of flow section in m, C the Chezy roughness coefficient in $m^{1/2}/s$, and g the acceleration due to gravity in m/s^2.

Ganges Tidal Plain

Almost the entire at-risk population is located in three regions, south-central (SC), south-east (SE) and Chittagong (WARPO 2001). The Ganges Tidal Plain (GTP) includes south-west (SW) and SC regions (Fig. 6.1). Few people are at risk in the extensive coastal zone of the SW because of the protection provided by the Sundarban mangrove forest. The SC region requires more than half of the total shelter (WARPO 2001). The section of the SC region in the GTP is selected as the study region (Fig. 6.1) to illustrate the shelter allocation model.

Flood data for different return periods for the GTP was generated using the flood simulation model. The simulation was carried out for the extreme condition when the peak surge reaches the coast during spring tide high water. Details of boundary conditions and simulation are given in Chowdhury and Karim (1996).

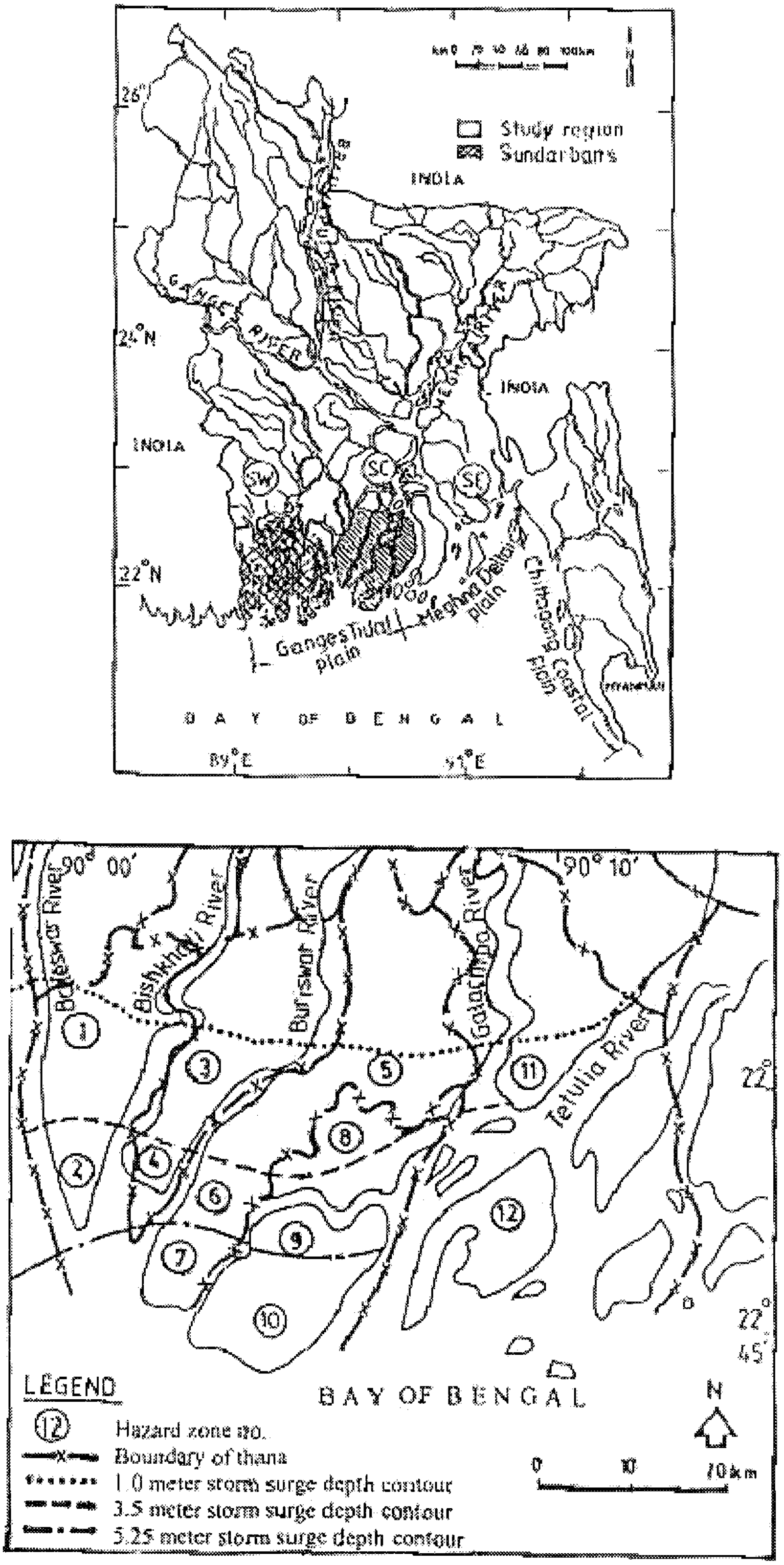

Fig. 6.1. Bay of Bangladesh, study region, and hazard zones

Delineation of Hazard Zone

Return Period for Design Surge Height

The NWMP's safe haven provision strategy is based on protection against the 1-in-30-year cyclone surge event in the medium term, with provision for improving to the 1-in-100-year level in the long term (WARPO 2001). A comparison of predicted 30- and 100-year surge heights at the coast for five regions is given in Table 6.1. As shown, the 100-year surge heights are approximately 2 m higher than the 30-year heights except for the SW and CS segments, which are in relatively less vulnerable regions. The NWMP does not explain how the shelters would be raised to the 100-year flood level after they are constructed for 30-year surge heights. Additionally, the effectiveness of the selected protection level is likely to diminish with time because of possible sea level rise due to climate change and geologic subsidence. This paper considers shelters for protection against 100-year storm surge event.

Table 6.1. Predicted Surge Heights at the Coast

Coastal segment	Surge height at the coast in m	
	1 in 30 year	1 in 100 year
South-West (SW)	3.57	5.14
South-Central (SC)	4.34	6.23
South-East (SE)	5.45	7.78
Chittagong-North (CN)	4.90	7.01
Chittagong-South (CS)	3.17	4.58

Hazard Zones

Structuring governmental planning units around appropriate hazard zones is critical to effectively allocate shelters. The lowest tier government administrative unit is the thana; there are five thanas in the SC region. To account for the spatial variability of flood depth, the thana is divided into hazard zones (planning units) where shelters will be allocated. A hazard zone is an area enclosed by the contour of critical flood depth (CFD) and the thana boundary. The CFDs are 1.0, 3.5, and 5.25 m. CFDs are selected on the basis of the *Multipurpose Cyclone Shelter Program Final Report* (BUET and BIDS 1993), which recommends that the shelters should be constructed where flood depth exceeds 1 m, and the height for the shelter stilts should be selected from three standard heights of 3.5, 5.25, and 7.0 m. The contours of CFDs were determined from the result of simulation for 100-year floods. The hazard zones were then delineated by overlaying the contours of CFDs on a map showing thana boundaries. Twelve hazard zones were delineated covering an area of 1,345 sq. km. in the SC region (Fig. 6.1). Because of the hazard zone criteria, all shelters in a zone will be of equal height, and consequently, unit cost of shelters in a zone will be constant as shown by Table 6.2. The unit cost of the shelter is based on Chowdhury and Rahman (1998).

Hazard Index for Hazard Zone

Mott Macdonald, et al. (1993) and Sener, et al. (1996) devised a scaling system based on flood depth and hazard intensity, respectively, for the preparation of hazard maps. This approach is used here to indicate the magnitude of flood hazard in a hazard zone. A hazard index (*HI*) of integer value based on spatial range of flood depth, d in m, is devised for this purpose. The scale selected for the *HI* is given in Table 6.2. The area with $HI = 1$ does not require shelter since flood depth is less than 1 m. Alternative scales for the *HI* were investigated by Chowdhury and Karim (1996). It was observed that the linear scale given in Table 6.2 produced a map of *HI*s consistent with the severely affected areas identified in the *Multipurpose Cyclone Shelter Programme Final Report* (BUET and BIDS 1993).

Table 6.2: Hazard Index, Height of Stilts of Shelters and Unit Cost of Shelter

100-year flood depth range	*HI*	Height of stilt of shelter	Unit cost of shelter
$0\ m < d \leq 1.00\ m$	1	Shelter is not required	–
$1.00\ m < d \leq 3.50\ m$	2	3.50 m	Tk. 3.44×10^6
$3.50\ m < d \leq 5.25\ m$	3	5.25 m	Tk. 3.53×10^6
$5.25\ m < d$	4	7.00 m	Tk. 3.77×10^6

Assessment of Risk

Risk to Human Lives

According to the manual for policy-makers and planners published by the International Decade for Natural Disaster Reduction (UNDRO 1991), risk can be expressed as the mathematical expectation of annual loss as given below:

$$\rho_s = \int_{m_c}^{\infty} V(m)\ \xi(m) dm \qquad (6\text{-}3)$$

where ρ_s is the risk for a specific element, $V(m)$ = vulnerability function (consequence function) representing the degree of loss to the element resulting from the occurrence of a natural hazard of a given magnitude m, m_c the critical (threshold) value of hazard representing the minimum or maximum value of m that causes loss, and $\xi(m)$ the probability density function for the hazard.

The vulnerability is usually measured by

$$V(m) = v(m)L \qquad (6\text{-}4)$$

where $v(m)$ is the vulnerability factor expressed on a scale from 0 (no loss) to 1 (total loss), L the maximum loss that can occur when full consequence of the hazard takes place.

For shelter planning, risk to human life is the only concern, and there is a possibility of loss of life when $m \geq m_c$. In this condition, the vulnerability function, Eq. 6-4, becomes a step function as follows:

$$V(m) = 0 \text{ when } m < m_c \text{ and } V(m) = L \text{ when } m \geq m_c$$

where L is now the number of people at risk.

Then from Eq. 6-3, risk to human lives is given by

$$\rho_s = L.P(m_c) \qquad (6\text{-}5)$$

where $P(m_c)$ is the probability of exceeding the critical hazard value m_c. In this study m_c is the critical flood depth of 1 m because shelters should be constructed where flood depth exceeds 1 m (BUET and BIDS 1993).

Residual Risk in Hazard Zones

Some shelters already exist in every hazard zone, and hence, the populations not covered by existing shelters are at risk, which can be termed as residual risk. Replacing L by Y in Eq. 6-5, the residual risk, ρ_{hz}, in a hazard zone can be expressed as

$$\rho_{hz} = Y.P(m_c) \tag{6-6}$$

where Y is the existing unprotected population in a hazard zone. Unprotected population implies the population not covered by existing shelters.

Residual Risk in the Region

Aggregating residual risk, given by Eq. 6-6, for all hazard zones, residual risk in the region for the existing condition (before construction of shelter) can be obtained as given below:

$$R_B = \sum_{i=1}^{n} P_i Y_i \tag{6-7}$$

where R_B is the residual risk in the region before allocation of shelter, P_i the probability of exceeding the flood depth of 1 m in the ith hazard zone, Y_i is the existing unprotected population in the ith hazard zone, and n the total number of zones in the region.

Similarly, the residual risk in the region after construction of shelters is given by

$$R_A = \sum_{i=1}^{n} P_i (Y_i - N_i K) \tag{6-8}$$

where R_A is now the residual risk in the region after shelter construction, N_i is the number of shelters allocated to the ith hazard zone, and K, the shelter capacity.

Allocation of Shelters

Equity-Based Weight for the Hazard Zone

Equations 6-7 and 6-8 account for the vulnerability of lives to the flood hazard. From an equity point of view, consideration of socio-economic vulnerability is also important because disadvantaged sections of the society usually live in the coastal areas most vulnerable to storm surge floods. The shelter allocation policy based on minimizing the residual risk in the region, given by Eq. 6-8, would maximize the number of people covered by shelters. However, this approach may lead to inequitable distribution of shelters mainly because the unit cost of shelter increases towards the coast (see Table 6.2) and the poorest people usually live in the most vulnerable areas, which are close to the sea where the depth of storm surge flood is highest. A methodology is needed to incorporate an equity factor in the objective function.

The depth of flood is higher towards the coast. Therefore, the hazard zones with a higher hazard index, *HI*, should be given greater weight in the objective function. For equal hazard magnitude, an area with higher concentration of socially disadvantaged people would be more vulnerable. Therefore, hazard zones having a poor socio-economic condition should also be weighted more heavily in shelter allocation. This can be done using a socio-economic vulnerability index. Density of population, D, is used here as the vulnerability indicator as was by Mott Macdonald et al. (1993) and Sener et al. (1996). Population density is an indication of the socio-economic status of an area (Sener et al.1996).

An equity factor, based on hazard and socio-economic vulnerability indices, is formulated to give weight to the hazard zones in Eqs. 6-7 and 6-8. The formulation is similar to that used for a hazard index by Mott Macdonald et al. (1993). The equity factor whose maximum value will not exceed 1, is defined as given below.

$$E_i = \left(\frac{HI_i}{HI_m}\right)\left(\frac{D_i}{D_m}\right) \qquad (6\text{-}9)$$

where E_i is the equity factor for the *i*th hazard zone, HI_i the hazard index for the *i*th hazard zone, and the scale for the HI is given in Table 6.2, HI_m the maximum value of HI_i among the hazard zones, D_i the density of existing unprotected population in the *i*th hazard zone, and D_m the maximum value of D_i among the hazard zones.

Incorporation of the equity factor in Eq. 6-7, results

$$Z_B = \sum_{i=1}^{n} E_i P_i Y_i \qquad (6\text{-}10)$$

where Z_B is the aggregated value of the weighted residual risk for the existing condition (before allocation of shelter) in the region.

Optimization Model

As explained previously, the shelter allocation is subject to a budget constraint. The reduced residual risk in the region as a result of the allocation of N_i numbers of shelters to the hazard zones is given by Eq. 6-8. The challenge is to find optimum values of N_i for the hazard zones by taking account of equity concerns arising out of socio-economic vulnerability. Incorporating the equity factor in Eq. 6-8, the objective function can be stated as follows:

$$\textit{Minimize} \quad Z_A = \sum_{i=1}^{n} E_i P_i (Y_i - N_i K) \qquad (6\text{-}11a)$$

$$\textit{subject to} \quad \sum_{i=1}^{n} U_i N_i \le T \qquad (6\text{-}11b)$$

where Z_A is now the objective function, U_i is the unit cost of shelters in the *i*th hazard zone, and T the available budget for the region.

The probability P_i of exceeding the flood depth of 1 m in the *i*th hazard zone was interpolated using water level profiles for different return periods. The water level profiles were generated using the flood simulation model previously discussed. Details of the method of interpolating flood profiles are provided in Chowdhury and Rahman (1998). The shelter capacity K is 1,750 per shelter (BUET and BIDS 1993); the population data is provided in Chowdhury and Rahman (1998).

Experience shows that long lapses occur between the decision to allocate shelter and the completion of shelter construction as allocated. There will be autonomous change in the population during this period not considered here, which is an interesting additional element to study.

In Eq. 6-11a, $(Y_i - N_iK)$ gives the number of people that would remain unprotected in the ith hazard zone after allocation of shelter while Y_i is the existing unprotected population in the *ith* hazard zone. Solving Eqs. 6-11a and 6-11b is possible using a linear programming model because the equity factors E_i, which are based on the existing unprotected population in a hazard zone, have constant values. In another formulation of the problem, Chowdhury et al. (1998) used a factor based on the population that would remain unprotected after allocation of shelter to a hazard zone. The solution required a non-linear programming model.

Equity Constraint

The formulation in Eq. 6-11 provides a solution that allocates shelters in hazard zones with high equity factors and large unprotected populations. It may not be acceptable for some hazard zones to receive very few shelters; besides, shelters are also designed for multi-purpose use as schools and community centers. To address this concern, another equity consideration is incorporated in the model by imposing a constraint to ensure a minimum fraction of the total number of shelters required in each thana, thus ensuring a minimum community facility in each. It can be expressed as given below:

$$\frac{N_j}{G_j} \geq \alpha \qquad for\ j=1\ to\ k \qquad (6\text{-}12)$$

where G_j is the total number of shelters needed in the j-th thana, α the desired minimum fraction of the shelters required, and k the total number of thana in the region.

Results and Discussion

The problem defined by Eqs. 6-11 and 6-12 is an integer programming problem. The solution begins by considering the problem as a linear programming problem that considers fractions of shelters and rounds them to the nearest integer value. This algorithm yields solutions that are nearly optimal. The rounding may reduce the total number of allocated shelters and keep the total cost considerably below the budget. This problem is overcome by distributing the number of shelters that can be supported by the remaining funds according to the remaining unprotected populations in the hazard zones. This problem depends on the type of solver used and can be eliminated by using a suitable solver.

A summary of results is given in Figure 6.2. The budget is assumed to remain consistent with the government's funding pattern. As seen from the lowest curve in the figure, for an investment of 150 million Taka, the value of the objective function (Eq. 6-11a) decreases to 64 percent when the equity constraint is not imposed ($\alpha = 0$). Doubling the investment to 300 million Taka reduces the value to 52 percent. The incremental decrease in the objective function value is 12 percent, which is much lower than the proportional value.

The two upper most curves in Figure 6.2 are for the residual risk in the region, which are assessed using Eqs. 6-7 and 6-*8*. With investments of 150 and 300 million Taka, the corresponding residual risk are 87 and 73 percent of the present value, given by Eq. 6-7, when the equity constraint is not imposed ($\alpha = 0$). This indicates that the decrease in the residual risk in the region is nearly proportionate with the increase in the investment.

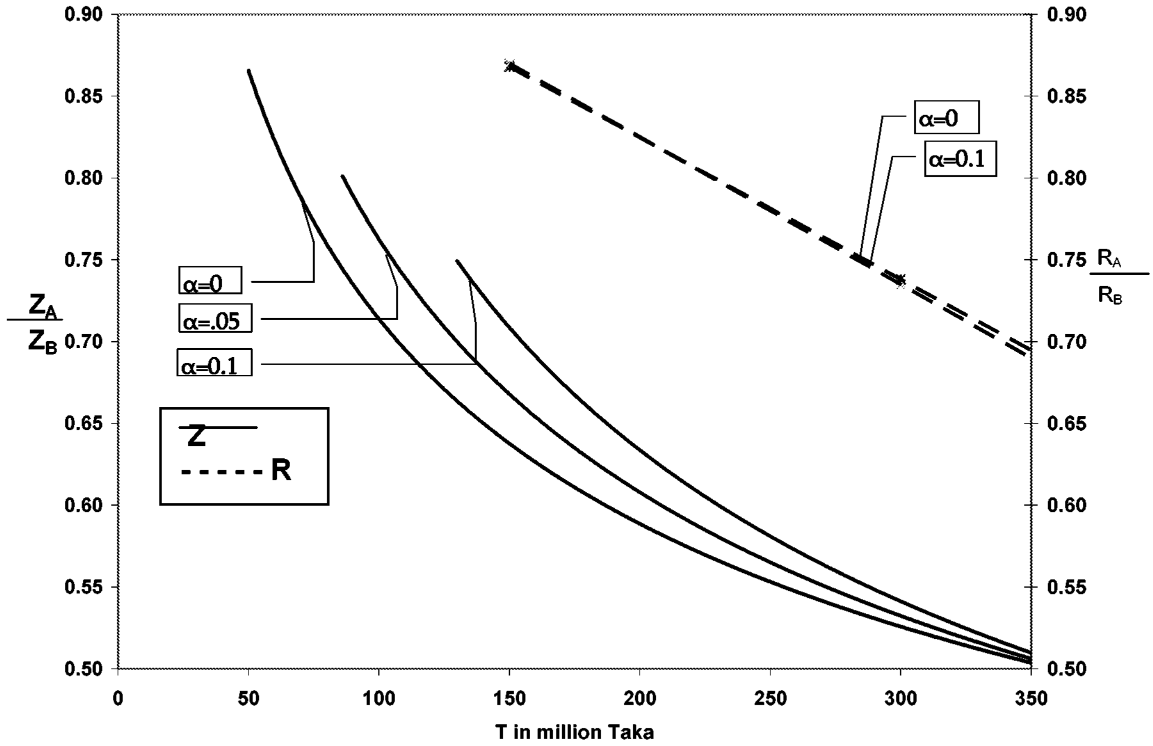

Fig. 6.2. Objective function value and residual risk in the region as fraction of their initial values for different budgets and equity constraints

Comparison between the curves for the objective function value for α = 0 and α = 0.05 or 0.10 in Figure 6.2 indicates a major change in the distribution of shelters is required to meet the equity constraint at a low investment level. For instance, the objective function value is 64 percent for an investment of 150 million Taka when equity constraint is not imposed (α = 0), while with the same investment, the value is 72 percent for α = 0.10. To reach same value of 64 percent with a retaining equity constraint at α = 0.10, a higher investment of nearly 200 million Taka is required. At an investment level of 350 million Taka and greater, there is no significant impact of the equity constraint. However, there is a budget level below which equity constraints cannot be met. The equity constraints of α = 0.05 and 0.10 cannot be met with investments lower than 60 and 120 million Taka.

The residual risk in the region are 87 and 74 percent of the present value for investments of 150 and 300 million Taka respectively for α = 0.10, and the curve for α = 0 is very close to the curve for α = 0.10 in Figure 2. This shows that, although the equity constraint brings significant change in the distribution of residual risks in the hazard zones, the resultant global residual risk in the region remains approximately the same.

Table 6.3. Disbursement of Fund to the Administrative Units Based on Allocation of Shelters to the Hazard Zones for Given Budgets for the Region

Thana	Hazard Zone no. i	Disbursement of fund for different budgets, T in million Taka, and equity constraint α			
		$T = 150$		$T = 300$	
		$\alpha = 0$	$\alpha = 0.1$	$\alpha = 0$	$\alpha = 0.1$
Patharghata	1, 2	3.44	20.91	10.41	34.67
Barguna	3, 4	141.85	55.31	203.77	165.93
Amtali	5, 6, 7	3.44	21.06	10.65	21.06
Kalapara	8, 9, 10	0	27.61	60.32	50.56
Galachipa	11, 12	0	24.08	14.42	27.85

Table 6.4. Allocation of Shelters to Hazard Zones in the Region for Given Budgets

Thana	Hazard zone no. i	Parameters of Eq. 11a			No. of shelters allotted for different budgets, T in million Taka, and equity constraint α			
		Y_i (thousand)	E_i	P_i	$T = 150$		$T = 300$	
					$\alpha = 0$	$\alpha = .1$	$\alpha = 0$	$\alpha = .1$
Patharghata	1	61.5	.31	.065	1	3	2	7
	2	26.1	.34	.08	0	3	1	3
Barguna	3	113.8	.50	.07	32	13	50	39
	4	23.5	.41	.10	9	3	9	9
Amtali	5	54.3	.24	.07	1	4	2	4
	6	18.1	.20	.10	0	1	0	1
	7	3.8	.08	.11	0	1	1	1
Kalapara	8	44.1	.24	.08	0	7	0	8
	9	35.3	.25	.10	0	1	0	1
	10	52.3	.33	.11	0	0	16	5
Galachipa	11	48.8	.26	.07	0	7	2	7
	12	60.2	.25	.11	0	0	2	1

Based on allocation of shelters to hazard zones, disbursement of funds to the thanas is shown in Table 6.3 to indicate the impact of the equity constraint. For a given budget $T = 150$ million Taka, most of the budget is received by Burguna Thana when equity constraint is not imposed ($\alpha = 0$). Patharghata and Amtali receive a nominal amount of funds, while Kalapara and Galachipa get none. When an equity constraint of $\alpha = 0.1$ is imposed, the change in the distribution of funds among the thanas is quite substantial, and the disparity is reduced considerably. At a higher investment level $T = 300$ million Taka, the change in the distribution of funds is not that dramatic.

Total number of shelters at budget $T = 150$ million Taka is 43 (which is 14 percent of the requirement) for both $\alpha = 0$ and 0.1; at $T = 300$ million Taka, the number of shelters are 85 and 86 for $\alpha = 0$ and 0.1, respectively. Shelter allocation to the hazard zones is shown in Table 6.4 to indicate the role of equity constraint. Hazard zone 3, which has the highest equity factor and the largest unprotected population, gets bulk of the shelters while other zones, except zone 10, get none or a small number of shelters when the equity constraint is not imposed. The disparity is reduced considerably when equity constraint is imposed. Allocation of shelters to the hazard zones in Kalapara and Galachipa Thanas is controlled by shelter construction cost. Hazard zone-based equity constraint would be better for these areas than thana-based constraint.

In summary, the incremental decrease in the objective function value is much lower compared to the proportional increase in the budget. The equity constraint has a significant controlling effect on the allocation of shelters among hazard zones at low budget levels, and the effect decreases with budget increases. Thus, the influence of equity consideration becomes less prominent with larger budgets. The residual risk in the region after shelter allocation decreases almost proportionately with the increase in the budget. The equity constraint has very little influence on the global residual risk. In other words the total number of people in the region that would be covered by the new shelters is not altered significantly by equity considerations. These results indicate the importance of equity consideration in shelter allocation when the available budget is low, which is the likely scenario in Bangladesh.

Studies are needed to develop improved representation of the equity factor, expressed by Eq. 6-9, based on socio-economic considerations. Better indicators than population density are needed to represent the socio-economic condition. The effectiveness of an indicator depends on how well it represents the socio-economic vulnerability of a hazard zone. Consideration should also be given to the percentages of children, women, elderly people, and seasonal migrant workers present in the unprotected population. A human development index, such as those used in development studies, can be utilized to represent equity concerns. The shelter allocation process should also take account of the higher risk for island populations and the changed risk for poldered areas.

Another similar issue is how to allocate the fund among the regions in the coastal area. On political grounds, the government may split the available budget among different regions proportional to the unprotected population in each. Distribution within the region can then follow the methodology discussed in this paper. Other methods of allocating the fund for shelter construction among the regions can also be investigated.

Possible sea level rise due to climate change and geologic subsidence has long-term implications for the management of storm surge hazard in the coastal areas of Bangladesh. The flood depth and the extent of flooded area are likely to increase. The constructed shelters may then become inadequate to protect against 100-year flooding. Shelters would be needed in additional areas because of the upland progression of the 1-m critical depth. Shelter planning should keep the provision so that adaptation to these changes in the storm surge risk is possible. This aspect needs adequate consideration in updating the NWMP.

Conclusion

Shelter planning should take socio-economic vulnerability into consideration to ensure social justice in the allocation of shelters among competing areas in the storm surge prone coastal region of Bangladesh. This paper illustrates how risk to life and equity criteria can be incorporated in the decision-making process for allocation of multipurpose shelters. Further study is needed to devise better socio-economic indicators to represent equity concerns.

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Chapter 7: Shelters—More Than a Safe Haven

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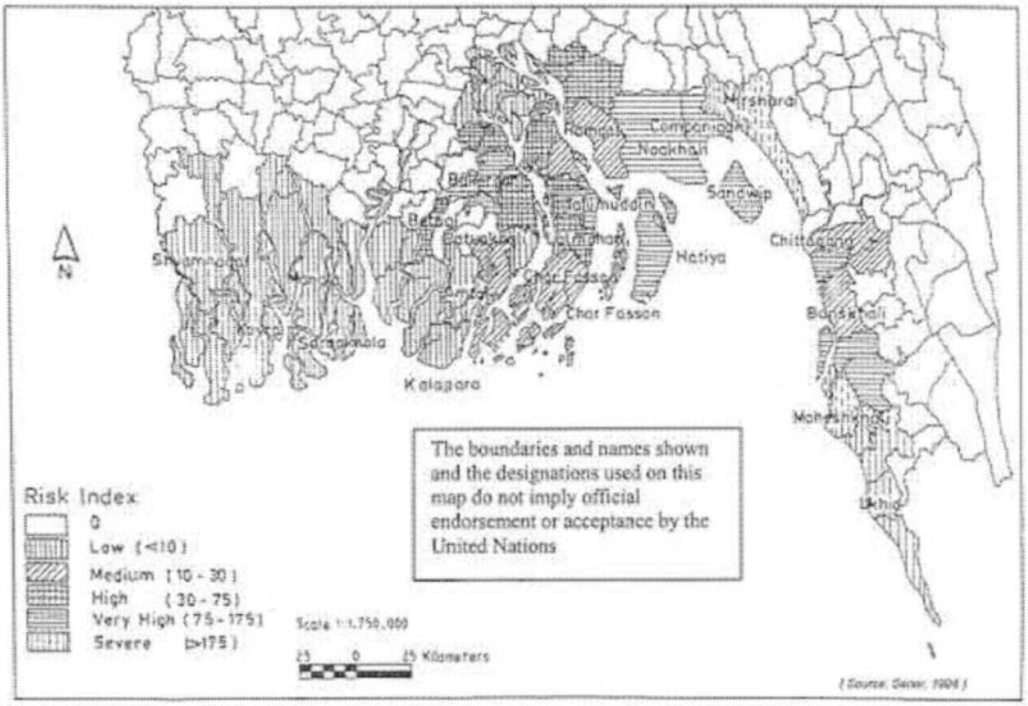
Introduction

Bangladesh is exposed to many natural and human-induced events including cyclones, flood, drought, tidal surge, earthquake, riverbank erosion, tsunami, and water-logging. It is not that more of these events occur in Bangladesh than in other countries; however, with a population density of approximately 1,000 persons per sq. km, Bangladesh is more vulnerable than most countries to such events. Since 1970 more than one million people have lost their lives with the cyclones of 1970 and 1991 claiming in excess of 900,000 lives. Financial costs (see Appendix 7.1) do not realistically reflect the total cost of these disasters when the broader impacts on the many millions that survived but lost everything are considered.

Assessing the Shelter Needs

In 1996 the government adopted a policy to construct 2,500 multipurpose shelters in high-risk areas to provide safe havens to both the humans and animals. This is in addition to the pucca buildings—schools, health centers, and killas schools—which can also be used as safe havens. To date 2,023 cyclone and 200 flood shelters have been constructed There is still a requirement to construct an additional 1,338 shelters to serve the 3.56 million people residing along the high-risk coasts (Fig. 7.1). In cyclone shelter planning, saving lives is the only criteria in contrast to flood control and drainage projects where protection against agricultural damage is the main consideration.



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations

(Source: Sener, 1994)

Fig. 7.1. Thana classified by risk index

Major Considerations in Shelter Construction

Building shelters is part of the government's broader strategy to protect people in high-risk areas. In general, the level of vulnerability to specific hazards, population at risk, availability of public and privately-owned buildings within the commanding area and availability of donor funds are the major considerations applied in shelter construction.

The assumptions are that shelters are built in low-risk areas and are highly accessible to the most vulnerable groups including women and children, the elderly, handicapped, and other groups that may be considered to be socially disadvantaged. In other words, they will provide a high level of safety during emergency periods.

In reality, location and accessibility are often determined by local politics. Shelters are typically designed and built to withstand specific rather than multiple hazards, with minimal consideration given to the social, gender, and cultural needs of vulnerable groups or to the broader multi-purpose use of shelters. Furthermore, without clear policy direction, these shelters are likely to become homeless entities that are neither properly maintained nor kept at a state of operational readiness. In the absence of such considerations, the poor and other disadvantaged groups are often forced to revert to alternate, less effective shelter options. Such shelters do not provide a sufficient level of protection for families or their livelihoods and as a consequence leave them extremely vulnerable to the risks associated with natural hazards.

The following are the key considerations for constructing a shelter:

- Shelters should be constructed in low-risk areas within 1.5 km of the community.
- Shelters should be built in well communicated and undisputed land to ensure accessibility by all.
- Shelters should construct with proper ventilation and heat control options.
- Shelters should have provisions for safe drinking water, lighting, and separate toilet facilities for men and women.
- Each shelter should have a workable plan for normal time use and shelter maintenance.

Use of Shelters

Seventy percent of shelters are currently used for education purposes, mostly as primary schools and madrasas in normal (nonemergency) times. About 1 percent are used for health centers, 3 percent for office uses, 2 percent for community purposes such as cultural/ceremonial events, and 5 percent for other use. The available statistics provide contradictory information about the use of shelters during emergency periods. Although there are different government statistics claiming the very high use of shelters during disasters, the recent CEGIS field study indicate that only 6 percent in 1991, 28 percent in 1997, 18 percent in 1998, and 5 percent in 2001 took shelter in safe havens during severe events.

Women, children, the elderly, and the disabled are the most vulnerable during major events such as flooding and cyclones. The disability study conducted by Handicap International (July 2005) illustrated that 60 percent of the country's 7.5 million disabled population are physically or visually impaired. The CEGIS survey found no provisions for this group to access shelter facilities during emergencies. Provisions of separate rooms and safe water and sanitation facilities for males and females are longstanding requirements.

Major Reasons People are Reluctant to Use Shelters

Among the primary reasons people are reluctant to use shelters are the following:

- Because of frequent false warnings, the accuracy and timing of the warning messages is not trusted.
- The warning messages are not in user friendly language.
- The distance to and from the shelters was too great. Most the shelters are located beyond the prescribed reachable area.
- Not all shelters are built on socially undisputed land and with a good communication system.
- Access by the community to existing shelters, *pucca* public buildings, and private houses is difficult.
- Shelters are not always gender friendly, lacking separate sanitation facilities for males and females. The recent CEGIS survey on 1,705 cyclone shelters and killas from 10 districts found that only 25 percent of the shelters have available water supply in the high-risk zone, 14 percent have storage facilities for vulnerable things, 26 percent have separate space for women, and only 36 percent have separate toilet facilities for women. There is almost no access for people with disabilities.
- Shelters being used for mosques and madrasas during normal times are not gender neutral; therefore, women believe they do not have sanctioned access and do not enter.
- Insufficient shelter space for livestock and for preserving foods are additional considerations for the poor, especially for the women responsible for the overall management of kitchen and tending poultry and livestock. According to the CEGIS study, only 21 percent of the shelters in high-risk zones have a place for cattle, 72 percent of their ground floor is open, 39 percent restricted, and 13 percent is too vulnerable to be used.
- Almost 13 percent of all the shelters are unusable due to lack of budget provisions for regular/routine maintenance (about 91 percent of cases) and also lack community participation (only 3 percent have community participation) in the maintenance program.

Shelters as a Safe Haven: Issues for Future Considerations

Shelters as a Viable Risk Reduction Strategy

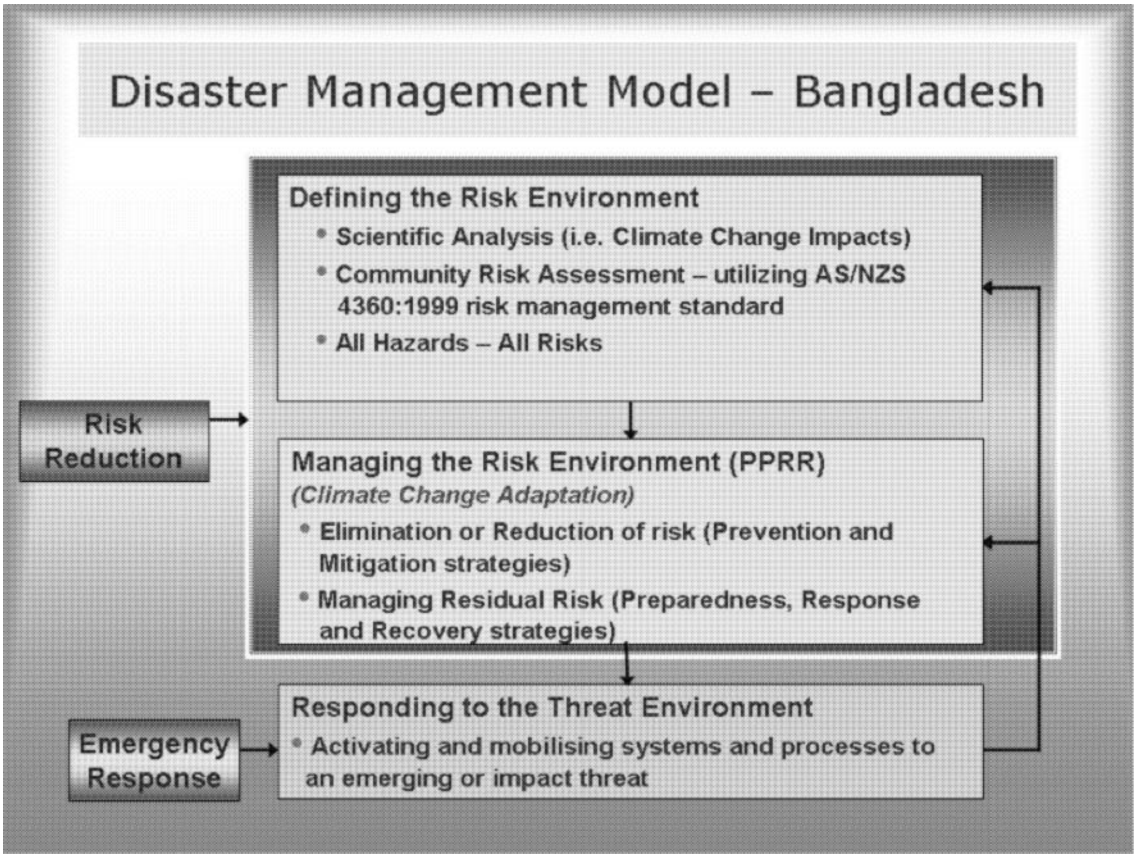
Whether designed for large communities or for fewer households, shelters play an important multi-purpose role in rural areas where the poor and most disadvantaged people live. Shelters must, therefore, be built to provide a sustained benefit during normal day-to-day life as well as during emergencies.

Shelters should be designed as an integral element of the development, such that providing a safe haven is just one element of broader multipurpose function. Government should establish policy governing the design, location, and use of shelters and enforce rigid adherence. Awareness training, particularly for woman and the elderly should counter the stigma that currently prevents or deters women from using the shelters. Empowering women is critical yet often difficult, if not dangerous, in today's environment.

The risk environment is also changing due to the effects of climate change and unplanned human interventions. Shelters must consider the full risk environment and be designed and constructed to provide a safe haven to the people and their livelihoods in any threatening situation. This all-hazards approach is consistent with the risk reduction model currently being introduced to Bangladesh through the Ministry of Food and Disaster Management.

The model follows a methodical and comprehensive approach to risk reduction by ensuring that both scientific and traditional risk assessment are used to design disaster management programs. The advantages of this approach are that risk is assessed for all geographical areas, all hazards, all risks, and all sectors (see Fig. 7.2).

The risk determination process will enable the government and communities to identify whether shelters are a good risk management option, and if so, the design considerations that should be incorporated for the specific areas. This approach helps define the multi-purpose value of shelters.



Disaster Management Model – Bangladesh

Risk Reduction

Defining the Risk Environment

- Scientific Analysis (i.e. Climate Change Impacts)
- Community Risk Assessment – utilizing AS/NZS 4360:1999 risk management standard
- All Hazards – All Risks

Managing the Risk Environment (PPRR)

(Climate Change Adaptation)

- Elimination or Reduction of risk (Prevention and Mitigation strategies)
- Managing Residual Risk (Preparedness, Response and Recovery strategies)

Emergency Response

Responding to the Threat Environment

- Activating and mobilising systems and processes to an emerging or impact threat

Fig. 7.2. Bangladesh disaster management model

A number of shelter strategies are currently being discussed. One is to test and adopt the small-scale community shelters for five to10 neighboring households accessible to all and free from the risks identified through the community risk assessment processes. A cost-sharing approach can be applied to ensure the target households' full participation both in the construction and post-construction phase. A flexible space utilization policy can also be adopted, providing more autonomy to decide their own priorities.

Shelter Management Strategy Should Be Fully Integrated Within the Established Emergency Response System

Mobilizing communities during emergency periods is always a difficult assignment. Shelter management plans should detail how to make this process operational. This includes usage conversion, in which the shelter ceases to be a school or clinic and becomes a safe haven and vice versa. In many cases it is best to adopt a staggered or incremental approach where vulnerable sections of the community such as the disabled, elderly, and children are relocated at certain trigger points in the national warning system.

It is critical for local authorities to understand the local meaning and impact of such warnings and to ensure that disaster or evacuation plans provide good detail about who (target group), when (timing with consideration to time of day and level of threat), and how (taking into consideration who and when). The credibility of the procedures hinges on the accuracy of the warnings.

Without full integration into an established emergency response system, the shelter's intended benefits are often diminished. Quantitative statistics are useful; however, qualitative community safety outcomes are far more impressive.

Conclusion

Shelters can be effective in providing safe havens during emergencies. Their multi-purpose role makes them an important asset to the broader development needs of the community.

A broad strategy to mass produce shelters without considering the full risk and development environment will not produce sustainable benefits.

A shelter management strategy that is not integrated into the broader emergency response management systems will not ensure the most vulnerable are fully protected.

A shelter management strategy that does not include an enforced policy framework governing design, construction, and usage will not improve the accessibility by women, the disabled, and the poor during emergencies.

Bangladesh is the first country in the world to have a separate ministry for disaster management. The Ministry of Food and Disaster Management was also the country's first government agency to finalize its corporate and strategic policy frameworks under which a number of policy and planning documents have been published. The ministry is currently revising and redrafting all of its policy and planning documents. This includes the standing orders for disasters issued by the ministry in August 1999 to guide and monitor disaster management activities in Bangladesh. Shelter construction, management, and capacity utilization should be fully integrated within the broader disaster risk and response management policy and operational frameworks. A large number of government departments and private-sector agencies are involved in shelter construction. A workable reporting mechanism should be in place to provide the ministry greater access to information and facilities to support its supervisory and coordinating role.

About This Paper

This paper was presented at the First United States-Bangladesh Workshop on Innovation in Windstorm/Storm Surge Mitigation Construction, 19-21 December 2005, LGED Bhaban, Agargaon, Dhaka, Bangladesh.

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Appendix 7.1: Major Cyclones in Bangladesh

Year	Losses	Location	Other info
1784	Deaths: 200,000	Bakergonj	
June 1822	Deaths: 100,000; Animal losses 100,000	Barisal	
May 1869	Deaths: 250, Huge property losses	Khulna	
October 1872	NA	Cox's Bazar	
October 1876	Deaths: 100,000	Bakergonj	3-10 m high tide
October 1895	NA	Bagerhat/Sunderban	
October 1897	Deaths: 175,000	Kutubdia is. Chittagong	
May 1898	NA	Teknaf	
Nov-01	NA	Sunderban	
Oct-09	NA	Chittagong	
Dec-09	NA	Cox's Bazar	
Apr-11	NA	Teknaf	
1912	Deaths 40,000		
May-17	NA	Sundarban	
Sep-19	Deaths 40,000	Barisal	
May-26	NA	Cox's Bazar	
May-41	Deaths 7,500	Barisal/Noakhali	4 m high tide
May-48	NA	Chittagong/Noakhali	
Nov-50	NA	Patuakhali	
Oct-68		Noakhali/nearbyu Islands	
May-60		Sundarban	3.2 m high tide
October 1960 Ist	Deaths 3,000	Noakhali/Island	5.1 m high tide 200 km/hr speed
October 1960 2nd	Deaths 8,149	Noakhali/Island	6.6 m high tide
May-61	Deaths 11,468	Noakhali	3 m high tide
May 1961(2nd)	Deaths 10,466	Chittagong, Cox's Bazar	6-8 m high tide
Oct-62	NA	Feni	
May-63	Deaths 11,520	Chittagong, Noakhali	8.1 m high tide
Jun-63	NA	Jessore	3.1 m high tide
Oct-63	NA	Teknaf	
May-65	Deaths 11,270	Barisal/Noakhali	
May 1965 (2nd)	Deaths 12,000	Chittagong	7.6 m high tide
Dec-65	Deaths 873	Cox's Bazar	8.8 m high tide

Oct-67	NA	Cox's Bazar	7.6 m high tide
May-70	NA	Cox's Bazar	5 m high tide
Oct-70	Deaths 300	Chandpur	4.7 m high tide
Nov-70	Deaths 275,000	Coastal districts	9 m high tide
Sep-71	NA	Chandpur	5 m high tide
Dec-73	Deaths 83	Patuakhali / Island	4.5 m high tide
Aug-74	NA	Khulna	6.7 m high tide
Nov-75	NA	Barisal/Noakhali	3.1 m high tide
Nov-83	300 fishermen unaccounted	Chittagong, Cox's Bazar	
May-85	Deaths 11,069, property losses: 9,400 homes	Chittagong Cox's Bazar, Island	4.3 m high tide
Nov-88	Deaths 5,704; unaccounted persons 6,000; animal desths 65,000; tiger death-9	Island	
Oct-90	Deaths 150 (fishermen)	Barisal	
Apr-91	Deaths 150,000; animal deaths 70,000.	Chittagong, Cox's Bazar	4-8 m high tide.
Apr-94	Deaths 400, Animal death 800	Offshore islands and chars of Cox's Bazar	
Nov-95	Deaths 650, Animal death 17,000	Offshore islands and chars of Cox's Bazar	
May-97	Deaths 126	Chittagong, Cox's Bazar, Noakhali and Bhola	3.05 m high tide.
Sep-97	NA	Chittagong, Cox's Bazar, Noakhali and Bhola	1.83-3.05 m high tide
May-98	NA	Chittagong, Cox's Bazar and Noakhali	1.83-2.44 m high tide
Nov-98	NA	Khulna, Barisal and Patuakhali	1.22-2.44 m high tide

Source: http://www.unhabitat.org/programmes/rdmu/

Chapter 8: Design Criteria for Shelters in Coastal Areas of Bangladesh Under Multipurpose Cyclone Shelter Program

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Abstract

Due to geographic vulnerability, Bangladesh has been on the path of many devastating cyclones and accompanying tidal surges. As a result, thousands of people and cattle have been lost. Immediately after gaining independence in 1971, the government of Bangladesh initiated a program to prevent such losses by constructing cyclone shelters and killas (earthen mounds) at various coastal locations. Between 1972 and 1979, the government and some private agencies constructed more than 300 cyclone shelters and hundreds of killas in the coastal areas. This project has been effective and has saved lives, but over the years, these shelters have been deteriorating severely due to poor construction specification and a lack of maintenance. Similar problems are also observed in other local concrete infrastructures. Due to the lack of proper specifications, different design criteria and material specifications have been used, resulting in the poor performance of concrete. The most common problems are random cracking, corrosion of embedded reinforcements, and large scale spalling, caused by a number of physical, chemical, and environmental factors. This paper deals with the appropriate design criteria and material specifications of cyclone shelters to be constructed in future.

Introduction

Following the disastrous cyclone and storm surge that hit the coastal areas of Bangladesh on April 29-30, 1991, an inter-ministerial task force was formed to study the need for construction of additional multipurpose cyclone shelters in the storm surge prone areas. The task force members, convened by the government's planning commission chief for physical infrastructure, drew its members from various relevant government ministries, autonomous and semi-government organizations, universities, research organizations, the Bangladesh Red Crescent Society (BDRCS), non-government organizations (NGOs), United Nations Development Program (UNDP), and the World Bank.

The task force in its preliminary report submitted in July 1991, recommended the development of a comprehensive study of the adequacy of the existing shelters and killas and a master plan for multipurpose cyclone shelters, including its socio-economic justification. This master plan could form the basis of all future cyclone shelter construction. UNDP agreed to provide funding for the study, with the World Bank acting as the executive agency. Based on a task force recommendation, a team of national experts from the Bangladesh University of Engineering and Technology (BUET) and the Bangladesh Institute of Development Studies (BIDS) was named to conduct the study and develop the master plan.

The six-month study began February 1, 1992, and the draft final report was submitted in August 1992. The report was discussed extensively in meeting of the task force and comments and suggestions were received. Comments and suggestions from a two-day national seminar held on January 30-31, 1993 organized by the Planning Commission were incorporated into the final report. One of the study's major objectives was to determine the planning and design criteria for multipurpose cyclone shelters in different coastal regions.

This article is intended for use by engineers, architects, builders, building officials, NGOs, specifiers, regulatory agencies, and other agencies interested in designing and constructing cyclone shelters in the coastal region of Bangladesh. Its objective is to improve the performance of cyclone shelters in the coastal areas during future cyclones and storm surges by developing the proper criteria for the design and construction of new shelters by recommending changes in design and construction practices based on previous experiences.

The design criteria have been prepared after a thorough review of the existing shelter design and taking into consideration the architectural, structural, geotechnical and water supply/sanitation aspects. This article presents details of the design criteria for structural considerations.

Background of Shelter Construction

Almost all the existing shelters have been built by one of the three following government/non-government organizations:

- Public Works Department (PWD);
- Bangladesh Red Crescent Society (BDRCS); and
- Caritas, an NGO.

The PWD shelters built between 1972 and 1979 under IDA Credit are based on the same design; Caritas followed the design used by BDRCS. After the April 1991 cyclone, a number of new designs were proposed by various agencies, and construction of shelters using some of these designs began.

Structural Engineering Considerations

General

A review of the design criteria and the structural design of the existing shelters found that the designers have been using widely varying design criteria and material specifications. These contributed to the durability problems facing most of the existing shelters.

Appropriate design criteria for the shelters in coastal areas must be developed before designing the structures. This ensures that the structures can perform their functions and can safely withstand the forces acting on them throughout their service life. This includes the loads and other forces they will be subjected to along with temperature fluctuations, foundation settlements, corrosive influences, environmental aggressions, and other detrimental agents. In addition to material characteristics, behavior under load in different environments is fundamental to the performance of structural concrete and to the safe, economical, and serviceable design of concrete structures.

The design criteria should consider basic design specializations, such as expected loads from all probable sources in the coastal areas, factors affecting choice of building systems, the design basis, the design codes and safety provisions, the material properties, and construction requirements.

Loads

Loads that act on structures can be divided into the following categories.

1. Vertical loads
   a. Dead load
   b. Live load
2. Environmental loads
   a. Wind load
   b. Seismic load
   c. Hydrostatic load due to storm surge inundation
   d. Temperature changes
   e. Soil displacement

Dead Loads

Dead loads are constant in magnitude and fixed in location throughout the life of the structure. Usually most of the dead load is the weight of the structure itself. This can be calculated with reasonable accuracy from the design configuration, dimensions of the structure, and the density of the materials used. For buildings like cyclone shelters, the floor finishes, lime concreting on the roof, partition walls, and other architectural details are usually included as dead loads.

Live Loads

Live loads consist chiefly of occupancy loads in buildings. They may be either fully or partially in place or absent and may also change location. Their magnitude and distribution at any given time are uncertain, and even their maximum intensities throughout the lifetime of the structure are not known with precision. The minimum design live loads for floors and roofs of buildings used as shelters in emergencies are usually not specified in the available building codes. However, from the information gathered from existing shelters, the occupancy pattern of the buildings during emergencies resembles the fire escapes of public buildings. The minimum live loads for these structures are prescribed to be 4.8 KN/m^2 (100 lbs. per sq. ft.). Hence a uniform load of 4.8 KN/m^2 (100 lbs. per sq. ft.) is considered to be a reasonable estimation of the live load on the floors and roof of the shelters for future construction.

Environmental Loads

Environmental loads for the structures in coastal areas of Bangladesh mainly consist of wind pressure and suction, earthquake loads (inertia forces caused by earthquake motions), hydraulic load due to storm surge inundation, soil pressure on subsurface portions of structures, and forces caused by temperature differentials. Like live loads, environmental loads at any given time are uncertain both in magnitude and distribution.

Wind Loads

The pressure exerted by the wind is related to the square of its velocity. Due to the roughness of the earth's surface, the wind velocity at any particular instant consists of an average velocity plus superimposed turbulence, referred to as gusts. As a result, a structure subjected to wind loads assumes a basic deflected position due to the average velocity pressure and vibrates from this position due to the gust pressure. In addition, there will generally be deflections transverse to the wind due to vortex shedding as the wind passes the building. The vibrations due to the gusts are a function of (1) the relationship between the natural energy of the wind gusts and the energy necessary to displace the building, (2) the relationship between the gust frequencies and the natural frequency of the building, and (3) the damping of the building.

In the absence of reliable data on past events, estimating the basic wind speed during cyclones in the coastal areas of Bangladesh is extremely difficult. The basic wind speed has been determined on the basis of statistical analysis of available data and values for 1-in-50-year and 1-in-100-year events. From the available information, the basic wind speed has been calculated to be 260 kph with the chance of exceedance of 1 in 50 years for buildings in coastal areas of Bangladesh.

Earthquake Loads

Reinforced concrete structures to be built in regions where there is significant risk of major earthquake damage must be designed with careful attention both to their overall behavior under lateral loads and to specific details of their construction. Because the coastal areas of Bangladesh fall within the regions of low to moderate seismic risk (basic seismic coefficient of 0.04 and 0.05 in Bangladesh Code), reinforced concrete or brick masonry building in those areas designed according to normal loading are considered to be satisfactory. No special measures need be taken in detailing the joints in frames or for ensuring ductility of the system.

Hydraulic Load Due to Storm Surge Inundation

Flooding of coastal areas and off-shore islands by storm surge during a cyclone causes most of the loss of human lives. Available data on cyclonic storm surge height and its effect on the structures around those areas are very limited. However, the present study aims to analyze the storm surge and a estimate the maximum surge height at the coast and the areal extent of land flooding by storm surges during cyclones. No guideline is available to estimate the hydraulic load on a structure during inundation by cyclonic storm surges. However, it is not likely that hydraulic forces would be excessive and dominate the structural design. An approximate analysis of hydraulic forces can be performed by following the guideline.

The major hydraulic loads on a structure during inundation by cyclonic storm surges are mainly due to two hydraulic phenomena. One is the storm surge wave, and the other is the wind generated wave on the surface of the storm surge wave. The storm surge wave is a gradually varied unsteady flow, while the wind generated wave is a rapidly varied unsteady flow. Thus the hydraulic load due to the storm surge wave is mainly drag force as a result of the velocity of flowing water. The hydraulic load from the wind generated wave is the dynamic force resultant of both drag and inertia. To compute hydraulic load, data on water depth, flow velocity, wave height, and wave period are required (Annex D3, Final Report MCSP).

The depth of water during inundation by a storm surge wave over the land will depend upon the distance of the structure from the seacoast (Annex D3, Final Report MCSP). Flow velocity data is not available. Estimation by steady flow formula indicates that the flow velocity during inundation by a storm surge wave inland where the bed slope is adverse to the intrusion direction is likely to be much less than 2.5 m/sec. The dynamic load due to wind generated wave is generally calculated using significant wave height. No such data is available. Discussion with people directly affected by cyclonic storm surge inundation indicates that the height of a wind generated wave on the surface of the storm surge wave is unlikely to exceed 2 m.

The hydraulic forces on the supporting column of a shelter are to be analyzed for drag force due to flowing water of the storm surge wave and for dynamic force due to wind generated wave on the surface of the storm surge wave. It is assumed that water flows freely around the column. Values for drag coefficient equal to 1.5, and inertia coefficient equal to 2.5 can be used in this analysis. There could be transverse lift loadings on a vertical circular column due to vortex formation around the column (known as vortex shedding). If this occurs, it will be of short duration and little concern.

The forces on the face of a structure's vertical wall must be calculated for the approaching wind-generated wave in addition to the hydrostatic pressure due to storm surge water. The hydrostatic force due to storm surge wave can be neglected if water levels on both sides of the wall remain nearly equal. If waves break directly against the vertical face of the wall, there could be very short duration impulsive force. The probability of such a damaging shock force is very small.

Choice of Building Systems

Structural elements, viz. slabs, beams, columns, footings, and walls are combined in various ways to create structural systems for buildings. An important part of the structural engineer's responsibility is to select from many alternatives the best structural system to build a multipurpose cyclone shelter in the coastal areas of Bangladesh.

The cyclonic storms accompanied with storm surges demand a rigid structural system capable of resisting the wind and surge forces in coastal areas. This led to the use of framed reinforced concrete buildings as shelters on varying stilt heights at different locations along the coast in the past. The present study also confirms similar structures on stilts or any rigid construction on lands above the level of the maximum surge water flooding to be suitable as shelters during cyclones and storm surges in coastal areas.

Whether the structure should be built of masonry on high lands or framed structures with in-situ reinforced concrete construction, precast concrete construction (either reinforced or prestressed concrete), steel in composite construction, on varying stilt heights as necessary at different locations, depends on the availability of materials locally and on a number of decisions based on the following considerations:

- economy;
- suitability of material for architectural and structural function;
- durability;
- fire resistance;
- speed of construction;
- rigidity;
- low maintenance; and
- availability of labor and materials.

Various building systems have been reviewed and the advantages and disadvantages of the following systems have been studied:

- masonry building system;
- cast-in-situ reinforced concrete construction system;
- composite construction system (steel and concrete); and
- precast concrete construction system.

Masonry Building System

Masonry structures are constructed from bricks bonded by cement-sand mortar. Such structures constructed on high lands, if available, or on killas above the maximum flooding level of the storm surges will safely bear the wind pressure of the cyclonic storms. If necessary, the walls may be reinforced with steel to enable them to resist bending moments and improve the strength and stability of the structure. This type of structure may be less expensive than an RC or steel framed structure. However, foundations built on newly constructed killas up to 6.5 m high demand special attention. Without proper protection during construction and regular maintenance afterwards, the use of reinforcements in the brick walls induces corrosion problems quickly in coastal areas. The roof should be of reinforced concrete slab.

Cast-in-Situ Reinforced Concrete Construction System

Cast-in-situ reinforced concrete structures, particularly framed buildings on stilts, are being used in almost all the existing shelters. When subjected to horizontal forces, such as wind or surge forces, which may act on a particular location of the frames, such reinforced concrete structures usually behave as monolithic or continuous units causing deformation and stress at all other locations. However, if the stilt height is adequate, surge water will flow below the usable floors during cyclones. Multipurpose cyclone shelters made with reinforced concrete meets functional, structural, and aesthetic requirements together with the special advantages of the material.

These advantages include:

- Versatility of form: Usually placed in the structure in the semi-fluid state, the material is readily adaptable to a wide variety of architectural and functional requirements.
- Durability: With proper concrete protection of the steel reinforcement, the structure will have long life even under highly adverse climatic or environmental conditions.
- Speed of construction: A concrete building can often be completed quickly when materials and other resources are available at the site.
- Availability of material and labor: It is always possible to make use of local sources of labor, and in many inaccessible areas a nearby source of good aggregates can be found.

- Fire resistance: With proper protection for the reinforcement, a reinforced concrete structure provides the maximum safety.
- Cost: In many cases the first cost of the in-situ concrete structure is less than that of a comparable steel structure or prefabricated concrete structure. In almost every case, maintenance costs are less.
- Rigidity: Occupants may be frightened if the building vibrates during cyclones. Due to the greater stiffness and mass, vibrations are rarely a problem in concrete buildings, particularly in low-rise construction such as cyclone shelters.

Composite Construction System

Multipurpose cyclone shelters may be constructed with structural steel columns, beams, and girders, plus a concrete slab floor. Composite construction in buildings is most efficient for longer spans heavily loaded with beams spaced laterally as widely apart as conditions permit. In all cases, the saving in steel weight resulting from composite action must be balanced against increased unit cost for material, fabrication, transportation, and erection, compared with non-composite members. Such structures are not suitable as shelters mainly due to following reasons:

- The transportation of heavy steel sections is difficult in many inaccessible areas where shelters will be constructed. Erection of the elements will also require different equipment such as cranes.
- The steel structures will be highly vulnerable against corrosion under the adverse climatic or environmental conditions of the coastal areas of Bangladesh; special protective measures will be necessary.
- The cost of construction will be much higher than reinforced concrete construction.
- Regular maintenance will be necessary as the exposed connections will require welding, riveting or bolting.
- Structural steel sections to be used as columns and beams are not available in Bangladesh and will have to be imported.

Precast Concrete Construction System

Another system to consider for building multipurpose cyclone shelters in coastal areas is precast concrete (cither reinforced or prestressed concrete). This type of construction has developed rapidly and continues to grow in importance, particularly in developed countries. Industrialization is achieved by mass production of repetitive and often standardized units, such as columns, beams, floor and roof elements, and wall panels. These are usually produced in precasting yards under factory conditions. Depending on requirements, precasting yards are sometimes constructed on or adjacent to the job site. More frequently, these yards are situated at a suitable location, and the precast members are transported to different job sites with reasonable ease.

The advantages of precast construction include less labor, in contrast to skilled mobile construction labor; short construction time because site labor mostly involves only foundations and connections of the precast units; better quality control and higher concrete strength achievable under factory conditions leading to improvement in durability; and greater independence of construction from weather and season.

Disadvantages are the greater cost of transporting precast units as compared with transporting materials and the additional technical problems and costs of connecting precast elements on site. In-situ reinforced concrete structures, by their very nature, tend to be monolithic and continuous. Connections, in the sense of joining two separate pieces, rarely occur in that type of construction. On the other hand, precast structures resemble steel construction in that the final structure consists of large numbers of prefabricated elements that are connected on the site to form the finished structure. These connections can be detailed to transmit gravity forces only, gravity and horizontal forces, or moments in addition to those forces. In almost all precast connections, bearing plates (mainly of steel) are used to ensure distribution and reasonable uniformity of bearing pressures. These plates of the two connected members are suitably joined typically by welding, so that horizontal as well as vertical forces are transmitted. However, to construct the moment resisting frames the precast members typically involve complicacies either in making the basic column and beam units or in making the connections. These connections are always vulnerable to corrosion due to climatic and environmental conditions.

Erection of component members is a complex mechanized process involving continuous assembly of buildings and installations from prefabricated elements. This erection process requires cranes and other equipment that have high initial investment costs.

Selection of Structural System

Based on the preceding sections, it is clear that the way lateral stability is achieved is an issue of fundamental importance in designing structural systems for multipurpose cyclone shelters in coastal areas. The way a structure resists lateral forces not only influences the design of vertical elements but also the horizontal spanning elements as well.

The adoption of one or more of the building systems discussed has a major influence on shelter design. If frame action is used to ensure stability, it is preferable to employ a structural system that can readily produce rigid joints. Not all of the systems discussed readily lend themselves to achieving moment-resisting connections, while other systems can easily provide joint rigidity. It is important to make the best fit between the intrinsic nature of the individual structural elements available and their most appropriate end conditions.

Precast concrete elements, for example, are not suited to such application because it is difficult to achieve joint rigidity in precast members. Steel systems lend themselves well to this approach. On the other hand, if frame action is being used to ensure the stability of the whole building, in-situ reinforced concrete system might be the most appropriate because with this approach joint rigidity can be achieved quite easily.

Often the unique characteristics of one structural element influence the selection of another. When masonry load bearing walls are used in low-rise buildings, as may be constructed on killas, the walls serve as shear walls in resisting in-plane forces in the lateral direction. The use of masonry walls implies that horizontal spanning elements (beams and slabs) should be simply supported because masonry walls, unless specially reinforced, cannot carry moments. Thus, attempting to use rigid connections at the end of horizontal elements would be counterproductive.

From the previous discussions, using brick building systems on killas and/or framed in-situ reinforced concrete system for multipurpose cyclone shelters in coastal areas may be considered suitable structurally.

Design Basis

Structural engineers have a variety of tools for structural analysis and design. They can analyze a structure elastically and design on the basis of working stresses. Alternatively, the structure can be analyzed elastically; however, the loads and shears shall be augmented by load factors, and the design of cross-sections can be carried out by the ultimate strength method. The structure can also be analyzed by the plastic hinge theory with the critical moments and shears scaled down by load factors and then the individual cross-sections designed by working stress method. Obviously, the structure may be analyzed by plastic hinge theory and designed by the ultimate strength theory. The interplay between these various concepts is illustrated in Figure 8.1.

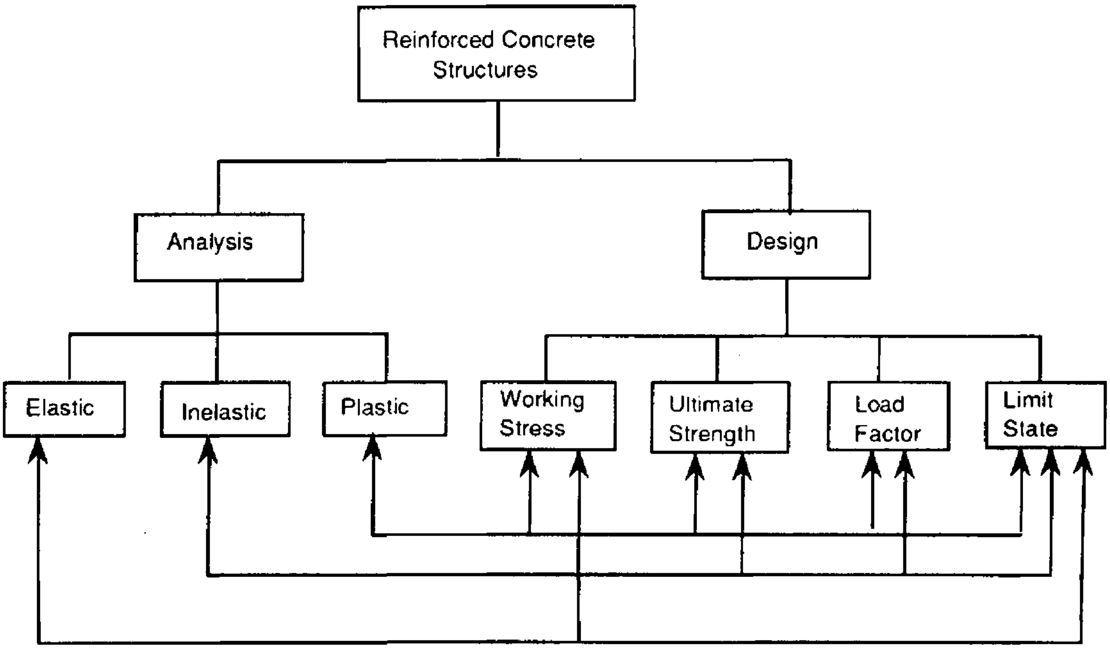

Fig. 8.1. Various methods of analysis and design of RC structures

The design of reinforced concrete structures, thus, can be performed by different methods. Two of these alternatives are very common and practiced in Bangladesh. The first directs attention to stress conditions within the structural member under working loads and is known as working stress design. The second focuses on the strength capacity of the member at conditions corresponding to failure and is known as ultimate strength design. By working these stress methods, allowable stresses are established as some fraction of the stress capacities of the materials, that is, the yield strength of the steel and the cylinder strength of the concrete.

In practice a variety of loads act on a structure, such as dead, live, and impact loads. While the self weight can be said to be constant (dead), the applied loads can vary in intensity, position, and duration (live). In fact the occurrence of loads acting on a structure is probabilistic in nature. The nature of this loading is such that there is always a probability, however small it may be, that the design load will be exceeded however high the design load may be. Since probabilistic data on the various types of loads acting on a structure have not been collected systematically, engineers estimate certain design loads, which they call working loads or service loads, and they design structures in such a manner that the resultant maximum stresses are within the allowable stresses. These stresses are kept well within the elastic limit so that even if the loads exceed the original estimates, there is enough reserve in strength, and the structure behaves elastically.

The second design approach, called ultimate strength design or more simply strength design, is based on predicting the load that will produce failure in a member rather than predicting stresses produced by service loads. This method is concerned with determining the load that will bring a structure to complete collapse and with the mode of failure when this load is applied. The preferred mode of failure is to ensure a controlled local failure of the member in a ductile rather than brittle manner. Because the design of a ductile structure that will fail locally is a foremost concern in reinforced concrete design, strength design is considered the more desirable approach. By controlling the ultimate strength of each member of a structure, the overall mode of failure of a total structural system can be controlled. In this way it is possible to design structures so that in the unlikely event of unanticipated overload, failures are confined to a limited region instead of causing the total collapse of the entire system. Using this method the load carrying capacities, instead of stresses at various points of different structural elements, can be directly estimated. As a result, it obtains more reliable information on the safety factors that relate ultimate loads to service loads.

A member designed by the strength method also must perform in a satisfactory way under normal service loading. For example, beam deflections must be limited to acceptable values, and the number and width of flexural cracks at service loads must be controlled. The crack width is significant because load induced tensile stresses result in cracks in concrete elements. Such cracks allow easy access for oxygen and moisture and thus induce the corrosion of embedded reinforcements. Serviceability limit conditions are an important part of the total design, although attention is focused initially on strength design. Hence a design procedure specifying not only the tensile forces to be carried but also both an adequate crack distribution and a reasonable limit on crack width is recommended.

What is essentially a probabilistic phenomenon has been rendered deterministic by estimating design loads in an arbitrary manner. In addition to the practical difficulty of defining working loads, there is the difficulty of maintaining uniformity in manufactured as well as natural building materials. Natural materials such as stone and timber are known to have considerable variation in strength; even man-made materials such as concrete, brick, and steel have significant variations in strength.

The working stress design method assumes that the ultimate limit states will automatically be satisfied by the use of allowable stresses. Depending on the variability of the materials and loads, this may not necessarily be so. The most serious drawbacks of the working stress design method stem from its inability to account properly for the variability of the resistances and loads, lack of any knowledge of the level of safety, and the inability to deal with groups of loads where one load increases at a different rate than the others. The last criticism is especially serious when a relatively constant load, such as dead load, counteracts the effects of a highly variable load, such as wind.

As a result, it appears that the ultimate strength design method is preferred over the working stress design method. Keeping in mind factors such as location of the structure and maximum live and environmental loads, the working stress design method for the design of shelters under the Multipurpose Cyclone Shelter Program is also considered adequate and suitable. However, elastic analysis does give a realistic representation of conditions in a member at working load and therefore is useful in predicting service load behavior characteristics, such as deflection and crack width. Reinforced concrete structures must perform satisfactorily at working loads but also be adequately safe against collapse. Consequently, if members are proportioned by working stress design methods, safeguards must be included to ensure that the actual factor of safety against failure is at least as large as implied.

The discussions are further supplemented by the practices followed in designs according to ACI Code of Practice. The 1956 ACI Code was the first to officially recognize and permit the strength design method. The 1963 ACI Code treated the working stress method and the strength design method on an equal basis; however, the major portion of the working stress method was based on strength. With the relegation of the working stress method, the 1971 ACI Code entirely accepted the strength design method. Later on the 1977, 1983, and 1989 ACI Codes again included Alternate Design Method in appendix form, permitting the use of service load design for those who prefer this older method. No matter which design method is employed, serviceability must be considered. Serviceability factors that may be as important as strength are excessive deflection, detrimental cracking, excessive amplitude, and undesirable frequency of vibration.

Design Codes and Safety Provisions

Design Code

When two different materials, such as steel and concrete act together, it is understandable that the analysis for strength of a reinforced concrete member, athough mostly rational, has to be partly empirical. These semi-rational principles and methods are being constantly revised and improved as results of theoretical and experimental research accumulate.

The design and construction of buildings made of such materials is regulated by bylaws called building codes, which exist to protect public safety. Codes of practice of various countries are used for the design and construction of reinforced concrete structures. Of the different codes being used, the American Concered Institute Building Code Requirements for Reinforced Concrete (ACI 318), is commonly used for the reinforced concrete design in Bangladesh. This code is partly a specification code, which gives acceptable design and construction methods in detail, and partly a performance code, which states desired results rather than the details of how to obtain them.

For any structure built in the coastal areas of Bangladesh, the ACI Code (ACI 318-89) is thought to be the most appropriate because it covers all the design and construction requirements in a given region. Locally, additional provisions to account for the regional conditions of coastal areas may also be specified. The specifications of the ACI Code, based on many years of research and field experiences with reinforced concrete, represent the minimum standards required to produce safe and durable structures.

Safety Provisions

Structures and structural members must always be designed to carry some reserve load above what is expected under normal use. Such reserve capacity is provided to account for a variety of factors, which may be grouped in two general categories—factors relating to overload and factors relating to understrength. Overloads may arise from changing the structure's use, from underestimating the effect of loads, and from the effects of construction sequences and methods. Understrength may result from adverse variations in material strengths, workmanship, dimensions, and control and degree of supervision, even though individually these items may be within required tolerances.

The safety provisions as recommended and detailed in the ACI code for the alternate design method (working stress design method) and ultimate strength design method for the proposed structures to be constructed under the Multipurpose Cyclone Shelter Program are adequate. The working stress provisions introduce the safety factor by means of allowable stresses, while the ultimate strength provisions use separate overload and capacity reduction factors. However, the provision of allowing an overstress of 33.33 percent under the working stress method for the structures when subjected to wind load simultaneously in combination with other loads as recommended by ACI code should not be considered. According to ultimate strength design method, the same effect, which is accomplished by using three-quarters of the factored load when wind load is included, also should not be considered.

Material Properties and Construction Requirements

Material Properties

The proposed structures for the Multipurpose Cyclone Shelter Program may consist of bricks for use in masonry work (either load bearing or non-load bearing), concrete (which is strong in compression and weak in tension), combined with steel reinforcement (which is primarily used to resist tensile forces). An understanding of the material characteristics and behavior under load is fundamental to understanding the performance of structural concrete or masonry and for the safe, economical, and serviceable design of these structures.

Locally manufactured bricks are widely used in construction all over Bangladesh. For use in coastal areas, the bricks must be graded as A in BDS 208, well burnt, strong, and uniform in color and shape. Concrete is a composite material composed of fine aggregate, generally sand; and coarse aggregate, generally crushed picked jhama bricks or crushed stones, chemically bound together by hydrated Portland cement. The most important properties of concrete in reinforced structures are its strength and mechanical properties, its shrinkage, creep and thermal volume change properties, and its durability. However, to produce the appropriate concrete for structures in coastal areas, the essential characteristics of materials are listed below.

- Cement: The ordinary Portland cement is to be identified by American Society for Testing Materials (ASTM) C150 as Type I.

- Aggregates: Since aggregates usually occupy about 75 percent of the total volume of concrete, their properties have a definite influence on the behavior of hardened concrete. Not only does the strength of the aggregates affect the strength of the concrete, their properties also greatly affect durability, that is, resistance to deterioration in coastal environments. Since aggregates are less expensive than cement, it is logical to use the largest percentage feasible. In general, for maximum strength, durability, and best economy, the aggregates should be packed and cemented as densely as possible.

  Natural stone aggregates conforming to ASTM C33 shall be used in the concrete construction for the coastal areas. Brick chips should not be used in making concrete in these areas. The highly porous brick aggregates react with the salts available in the coastal environments causing a long-term expansion of the concrete that destroys the structure. Concrete strength is also affected by the bond between the aggregates and the cement paste. Crushed, angular pieces of aggregates that are well graded produce a concrete with less porosity. Such a concrete tends to be stronger. Preferably the aggregates shall be washed before use. Clean sand with a minimum fineness modulus (FM) of 2.5 shall be used in concrete making.

- Water: Any natural water that is drinkable (potable) and has no pronounced taste or odor is satisfactory mixing water for making concrete. Excessive impurities in mixing water may affect not only setting time, concrete strength, and volume stability, but they may also cause efflorescence or corrosion of reinforcements. When in doubt about the suitability of water, particularly in remote coastal areas where water is derived from sources not normally utilized for domestic purposes, the water shall be tested.

- Admixture: Admixtures are the materials other than the basic ingredients of concrete cement, aggregates, and water added to concrete mix immediately before or during mixing to modify one or more of the specific properties of concrete in the fresh or hardened state. The particular type, such as an air entraining admixture conforming to ASTM C260, shall be used if available to modify the concrete properties to better serve its intended use and to increase resistance to the wetting and drying cycles and saline coastal environments where the shelters will be constructed.

- Concrete Mix Proportion and Strength: It is difficult to determine accurately the water-cement ratio of concrete during production; hence, the specified concrete strength should be reasonably consistent with the water-cement ratio required for durability. At the same time, a reasonable and compatible mix proportion should be used. Thus, the minimum mix ratio shall be 1:1.5:3 (cement : sand : coarse aggregate) by volume (per local practice) for concrete used in coastal areas. The minimum quantity of cement content shall be 388 kg per m^3 (1,100 kg per 100 ft^3) of concrete. The maximum water-cement ratio for reinforced concrete exposed to alternate wetting and drying cycles, brackish water, sea water, or spray from these sources as found in coastal environments shall be 0.45. The minimum compressive strength of concrete at 28 days shall be 20.7 MPa (3,000 psi) tested on 15 cm diameter and 30 cm high cylinders.

- Reinforcement: The most appropriate grade of steel reinforcement shall be Grade 60 or 415 MPa (60 $kips/in^2$) yield stress for use in concrete structures in the coastal areas. Deformed bars of Grade 40 and Grade 50 may also be used. However, Grade 60 steel will result in a relatively more economical structure because the cost of different grades of steel is about the same. This grade will also reduce the congestion of steel in the members. The permissible tensile stresses in reinforcement shall be limited to 138 MPa (20,000 psi) for Grade 40 and Grade 50 steel and 165 MPa (24,000 psi) for Grade 60 steel per ACI Code (318-89). Plain bars of Grade 40 or higher grade may also be used. However, they should be avoided if possible.

Construction Requirements

Though concrete is quite strong mechanically it is highly susceptible to attack in extreme environments; thus, concrete structures are damaged and even fail unless measures are adopted during construction to counteract concrete deterioration and increase the durability of the structure. The durability of concrete is defined as its resistance to deteriorating influences. For reinforced concrete the ingress of moisture or air leads to corrosion of steel, cracking, and spalling of the concrete cover. A durable concrete is dense and workable, and it has as low a permeability as possible under the given situation.

For the cyclone shelters in coastal areas, the recommendations for making durable concrete usually include limits for maximum water-cement ratio, type of cement, mix proportion, concrete strength, and aggregate types as discussed earlier. Making a denser concrete during construction with the least porosity is the most effective way to reduce concrete deterioration. However, a physical survey of the existing shelters indicates that the reinforced concrete structures have deteriorated greatly due to the corrosion of embedded reinforcements resulting in widespread spalling of the concrete cover. Permeability of concrete is probably the most important single factor affecting the corrosion of reinforcement. Low-quality concrete construction is characterized by voids adjacent to the reinforcements, which may retain high moisture content leading to rapid corrosion attack. Additionally, the thickness of concrete cover over steel is of great importance as this cover protects the steel from the factors that promote corrosion. For corrosion protection the minimum clear cover to reinforcing bars of the proposed cyclone shelters shall be as follows according to clause R 7.7.5 of ACI code (ACI 318-89).

Slabs	50 mm
Beams	63 mm
Columns	63 mm
Concrete cast against and permanently exposed to earth	75 mm

Design Criteria for New Shelters

From the above discussions, the design criteria for the cyclone shelters to be constructed under the Multipurpose Cyclone Shelter Program are recommended as follows.

1. For calculation of dead loads the following will be considered.

Unit weight of reinforced concrete	24 KN/m^3 (150 pcf).
Floor finish and ceiling plaster	1 KN/m^2 (20 psf).
Unit weight of lime concrete	20 KN/m^3 (120 pcf).
Unit weight of solid masonry wall	20 KN/m^3 (120 pcf).
Incidental partition walls	1 KN/m^2 (20 psf).

2. Live load on floors and roof shall be 4.8 KN/m^2 (100 psf) minimum. No live load reduction shall be made.
3. Minimum basic wind speed shall be taken as 260 kph (160 mph).
4. Design shall be based on alternate design method (working stress design method) according to ACI Standard Building Code requirements for reinforced concrete (ACI 318-89).
5. Standard cylinder crushing strength of concrete at 28 days shall be minimum 20.7 MPa (3,000 psi) with stone chips as coarse aggregate. The minimum mix ratio shall be 1:1.5:3 by volume. The minimum quantity of cement shall be 388 kg per m^3 (1,100 kg per 100 ft^3) of concrete. The 7-day

crushing strength shall not be less than 70 percent of the specified 28-day crushing strength.

6. High-grade deformed bars with yield strength 60,000 psi (415 MPa) as reinforcing bars shall be used. Allowable tensile stress shall be limited to 24,000 psi (165 MPa).
7. Members shall be proportioned for stresses developed for both vertical and horizontal loads acting simultaneously. No increase of allowable stress shall be considered.
8. Design wind pressure for the structures shall be determined for any height according to Uniform Building Code (UBC 1991). The structure will be classified as essential facility.
9. Clear covers to reinforcing bars shall be as follows.

Slabs	50 mm
Beams	63 mm
Columns	63 mm
Concrete cast against and permanently exposed to earth	75 mm

10. Foundation design shall be made on the basis of soil investigation report of individual shelter locations.

Conclusions

Improving the performance of concrete for the shelters to be constructed under Multipurpose Cyclone Shelter Program meeting stringent quality requirements in the coastal areas of Bangladesh is a challenging task. Concrete construction may be influenced by design criteria, environmental and climatic conditions, and construction practices. Adequate measures must be taken to ensure long-term durability of the shelters' structural concrete, and for that there is need to specify appropriate design criteria for the shelters and to develop guidelines for proper construction practices, standards, and specifications. For durable shelter construction in the coastal areas of Bangladesh a design criteria has been recommended taking into account the physical, environmental, and climatic conditions of that region, construction materials, and the existing construction practices.

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Chapter 9: Wind Field Statistics: Literature Review and Research Needs

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Abstract

This paper reviews recent research developments on modeling annual maximum wind speeds as well as wind speed extremes associated with tropical cyclones and tornadoes. Current wind-related structural damage and risk assessment methodologies are also discussed.

Introduction

The assessment of safety and economy of structures critically depends on reliable estimates of the design-level loads they may experience during their remaining operational lifetimes. The paper's principal goal is to provide an overview of recent research on statistical modeling of extreme wind speeds during (1) normal wind, (2) tropical cyclones, and (3) tornadoes.

For structures located along the eastern and southeastern coastlines of United States, extra-tropical cyclones, including hurricanes, are among the most important factors in their design. A recent analysis of windstorm damage on the U.S. East and Gulf Coasts by Pielke and Landsea (1998) suggests that the average annual economic loss may be about $5 billion. Statistics published by the Munich Re Group for 2001 indicate that windstorms were responsible for 55 percent of the $36 billion in economic losses worldwide and 88 percent of the $11.5 billion in insured losses due to all natural disasters combined. According to American Re Topics 2004, the insured property losses from natural catastrophes in United States in 2004 surpassed $30 billion, the highest on record. Among all natural catastrophes, hurricanes were the largest source of insured loss, collectively causing more than $28 billion in insured property loss.

For the purposes of structural design and risk assessment for wind hazards, statistical methods to estimate largest wind speeds, both of normal wind (on an annual basis) and of wind during hurricanes, are widely accepted, and logically form the basis for the further work. This paper focuses on recent research on stochastic modeling to estimate extreme wind speeds for both non-hurricane-prone and hurricane-prone areas, as well as on risk-based assessment of structural damage and failure during hurricanes and tornadoes. The first and second parts of the paper are on estimating wind speeds in non-hurricane-prone and hurricane-prone areas; the third is on predicting extreme wind speeds during tornadoes; and the fourth is on risk-based assessment of damage and failure during both hurricanes and tornadoes.

Estimation of Largest Wind Speeds in Non-Hurricane-Prone Regions

Extreme Value Distributions

Normal wind gives rise to one of the main loading conditions structural designers need to consider. Although for most low-rise buildings, load effects due to normal wind are generally small compared to those caused by earthquakes, wind effects often dominate for high-rise structures, which possess relatively large fundamental periods of vibration.

Normal wind speed is often seen as the sum of two components—the slowly varying mean wind speed and a rapidly fluctuating (turbulent) component. Since in the design of most regular structures the effects of the mean wind load dominate, it is of practical importance to engineers to predict the annual maximum mean wind speed. The annual exceedance probability p of a given value (of mean wind speed) x_p is: p = Prob(X > x_p) = 1 – F(x_p), where $F(x_p)$ denotes the cumulative distribution function (CDF) of annual maximum mean wind speed. The basic design wind speed x_p corresponds to a specified value *p* of annual exceedance probability or to its reciprocal, the mean recurrence interval N (expressed in years). Normal wind with mean speed corresponding to an N-year mean recurrence interval is commonly referred to as the N-year wind (Simiu and Scanlan 1996). Clearly, the upper tail of the probability distribution of annual maximum wind speeds is critical to the estimation of the basic design wind speed.

Over the years, several types of probability distributions have been proposed to model extreme wind behavior. The three classical extreme distributions are the Type I (Gumbel) distribution, the Type II (Fréchet) distribution, and the inverse (negative) Weibull distribution. The Fréchet distribution is adopted in the design codes of several countries, including the United States (see *American National Standard* ANSI A58.1, 1972) because it is regarded as best fitting non-tornado extreme wind speeds blowing in any direction in regions not subjected to mature hurricane winds. Simiu et al. (1978) suggested, however, based on extensive investigation, that the Gumbel distribution may be a more appropriate model.

Extreme wind speeds are of course bounded, while both the Fréchet and Gumbel distributions have an unbounded upper tail. Safety indices for wind-sensitive structures estimated based on the Gumbel model appear to imply unrealistically high failure probabilities (Ellingwood et al. 1980, 1999); this may be due to the unrealistically extended (infinite) upper tail of the Gumbel distribution. The inverse (negative) Weibull distribution, whose upper tail has a finite value, is for this reason regarded by some as perhaps the most appropriate model, reflecting facts about normal extreme wind as discussed by Simiu et al. (1996). As these authors indicate, however, the practical use of the inverse Weibull distribution is still hampered by insufficient data to estimate the distribution's parameters, especially its tail-length (or upper-bound) value.

Naess (1998) shows that the Gumbel distribution is just as good a choice as the reverse Weibull, the key question being how the data are analyzed. In the method advocated by Naess (1998), the entire analysis is based on the assumption that the quantities to be estimated can be modeled as random variables. More specifically, the underlying phenomenon manifesting itself in the observed data can be modeled as a stochastic process. The method proposed by Cook (1982, 1985) involves a procedure for extrapolating data on extreme wind speeds based on plotting dynamic pressure, which is proportional to the square of the wind speed, instead of the wind-speed data themselves, on the Gumbel probability paper. It is observed that the distribution of extreme wind pressure values exhibits faster convergence to the Gumbel distribution than the distribution of the corresponding wind-speed values.

Insufficient Data for Choosing an Extreme Value Model —Peak Over Threshold Method

A fundamental assumption underlying the classical extreme value distributions is that a large number of observed values are (or can be thought of as) realizations of independent and identical distributed random variables with a common but unknown probability distribution (Galambos 1987, Resnick 1987). It is likely, however, that an array of physical phenomena produces varying levels of these observed values of (annual maximum) wind speed. However, all the observations in combination can hardly be expected to fit a single distribution that accurately predicts future extremes. Additionally, the classical method of statistics of extremes uses only one datum per period, typically the largest value in each data set covering a single year, so that, for example, a 30-year record yields only 30 data points (Dougherty et al. 2003). Clearly, such an amount of the data is not sufficient to estimate the distribution's upper tail reliably. An important defect of the classical (extreme value statistics) methodology is the extrapolation to long-term recurrence, such as a 100-year or 500-year return period wind speed estimated based on short-term data, yielding notably unreliable estimates. The degree of conservatism is reduced as the mean recurrence interval grows (Simiu and Heckert 1998).

The insufficient amount of data, according to Simiu and Heckert (1996), provides an argument for adopting the reverse Weibull distribution to fit the data on largest daily wind speeds by the peak over threshold method (Dekkers and de Haan 1989). The basic idea behind this method is that values below the threshold likely do not belong to, or originate from, the same distribution as that describing the highest values, so that the inclusion of the lower values distorts the sought-after peak distribution. Only values high enough to be assumed to arise from circumstances that generate extreme conditions should be counted.

If the threshold is set too high, only a small fraction of the data remain available for estimating the peak distribution; if it is set too low, the resulting calibration is contaminated by values that are not germane to generating peaks. The peak-over-threshold methodology can also be used to estimate extreme wind speeds during events such as hurricanes and tornadoes.

Simiu and Heckert (1996) also suggested a method for modifying the data to achieve stochastic independence; it is described in the next subsection. The application of this model to the statistical analysis of some samples of non-tornado wind speeds in the United States yields ambiguous results: Some of the daily largest wind speed sets best fit the Weibull distribution, while others agree best with the Extreme Type II (Fréchet) distribution. It may be unreasonable to expect the same distribution to fit different populations of data, in part because the requirements on the number of observed values above the threshold are contradictory.

Statistical Independence and Homogeneity

The method for modifying records of wind speed data to achieve stochastic independence, presented in the paper of Simiu and Heckert (1996), is based on evidence, pointed out by Cook (1985), that storm events separated by more than 4 days can be considered as statistically independent events. Further development of the idea, presented by Xu et al. (2001) and Corotis and Dougherty (2004), focuses on the statistical homogeneity of wind speed records. By dividing the data into groupings by season, the data of one group can be expected to be as homogenous as practically achievable, that is, most likely to obey the same underlying distribution. The mixed distribution of peak wind speeds for one year is then obtained by combining the season-specific distributions, their weights estimated based on both data and experience.

ASCE 7 Peak-Gust Map

An important recent development in extreme wind speed estimation for design is the peak-gust wind speed map produced by Colorado State University (CSU), in particular the ASCE 7 peak-gust map covering the continental United States and Alaska (Cooperative Program in Wind Engineering). The ASCE 7 peak-gust map differs from the ASCE 7-93 wind map (ASCE 1993) in three major ways, according to Simiu et al. (2003). First, it provides values of 50-year peak-three-second gust speeds, instead of 50-year fastest-mile wind speeds. Second, it is based on analyses of data from sets of stations, called superstations, rather than on analyses of data for individual stations. Third, with the exception of hurricane-prone areas and areas with special wind regimes, the ASCE peak-gust map is divided into adjacent zones, each with its own 50-year peak-gust and fastest-mile wind speeds.

The super-station method has the drawback of non-homogeneity, that is, different stations have a different distribution of data because of variations in physical geography and meteorological features.

The analysis shows that fastest-mile wind speed data are more stable (have smaller inherent variability) than peak-gust data. The potential for the development of a significantly improved, more realistic wind map exists and should be used. Where appropriate, such development may include the use of the superstation concept, provided careful consideration is given to relevant meteorological and physical geography factors and good statistical practices are used. Current research at the National Institute of Standards and Technology (NIST) addresses the different types of errors, in particular observation errors, errors in the estimation of terrain roughness and the corresponding wind profile characteristics, and sampling errors in the estimation of extreme wind speeds. It is expected that this effort will yield results that will be very valuable in the development of an improved wind map and improved wind load factors.

Distributions Accounting for Wind Direction

The correlation between the velocities of wind from any two of the eight principal compass directions is in most cases weak; the coefficient of correlation for any pair of the eight directions does not exceed 0.6 (Simiu et al. 1985). Because the responses of structures do depend on wind direction, the estimation of the distribution of peak-gust wind speeds should involve searching for non-homogenous and non-independent features that vary with direction (Toriumi 2000). This is hampered, however, by the lack of wind data with information on direction; the original wind-speed record typically gives the value of the largest wind speed (possibly with direction) but ignores lower wind speed data and the corresponding directions.

Estimation of Largest Wind Speeds in Hurricane-Prone Regions

Windstorms, hurricanes in particular, constitute one of the costliest natural hazards in the United States in recent decades, far outpacing earthquakes in total damage (Landsea et al. 1999). For the purpose of assessment of damage and losses due to hurricanes, the mathematical simulation of hurricanes is the most widely accepted approach for estimating wind speeds. The Monte Carlo simulation approach, based on the climatological and physical models, was first described by Russell (1968, 1971). Since that pioneering study, many others have expanded and improved the modeling technique. The basic approach in all these studies is similar: Site-specific statistics of key hurricane parameters are obtained, including the central pressure deficit, radius to maximum winds, heading, translation speed, and coast-crossing position or distance of closest approach. Most studies ignore the details of the non-straight path the hurricane actually follows, and the major differences are associated with the specific physical models used, including the filling rate models and wind field models. Other differences include the size of the region over which the hurricane climatology can be considered uniform (that is, the extent of the area surrounding the site of interest for which the statistical distributions are derived or estimated) and the use of a coast segment crossing approach (Russell 1971; Batts et al. 1980), or a circular sub-region approach (Georgiou et al. 1983, 1985; Neumann, 1991; and Vickery and Twisdale, 1995b). Once the statistical distributions of these key hurricane parameters are known or assumed, a Monte-Carlo approach is used to sample from each distribution, and a mathematical representation of a hurricane is passed along the straight-line path in a way that is consistent with the sampled data, and the simulated wind speeds are recorded. Vickery and Twisdale (2000a & b) developed a new method to model the entire track of the hurricane or tropical storm, beginning with its initiation over the ocean and ending with its final dissipation. In this model, the central pressure is modeled as a function of sea surface temperature, and the storm heading, translation speed, and such are updated at each 6-hour point in the storm's history. Linear interpolation is used between the 6-hour points. This approach allows the storms to curve and to change speed and intensity as they move, and it is able to reproduce the continuously varying statistics associated with central pressure, heading, and such along the U.S. coastline.

A key factor in simulating hurricanes for the purpose of damage estimation concerns modeling the wind field. A new wind field model based on the works of Chow (1971) and Thompson & Cardon (1996) is presented by Vickery and Twisdale (2000a). This model is an improvement over the numerical model used by Georgiou (1985) and Vickery and Twisdale (1995a) in that the asymmetries in fast-moving hurricanes and the effect of the sea surface roughness are more accurately represented. The model is based on the full nonlinear solution of the equations of motion of a traveling hurricane. The wind field is coupled with a parameterized hurricane boundary layer model that accounts for the effects of the sea surface roughness and the air-sea temperature difference. The hurricane wind field model presented by Vickery and Twisdale (2000a) is based on a dynamic numerical model of the planetary boundary layer (PBL) instead of the empirical parameter approach giving rise to the traditional wind field model.

It is straightforward, using standard extreme value models, to infer expected extreme behavior in a series of simulated wind speeds (Coles 2001). The difficulty lies in quantifying the statistical uncertainty of the mean return periods estimated. Quantifying uncertainty is an essential, and arguably the most important, of any extreme value prediction. Only a small degree of uncertainty is attributable to the Monte-Carlo simulation itself. A re-sampling procedure described by Coles and Simiu (2003) seeks to quantify the uncertainty in the extreme values due to various aspects of the modeling procedure. The basic idea behind the procedure is to generate new data sets by sub-sampling from the available data, refit the model to each of the sub-samples, and then quantify extreme-value uncertainty by analyzing the variability in the extreme-value estimates across the sub-samples. The disadvantage of the re-sampling technique is that while the original data used for the model always include the whole range of information on the meteorology and the physical processes, the output of the re-sampling reflects only the simulated hurricane wind speeds, and there is a tendency for the bootstrap samples to generate shorter upper tails than that of the true (original-sample-based) distribution.

Spatial aspects of hurricanes, including directional characteristics combined with wind speed, are also simulated in the model presented by Casson and Coles (1998). In their model, a non-linear regression technique is applied to hurricane wind speed data simulated at consecutive locations, and the distribution of directions of the r-largest hurricane wind speeds at each site is estimated by regression analysis. They try to construct a model capable of yielding the joint distribution at each location of hurricane wind speed extremes and associated wind directions. At the basis of the regression analysis is Markov-chain-based Monte Carlo simulation. The spatial models, including the direction-dependent features, are based on the assumption that at nearby locations, extreme wind speeds may be expected to possess similar GEV (generalized extreme value) parameter values, the random differences at nearby locations being modeled as a zero-mean Gaussian stochastic process. The Von Mises distribution model (Edgoose et al. 1998) is applied to simulate the directional behavior; this model has two parameters, one for the principal direction and another for the degree of uniformity. The accuracy of the estimation based on this model depends on the degree of uniformity of the hurricane speed distribution in space and as a function of direction. Specifically, if the features of extreme hurricane speed tend to vary greatly at different locations, then the model may not fit reality well.

Modeling Wind Speeds During Tornadoes

Tornadoes are observed as funnel-shaped clouds consisting of a vortex of air with maximum tangential speeds ranging between 250km/hr. and 800km/hr. Contrasted to the characteristics of hurricanes, those of tornadoes involve small affected regions, high tangential velocities, short lifetimes, straight propagation paths, and much lower frequencies of occurrence at any given location (Ying and Chang 1970; Fujita 1973). Since Fujita developed the F-Scale in 1971 at the University of Chicago, it has become a widely used and practical way of rating the intensity of a tornado based on the observed damage it has caused, ignoring the width and length of the path (or other physical characteristics) of the tornado. Allen Pearson, director of the National Weather Service's National Severe Storms Forecast Center, added descriptors to the width and length of a tornado path; the resulting scale is known as the Fujita-Pearson scale.

Let $P(S)$ denote the risk of a tornado striking a particular location in one year; it is proportional to the regional mean frequency of tornadoes and the mean area of a tornado's land-falling path. In certain applications, it is of interest to estimate the annual probability of occurrence of a tornado with maximum wind speed above a given value v_0 at a location, $P(S, v_0) = P(S)\ P(v_0)$, where $P(v_0)$ denotes the probability that the maximum wind speed in a tornado exceeds v_0. Because the F scale is also associated with a range of wind speeds, $P(v_0)$ can be used to express relative frequencies of tornadoes with different values on the F scale. Weibull distributions have been used to fit sets of data of tornado wind speeds (Rutch et al. 1992). It deserves mention that the F-scale-based wind speeds cannot be used or interpreted literally. The wind speed numbers in F scale are mere guesses and have not been scientifically verified. Engineering assessments of tornado damage by Minor et al. (1977) questioned the accuracy of the F-scale-based wind speeds. Marshall (1983) used load and resistance statistics to demonstrate how uncertainties in assessing building damage can lead to large errors in assigning F-scale ratings, especially in the upper ranges of the F scale. One of the sources of uncertainty discussed by Rutch et al. (1992) is that only a small portion of the damage area will experience F5 wind speeds, while the rest of the tornado-stricken area presumably experiences something less than F5 speed.

In addition to the somewhat vague definition (in terms of damage caused) of the F scale, there are other uncertainties in risk assessment for tornadoes. One is that the size of a tornado is not necessarily an indication of its intensity. Large tornadoes can be weak, and small tornadoes can be violent. The relationship of the size of a tornado to the intensity of its damage is an important feature sought to be captured by more realistic models (Schaefer et al. 1986, 2002; Meyer et al. 2002). Weibull distributions are used to model the path lengths and widths of tornado for different F scales (Brook 2004). Although goodness-of-fit tests imply that the Weibull distributions may be useful in developing statistically based models of tornado hazards, there is a wide range of F-scale values associated with sets of most probable path lengths and widths. The inhomogeneity of the spatial distribution of tornado damage intensity within a stricken area weakens the value of information about path length and width in forecasting damage intensity.

Statistics-based modeling of tornadoes is also severely limited by a lack of records. It was observed that a sharp increase occurred in the number of low-intensity tornadoes in the 1950s. The reason may be increased efficiency in reporting and classifying. In addition, the widths were rarely reported while the lengths were reported for all tornadoes. The inhomogeneity of the distribution of tornado damage intensity may also be interpreted as providing information about the spatial and temporal variation of the extreme wind speeds within the area stricken by a tornado. Observations of (the variation of) space-time histories of wind speed and recording of pressure drops in tornadoes are targets of ongoing research in meteorology.

Predicting Structural Damage and Failure During Hurricanes and Tornadoes

Although a number of property loss projection models have been developed, most of them use post-disaster investigations (FEMA 1993) or available claim data to fit damage versus peak wind speed vulnerability curves. Such a relationship, derived from insurance data, between home damage and wind speed is proposed for typhoons Mireille and Flo (Mitsuta et al. 1996). The difference between these models is often just in the type of curve fitted. Almost all of them ignore the damage mode of structures, one of the most important bases for more accurate assessment of the risk of hurricane damage to structures. There is a clear need for more thorough post-disaster investigations to better formulate and validate damage prediction models, although this effort is hampered by the lack of clarity, transparency of data, and the complex physics of hurricanes. Huang (2001), Khanduri and Morrow (2003), and Stewart et al. (2003) also present a method to assess the fragility curve for damage during hurricanes by regression techniques applied to insurance claim data following hurricane Andrew. The drawback of these methods is that they are highly dependent on the types of construction and construction practice that are common in the areas represented in the claim data, and they do not reflect more recent changes in building codes and construction practices. In addition, damage curves obtained by regression from observed data can be misleading because often, as was the case for hurricane Andrew, few reliable wind speed data are available. In addition, damage curves inferred from observed damage do not adequately represent the influence of primary storm characteristics, such as central pressure, forward velocity, radius of maximum wind, amount of rain, duration, and other influential factors including the degree of advance warning and preparedness.

As pointed out by Pinelli, Simiu, et al. (2004), the most reasonable approach may be to combine the (relatively recent) probabilistic approach to structural damage estimation and the wind field model. Examination of insurance claim files from hurricane Hugo and Andrew revealed that most wind damage to houses is restricted to the envelope of the building. The risk of death and injury from hurricanes is very low, so the main criteria for minimizing insurance company and homeowner losses are economic, that is, reducing damage to buildings and their contents, instead of related to life safety. These investigations seek to define damage modes for different types of construction and building materials. Indeed, there are better prospects for sorting damage modes of structures during hurricanes, considering the envelope character of the damage, compared to the more complex patterns of damage and failure of structures during severe earthquakes. Of course, the combined effects of wind and earthquakes are also of great interest to engineers.

Doswell and Burgess (1988) found that building damage and tornado intensity are related, but quite imperfectly. Different extreme wind speeds may cause similar damage from site to site and from building to building (Phan and Simiu 1998). The performance of buildings in a tornado-stricken area depends on their construction and whether they are in open country or in a built-up area (Schaefer and Galway 1982). Finally, there is a human factor in determining the tornado intensity based on observed damage, in light of the definition of the F-scale.

Conclusion

Based on the preceding account of recent developments in modeling annual maximum wind speeds, there appears to be no general consensus on the type of extreme value distribution that best fits the available information about normal wind and can best serve to predict long mean-return period values of wind speed. The main obstacle is insufficient data to analyze extreme value statistics for wind speed and to discriminate between extreme-value distribution models. In this context, further research is needed along the following lines:

1. A key question is how to find an appropriate model for simulating extreme wind speeds in light of the insufficiency of data. Related is the need for reliable extrapolation of long-return-period wind speed from short-term data, considering the reality of the complex physical, space-time varying, and multi-component nature of wind speed. Corotis and Dougherty (2004) states, "The user must be very wary of estimating design forces from natural time series that are much longer than the record length, or even equal to the length of observed data." Probability distributions calibrated based on the bulk of the data, even when filtered to read only the maximum 4-days gust, are unreliable for the purpose of predicting wind speeds with mean return periods of more than a few years.

2. Adopting a statistical distribution and its parameters can be seen as the outcome of a decision process, one that should be dynamic, intermittently incorporating new information. A stochastic simulation model (to assist in reliability-based design of new structures or risk management of existing ones) and the underlying probability models for wind speed and structural properties should be modified dynamically during the service time of structures. The relevant tools include Bayesian probability analysis (for example, Liu et al. 2003), discrete Markov chain models, and local-average-based random field models (Vanmarcke 1983). The results might be estimates of

time-dependent reliability or the probability distribution of useful service life remaining, possibly conditioned on knowledge (or anticipated information) about damage during extreme events.

3. A principal concern of the insurance industry is the assessment of expected losses due to hurricanes. In addition to statistical processing of post-disaster information about insured and other losses, a promising line of research involves combining investigation of damage modes of structures and more realistic modeling of wind fields on a range of spatial and temporal scales.

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Chapter 10: Initial Assessment of the New Orleans' Flooding Event During the Passage of Hurricane Katrina

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Abstract

Hurricane Katrina made landfall in Louisiana at 6:10 a.m. on Monday August, 29, 2005. The storm's track took it north along the eastern edge of New Orleans. After the storm, 85 percent of greater New Orleans was flooded. More than 1,200 people had lost their lives, and about 100,000 families were homeless, most of which had heeded the evacuation orders. The hurricane protection system that residents of New Orleans had depended on for security from surge floods had failed catastrophically with more than 50 breachings or breaks.

This paper provides a preliminary assessment. The flooding of New Orleans represents two separate events, distinct in time, space, and intensity. In eastern New Orleans, levee failure accompanied a surge overtopping event, flooding surrounding communities. In western New Orleans, catastrophic levee failure caused the flooding. Both flooding events reflect engineering failures.

Research Activities

The objectives of our study included the following:

1. Quickly preserve all perishable data such as surge high-water marks, and use them to calibrate an advanced circulation (ADCIRC) storm surge model used in emergency operational support by the LSU Hurricane Center.
2. Determine the timing and mechanism of the various flooding events that led to the New Orleans catastrophe. This included the center's "stopped clock program," which obtained stopped battery operated and mechanical hand-dial clocks from flooded homes, noting the clocks' elevation about ground. The actual water elevation at the time the clock flooded was then determined using available high-resolution LiDAR data. Video camera footage as well as survivor interviews were also used to understand how rapidly the floodwater spread.
3. Use all available satellite imagery and oblique air photographs to map the flood front as it advanced throughout New Orleans.
4. Conduct a forensic investigation of how the levees failed including site investigations, and review all design documents including as-builts, CPT surveys, and seismic (pinger) sheet pile depth determinations.

Narrative

Initial Breaches

The first Katrina flooding of residential areas in greater New Orleans occurred almost 2 hours before the storm's landfall. Between 4:30 a.m. and 5:00 a.m. the levees were breached where the CSX Railroad crosses the northern arm of the Industrial Canal, adjacent and parallel to Interstate

10 (Fig. 1.1). Here sand bags had been used to seal the levee "I" walls where the railroad passed through the wall. The metal gates that would normally have been used in this area had apparently been damaged during a train derailment and were not functional. At the time of the breaches, the surge was 9 ft. above sea level, and it rapidly fell 4 to 5 ft., reflecting two rivers of surge—one flooding to the east and the other to the west. As a result, the first flood waters started to enter Orleans Parish around 4:45 a.m. Monday morning.

MRGO Levee Erosion

Prior to landfall an 18-ft. surge with huge waves developed in Lake Bourne, east of the city, peaking around 7:00 a.m. However around 5:00 a.m., the westward directed waves on Lake Borgne rapidly eroded the levees fronting the Mississippi River Gulf Outlet (MRGO). These make up the easternmost length of the ring of hurricane protection levees surrounding St. Bernard Parish and the Lower Ninth Ward. The MRGO levees were rapidly overwhelmed and in some places completely destroyed (Fig. 2). The surge then roared westwards into St. Bernard and Orleans Parishes flooding all the lower areas of Chalmette, Meraux, and Violet. In some areas the flood reached to the toe of the very large levees along the Mississippi River. The flooding surge water also started to spread towards the Lower Ninth Ward such that homes on Tennessee Road started to flood from the east around 6:30 a.m.

The "Funnel" Effects

As the eye of the storm approached the latitude of New Orleans a 14- to 17-ft. surge was pushed into an area know as the Funnel, so called because the MRGO and Gulf Intra Coastal Waterway (GIWW) levee systems converge from about 10 miles apart to a few hundred yards. At approximately 6:30 a.m. with the eye still south of the city, the surge overwhelmed the levees in the Funnel and started to flood both sides of the GIWW channel (Fig. 1). To the south of the GIWW in St. Bernard and Orleans Parishes, these flood waters added to those coming from the southeast, resulting in the MRGO breaches. Flood waters started to rise even faster in the Lower Ninth Ward (Orleans Parish). Concurrently, the surge pushed westwards along the GIWW towards the Industrial Canal, where it branched to the south to be stopped by the closed locks separating the Industrial Canal from the Mississippi River. It then branched into the northern arm of the Industrial Canal and poured into Lake Pontchartrain, which was 10 ft. lower in elevation. At approximately 6:50 a.m. the levees along all reaches of the Industrial Canal were overtopped, and water started to pour into the city both to the east and the west. In the Lower Ninth Ward, the surge water overtopping the levees exacerbated the flooding, adding to the surge water entering the area from the Funnel. At the Louisiana National Guard's Jackson Barracks in Arabi, which is situated on the high ground of the Mississippi River's natural levees, flood waters were first seen about 7:00 a.m. However, the flood conditions were about to deteriorate rapidly.

Flooding the Lower Ninth Ward

Along the southern arm of the Industrial Canal, the stage was being set for major levee breachings. In the Lower Ninth Ward, these levee overtopping surge waters had started to erode the backs of the earthen levee embankments, scouring out trenches along the entire back length of the levee wall. The water pressure from the rising head in the Industrial Channel pushed the walls outwards causing four sections along the length of the levee "I" wall to start leaning backwards; cracks appeared in the concrete "I" walls. As the "I" walls were tilted and in some cases moved laterally (translational slide) backwards, large cracks developed in the soil at the wall's canal-side bases. Water started to percolate down these cracks and then under the pilings resulting in sand boils and weakening of the soil foundation. Meanwhile the scour trenches deepened, and the pressure on the walls and especially the soil foundations increased. Around 7:45 a.m. the levees along the eastern side of the Industrial Canal were explosively breached, and the Lower Ninth Ward flooded extremely rapidly (Fig. 2). All evidence of the failure mode at both breaks was washed away, so the exact mechanism of collapse may never be known. However, evidence of the mechanism of levee collapse may be gleaned from sites where the levee almost failed. Here insufficiently deep sheet pile foundations could not hold the static loading due to the surge as well as form an effective hydrologic barrier for seepage under the system. The geotechnical collapse was aided in part by the overtopping scour trench development on the back embankment. In the huge surge flood scour areas adjacent to the breaches, all the houses were totally destroyed by a head of water almost 20 ft. high. Further away many were pushed off their foundations. These breechings ensured that the flood waters in all areas east of the Industrial Canal reached to about 12 ft. above sea level, and because the area is about 4 ft. below sea level, many homes were totally submerged. A barge floated over the major breach knocking the top 9 in. off the concrete wall that had already failed. All indications are that the barge floated in after the breach was well established.

Industrial Canal Levee Overtopping

The flooding in Orleans East was further exacerbated by surge waters pouring over the levee system of the northern arm of the Industrial Canal, while areas of the city west of the northern arm started to flood because of the surge overtopping those levees. Later in the day around 10:00 a.m., floodwater also poured into Orleans East for a few hours due to levee overtopping from Lake Pontchartrain near the Lake Front Airport. The waters overtopped a section of concrete levee wall that strangely was almost 2 ft. lower than the earthen walls it was attached too, as well as breaching a small section of an earthen levee.

Once the eye of Katrina reached the southern shore of Lake Pontchartrain, the surge in the Industrial Canal and Funnel leveled off and started to drain due to the westerly winds. The surge flooding event had peaked for all areas east of the hurricane's track. In addition to the major breaches along the east bank of the Industrial Canal, miles of levees along the MRGO had now been totally eroded, and St. Bernard and Orleans Parishes between the MRGO and the Mississippi River were completed flooded. The westerly winds then started to push water out of these areas, rearranging some of the sheet piling used to raise levee heights along the MRGO.

Inner City Floods

Lake Pontchartrain was now about 8 ft. above normal, the wind generated waves were huge, and the turbulence from the waves eroded the lake bottom. By the time the winds calmed, some areas of the lake had deepened by at least 2 ft. The lake waters now had a large amount of suspended sediments entrained and dispersed through the water column. The eye of Katrina then continued its trek north moving at about 14 mph. By noon it had moved north of Slidell, on the lake's north shore, having pushed a 12-ft. surge into that city and surrounding areas.

Because New Orleans is below sea level, it is totally surrounded by hurricane dykes, commonly known as levees. As a consequence, every drop of rain that falls in the city must be pumped out into Lake Pontchartrain, and a series of internal drainage canals, pump stations, and their associated levees are required to keep the city dry. The city is divided into two parishes, which are governed by two separate authorities. The dividing line is 17th Street Canal, which runs north to south approximately splitting the area into two equal-sized halves (Fig. 3). The pump stations for the western half, Jefferson Parish, are at the lake side of the drainage canals, and the pump station structure is a part of the levee protection system. Well-engineered, substantial concrete levee walls connect the pump stations to the earthen levees along the lake shore. However, the eastern half of the city, Orleans Parish, uses a very different drainage system. The pumps are located at the inner most city limit of the canals and their southern ends, and a complex levee consisting of an earthen embankment topped by a concrete wall anchored with metal sheet piling lines to each side of the canal. The canals are always open to Lake Pontchartrain and experience the full levels of surge that may enter from the lake. This unusual engineering set the stage for one the U.S. greatest natural disasters.

The 17th Street Canal

As the eye of the storm began to cross the Rigolets, the winds along the south shore of Lake Pontchartrain swung to the northwest, pushing the highly turbulent surge water against the levees along the south side of the lake. Surge levels rose to 10 ft. in places. At the mouth of the 17th Street Canal, small homes and house boats immediately west of the canal's lake entrance flew apart, and the debris was blown into the canal. Restaurants at the mouth of the canal, along its eastern flank, were also annihilated by the winds and waves, and some of this debris entered the 17th Street Canal. The surge peaked at 9:00 a.m. at about 10.5 ft. above mean sea level. At approximately 10:30 a.m., the eastern levee of the 17th Street Canal, 100 yards inland from the Metairie-Hammond Highway hurricane-proof bridge, crossing the canal near the lake shore, was breached, and surge waters immediately started to flow into the western portion of Orleans Parish. Eye witnesses reported that the flood waters rose rapidly. As the waters gushed into the canal from the lake, the debris floating in the canal's mouth was swept against the Metairie-Hammond Highway hurricane bridge, whose design restricts the cross-sectional area of the canal due to its piers and low base level. The debris rapidly packed to form a substantial, albeit porous, dam.

The London Avenue Canal

Surge levels similarly rose in the London Ave. Canal to the east of the 17th Street Canal until 9:00 a.m. The physical morphology of the two canals is similar; each has a pump station at its most inner end and concrete "I" walls atop earthen embankments comprising the levees. About half way down the length of the London Ave. Canal, just inland of the Robert E. Lee Bridge, the levee walls started to creek and bent outwards on both sides of the canal. A similar failure pattern was developing further down the canal. At approximately 9:30 a.m., just after the peak of the surge, a catastrophic failure of the London Ave. Canal occurred 1,500 feet from its inner edge near the Mirabeau Ave. Bridge, and floodwaters immediately poured into the city, displacing one home off its foundations and sliding it 90 ft. across a road. Floodwater from the lake then started to stream down the canal toward the breach. While water levels were lowered close to this inner, easterly breach, elsewhere along the canal the surge level continued to slowly fall until around 10:30 a.m., when a second levee failure occurred on the London Ave. Canal. The levee wall failed along the west side of the canal, just south of the Robert E. Lee Bridge, where the levee walls had started to bend outwards. The surge at this time was 7 ft. above sea level—down 3 ft. from the peak 90 minutes earlier. The breach sent an 8-ft. high wall of water cascading into the surrounding neighborhoods. New Orleans's fate was now sealed due to the catastrophic failure of the engineered levee walls, which were constructed to protect the city from a surge of at least 11.2 ft. above sea level. Thus, the levee walls failed before their design criteria were exceeded. It took another two days for the flood waters inside the city to equalize with the lake at about 3 ft. above sea level, leaving the average home in 6 to 9 ft. of standing water.

Unlike the 17th Street Canal, there was no debris dam at the entrance of the London Ave. Canal. Lake waters with their full suspended sediment load poured down the canal at velocities high enough to keep all the sediment, originally eroded by waves from the floor of Lake Pontchartrain, in suspension. At the Mirabeau breach, a deep layer of beach sand 10 ft. beneath the "I" walls and exposed in the canal bottom was scoured. This fine sand, along with the high suspended load coming from Lake Pontchartrain, led to the deposition of a thick layer of sand around the homes. The beach sands below the "I" wall appear to have blown out as a huge sand boil, and the wall segments collapsed into the void created. In a classical river delta manner, once these flood waters exited the confined levee bounded by the London Ave. Canal and became unconfined and unconstrained as they spread through the subdivisions, the coarse sediment load was dropped first, followed by the white fine sands. As a result, the aftermaths of the two floods were dramatically different from the 17th Street Canal flood. With the London Avenue Canal flood tons of sediment spread over a large area with river-sized white sand bars, whereas the 17th Street Canal flood only deposited fine mud because the canal was partially blocked by the debris dam, but mostly reflecting the very thick layer of beach sand in the London Ave. Canal that was eroded by the waters rushing out the breach.

Levee Failure Mechanisms

Why were these complex flood walls breached? What caused the catastrophic failure? Investigations are still in their preliminary stage, and while the overtopping of the Industrial Canal levee led to the development of an ever expanding scour trench behind the levee wall and the eventual failure of the wall as it collapsed into this scour trench, evidence exists that this scour collapse was hastened by soil foundation failures. What is painfully evident is that the London Ave. and 17th Street canals were not overtopped, and their failure did not reflect the scour trench collapse mechanisms that aided the failure of the Industrial Canal levees. Rather there was a heave—a lateral displacement of the whole levee wall complex due to the surge head—the equivalent of a pressure burst in a dam or reservoir. The soil foundation failed catastrophically. The levees were pushed laterally up to 45 feet, heaving everything in their way forwards and upwards so that some buildings ended up almost 9 ft. higher; previously flat and level back yards became hummocky terrains due to the bulldozing action of the heave.

There is evidence of other structural failures. When the concrete walls were made in the early 1990s, the concrete was attached on top of steel sheet pilings. The attachment overlap was about 20 in. Some wall segments exhibit failures at the pivot point of the termination of the steel piling inside the concrete wall; some show that the reinforcing bars (to add strength to the concrete section) were not welded to the sheet pilings and thus may not have been designed to sufficiently handle the loads associated with an above normal surge.

The 17th Street and London Ave. Canal breaches were not induced by the surge associated with Hurricane Katrina per se. Rather they reflect the catastrophic failure of man-made and engineered complex levee walls. This is particularly senseless in contrast to the secure and robust canal lake end seals in Jefferson Parish. The failure of the 17th Street, London Ave., and Industrial Canals in Orleans Parish reflects poorly on the federal government and the U.S. Army Corps of Engineers, who designed and supervised the construction, maintenance, and inspection of these levees.

Acknowledgements

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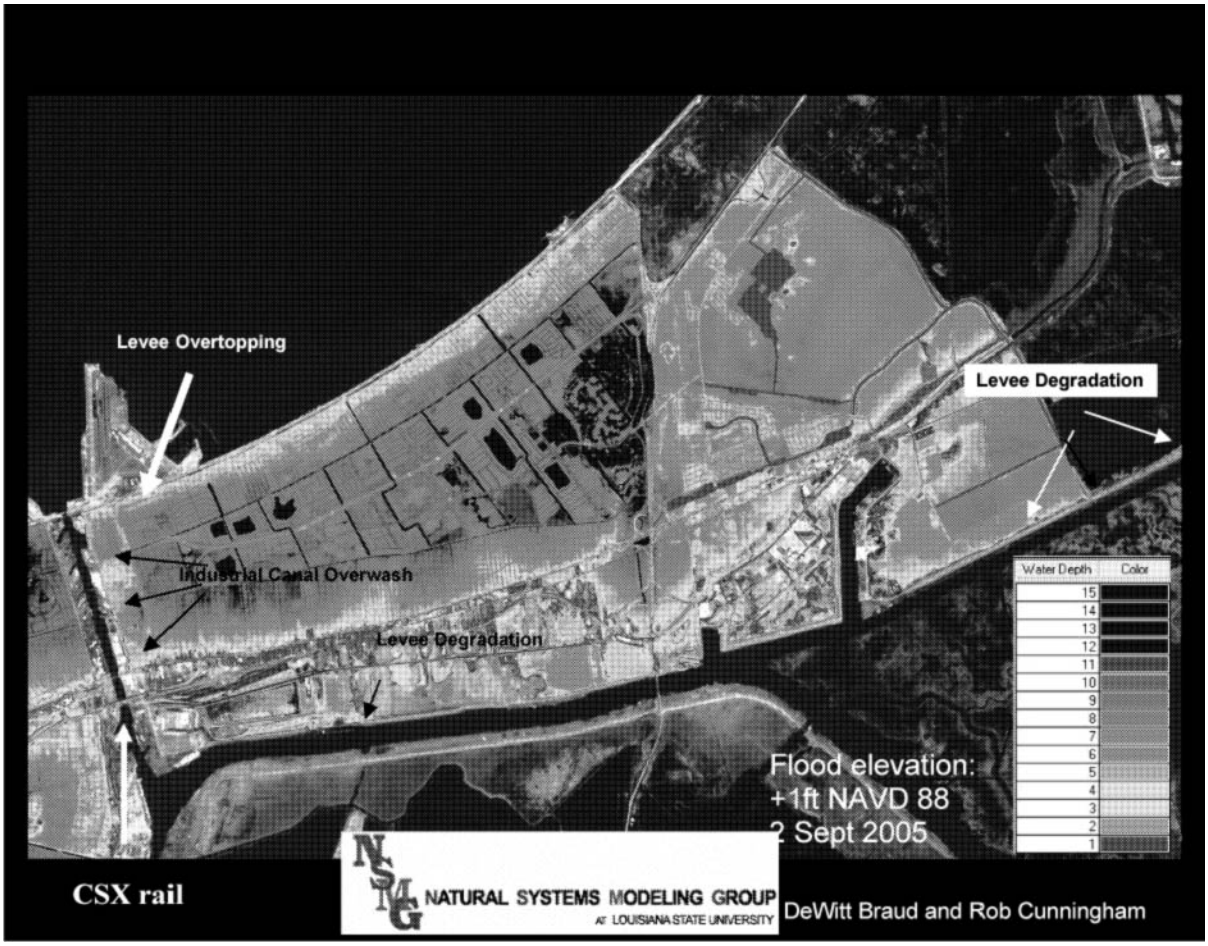

Fig. 10.1. 10 M SPOT satellite image: September 2, 2005 with water depth overlays – Orleans East

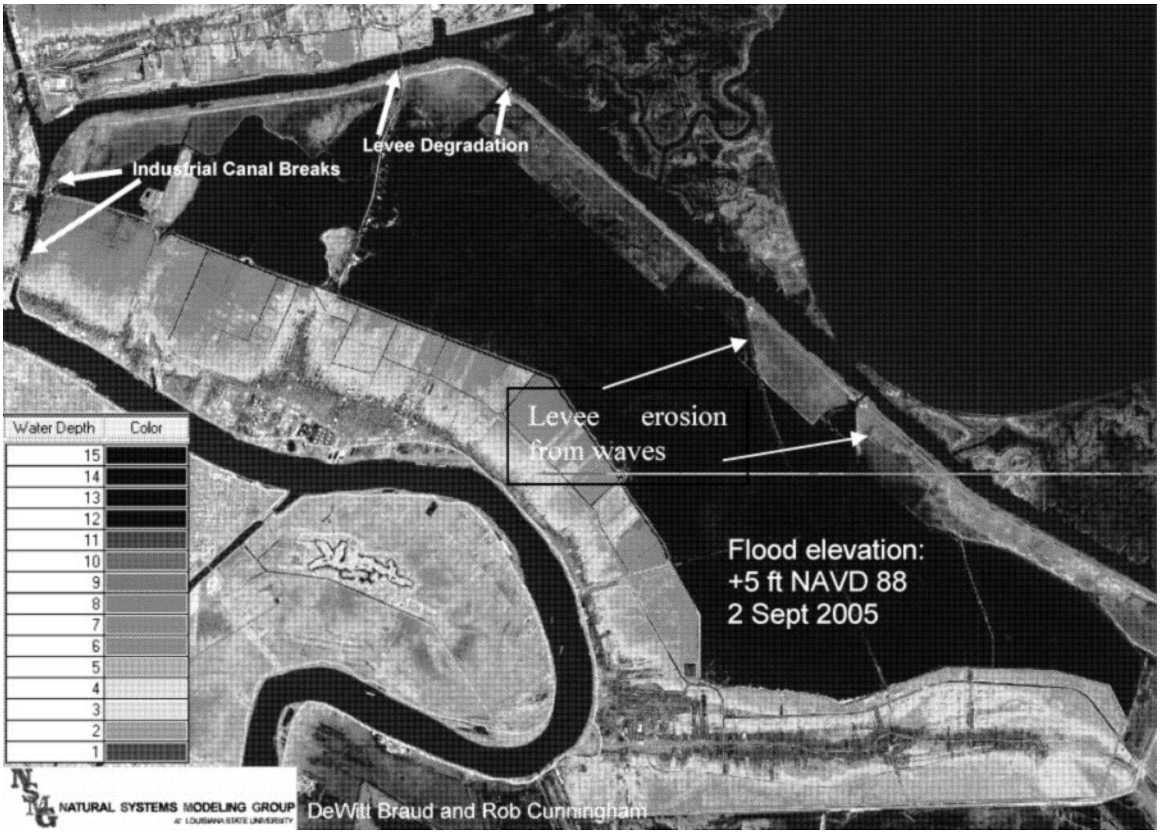

Fig. 10.2. 10 M SPOT Satellite Image: September 2, 2005 with water depth overlays

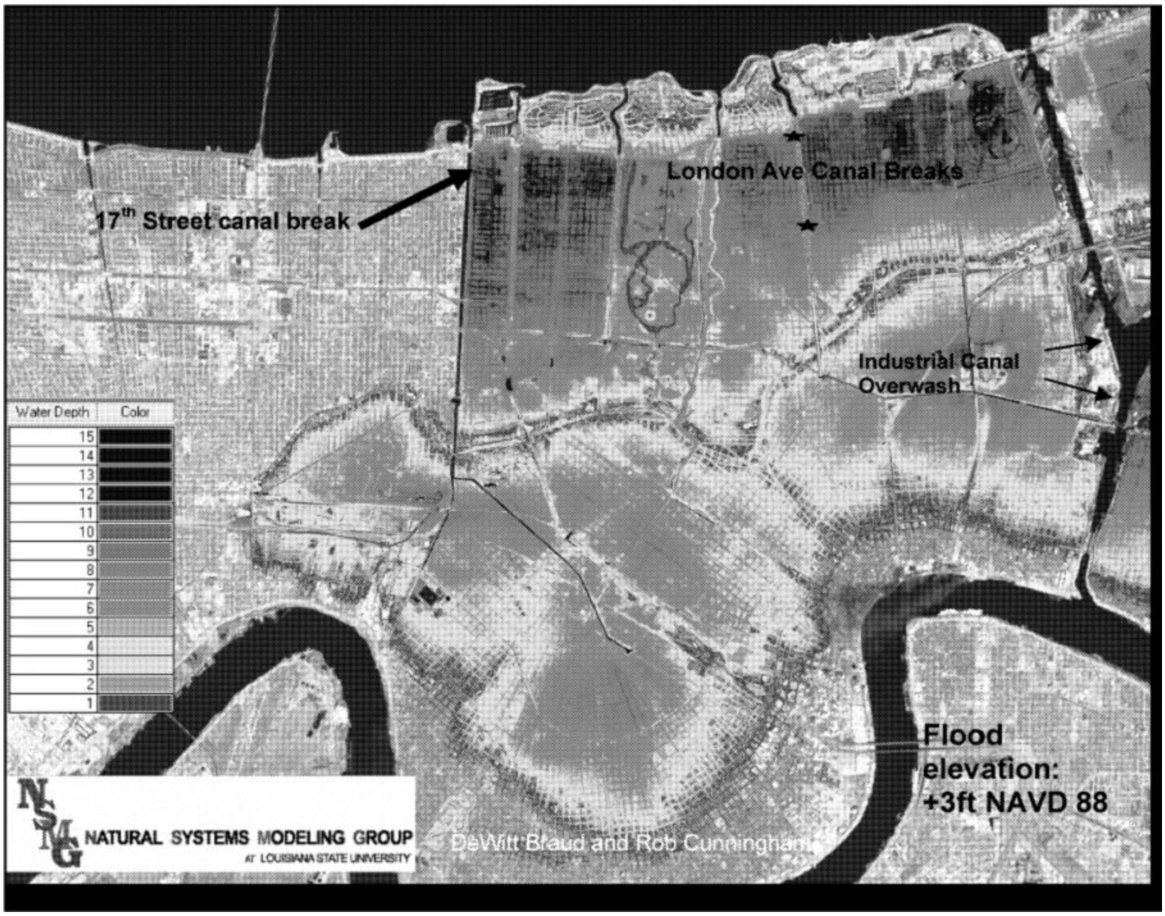

Fig. 10.3. 10 M SPOT satellite image: September 2, 2005 with water depth overlays

Chapter 11: Improvements in Flood Fatality Estimation Techniques Based on Flood Depths

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Abstract

Accurate and reliable estimation of the number of expected fatalities from flood events requires a quantitative understanding of the relationship between the flood hazard characteristics and the fatality rate of the population exposed to the hazard. This article builds upon previous methods of estimating flood fatalities by further specifying the depth-based flood fatality function. This chapter presents basic principles that indicate an s-shaped relationship between flood depth and flood fatality rate. It also presents a preliminary data analysis indicating that a logistic equation with an unknown asymptote provides the best fit to the available flood fatality data.

Introduction

This chapter reviews analytic methods for obtaining an accurate and reliable estimate of the number of fatalities of a storm surge induced flood disaster and presents a refinement on the method proposed by Jonkman (2005). While the current article focuses on direct drowning during storm surge flooding, the proposed principles and method of analysis apply to floods in general. The data used for verification and calibration, however, remain specific to drowning during storm surge events.

Since 1900, nearly 3,000 flood disasters have affected almost 3 billion people and killed close to 7 million. These figures imply that on average each year more than 27 million are affected by floods and about 65,000 die. While storm surges are not the most common type of flood, they remain among the most lethal. Many of the deadliest flood disasters resulted from storm surges.

In the United States, a storm surge in Galveston, TX, killed more than 6,000 people in 1900. More than 2,500 people perished from the storm surge of Lake Okeechobee, FL, in 1928. A 1953 storm surge killed almost 2,000 in Holland and England. While the death tolls of these events are high, the deadliest storm surges occur in Asia. Two typhoons in China, one in 1912 and the other in 1922, each killed more than 50,000. Even worse, the surge from a 1991 cyclone in Bangladesh killed close to 191,000 people. Likely the deadliest in recent history, a 1970 storm surge killed between 300,000 and 500,000 in Bangladesh.

Most recently, the landfall of Hurricane Katrina along the Mississippi-Louisiana Gulf Coast of the United States resulted in more than 1,200 fatalities. In Mississippi, a 25 to 30 ft. storm surge resulted in nearly 200 direct deaths. While New Orleans avoided the brunt of the surge from Katrina, this devastating hurricane still resulted in a number of levee breeches around a densely populated area. For the two days that followed, Lake Pontchartrain slowly drained into the city and finally inundated 80 percent of New Orleans and large parts of the surrounding area. An estimated 100,000 people in the metropolitan area were exposed to these floods, and countless thousands were rescued from roofs and attics by boat and helicopter. At least 700 people died in Orleans parish, while 123 perished in neighboring St. Bernard perish. Most of these are considered Katrina-related fatalities, but the exact number of drowning deaths is not known at this time (Warner 2005). We can assume that up to 95 percent of these fatalities were directly related to the storm surge induced flooding.

Storm surges result from the lower atmospheric pressure and high wind speed near the center of a tropical cyclone. In the northern hemisphere, the counter-clockwise circulation of the storm means that the surge is east and north of the eye, and vice-versa for storms in the southern hemisphere.

Storm surges manifest themselves as an extremely high tide that rises quickly as the storm approaches land. While a typical daily tidal range is less than 1 m, during a storm surge the water level can reach and exceed 5 m above mean sea level (MSL). As a result, populated areas near the coast quickly become inundated with water well above head level and houses are submerged to the point where only roofs remain above water. The actual height of a surge depends on many factors such as the climatic characteristics of the storm and the geographic characteristics of the landfall region. The height of the water is also affected by the astronomical tide. One of the most important effects of storm surges is the tremendous energy that surface waves can bring to inland locations resulting in devastating effects on people and the built environment. The world witnessed the destructive power of these waves the morning after Hurricane Ivan, when footage of a missing interstate bridge section was broadcast from Florida. Following Katrina, more than a dozen bridges were destroyed in Louisiana and Mississippi.

The historic record of storm surge fatalities in the United States shows an interesting pattern and introduces an important question for disaster mitigation and planning policies. In a review of loss of life from Atlantic hurricanes between 1970 and 1999, Rappaport (2000) found only six cases of storm surge drowning. This low count contrasts sharply with the 11 years preceding his study. During this time period, three events alone—Audrey, Betsy, and Camille—account for close to 600 surge fatalities. While the sharp decrease in fatalities is often attributed to early warning technology and efficient evacuation of surge regions, another hurricane related trend may also, at least partially, explain this drop.

Both the severity and frequency of hurricane activity in the Atlantic basin follows trends closely coupled with multidecadal fluctuations in the Atlantic Ocean thermohaline circulation, also known as the North Atlantic Oscillation (NAO). Rappaport's study period, 1970 to 1999, corresponds roughly to an era in the NAO cycle characterized by low Atlantic hurricane activity. In contrast, the era before the study period is characterized as high hurricane activity in the Atlantic. Likewise, since the end of the study period, the Atlantic Ocean has entered a new period of increased hurricane activity. Indeed, as this chapter was being drafted in August 2005, tropical storm Harvey set a record as the first "H" in August, and the U.S. National Oceanic and Atmospheric Administration warned that the bulk of this season's storms were still to come. In October 2005, Hurricane Beta, a record breaker in many senses, made landfall in Honduras, with a month still remaining in the Atlantic hurricane season.

The observed surge-related fatalities during the 2004 season provide some indication that the new period of increased hurricane activity may also be one of increased surge fatalities. In comparison to the six surge-related fatalities in the 30 years before 1999, two storms in 2004 produced seven fatalities. The surge of Hurricane Francis caused two fatalities (Beven 2004), while Ivan's 5-m storm surge caused five fatalities (Stewart 2005). Thus, disaster analysts must ask, as Atlantic hurricane activity increases, could more frequent and more intense storm surges result in a period of increased surge related mortality? Has the lull in storm surge deaths observed between 1970 and 1999 introduced a false sense of security from this hazard? Should the disaster planners along the Gulf and Atlantic coasts prepare for more surge events like Ivan or ones that are even deadlier? Indeed, as Katrina has resoundingly answered these questions, it seems imperative that important steps be taken to better protect live from deadly storm surge events.

Thus, it would be extremely beneficial to have a reliable quantitative method for estimating the potential impact of storm surges before the events occur. It seems reasonable to think that such estimates should be possible through analytical techniques based on the physical hazard characteristics of the surge and the human vulnerability characteristics of the exposed population. With such a method available, disaster analysts could consider different scenarios and identify the specific events that could lead to high mortality.

In addition to the questions posed above, a flood fatality model would help disaster mitigation and planning and disaster response and recovery. It would also help planners identify levee designs and configurations that minimize the threat to life. Likewise, by identifying areas of high potential mortality, disaster planners can identify optimal locations for shelters of last resort. A flood fatality model used in conjunction with real-time storm surge monitoring and simulation would also help search and rescue officials direct assets to areas of greatest concern.

This article presents a refinement of a previously published method for estimating storm surge fatalities, specifically in estimating the flood fatality rate based on the flood water depth at a location. A flood fatality function provides a crucial module for estimating the number of fatalities during the storm surge. The two other important modules are the storm surge simulation, such as provided by ADCIRC (Westerink 2003, Westerink 2004), and a module that estimates the exposed population. The exposed population is defined as individuals directly exposed to the physical hazard agent of surging water. The flood fatality function determines the fatality rate of the exposed population. The total number of fatalities is estimated from the fatality rate multiplied by the size of the exposed population. Again, while the current discussion focuses on storm surges, the principles apply to floods in general, and the method could be readily applied to other flood types given the appropriate data.

As the following discussion describes, the flood fatality rate depends on a number of variables. Some of these variables describe the flood hazard while others describe the vulnerability of the exposed population. As many experts in this field will testify, the number of variables in a real world flood event is large. In contrast, the flood fatality function that is presented, representing a simplification of reality and a work in progress, utilizes the one variable that we consider most important—water depth.

Literature Review

In her seminal work on methods of assessing a community's vulnerability to natural hazards, Cutter (1996) notes the importance of analyzing the variables that produce explicit spatial outcomes. Wisner calls attention to the complexity of such a task when he discusses shaping the spatial and social distribution of risk (Lund 2000). In the context of floods, approaches to estimating explicit spatial outcomes from what is known about the distribution of risk have improved over the years though a number of uncertainties remain in this complex problem. McClelland (2002) and Jonkman (2005) provide comprehensive reviews of proposed methods for estimating the loss of life resulting from flood events.

One early approach (Brown 1988) looks at dam breaks and estimates the number of resulting fatalities using the evacuation time and the size of the population at risk. This method handles evacuation time as an ordinal variable with three categories specified by the authors. While groundbreaking, this early method is criticized for the discontinuities that result from this operationalization of wait time and the lack of variables to control for the physical aspects of the flood hazard.

As Jonkman (2005) describes, early flood fatality researchers in the Netherlands used the flood depth of a location to determine the local flood fatality rate (Duiser 1989, Waarts 1992). Using data from the 1953 flood in Holland, Waarts finds a good fit when modeling the flood fatality rate as a function of the flood depth. He also sketches a more refined model that includes the effects of warning time, evacuation, high flow velocities, and building collapse, but notes that a lack of historical data prevents a quantitative specification of the affect of these factors. Vrouwenvelder and Steenhuis (1997) add the rate of rise of the flood to the fatality rate equation, but they do so in an ad-hoc manner that limits the domain of the two explanatory variables. Jonkman notes that this specification is inconsistent with observations from the 1953 Dutch flood.

In 1993 motivated by dam failures and flash floods, DeKay and McCelland (1993) propose two loss-of-life equations—one for highly lethal floods and another for low-lethality floods. In both equations, the number of flood fatalities depends on the population at risk and evacuation time. Jonkman (2005) points out that, contrary to other results and to basic expectations, the number of fatalities depends nonlinearly on the population at risk in the equations proposed by DeKay and McCelland.

Prefacing their article with the important statement that "this is not a model," McClelland and Bowles (1999) present a comprehensive listing of realistic input variables inferred from a review of 38 flood events from the historical record. Central to their conceptual approach is dividing the population at risk (PAR) into homogeneous sub-PAR characterized by "predictable life loss distributions, with variance governed largely by chance." These populations are termed homogenous base units (HBUs). For each HBU, many variables related to evacuation effectiveness determine the threatened population, while many variables related to the hazard exposure determine fatality rate. In comparison to previous approaches that focused exclusively on the flood hazard and evacuation logistics, this article begins to include the social distribution of risk in the flood fatality model framework.

Implementing this conceptual framework, Aboelata et al. (2002, 2003) present a GIS model for estimating life loss resulting from dam failure. In this model, fatality rates are estimated by characterizing an HBU as one of three possible lethality zones. Safe zones are characterized by an average fatality rate of virtually zero. For compromised zones the fatality rate averages around 10 percent, and in the chance zones, the average fatality rate equals around 90 percent. However, we do not provide specific equations for calculating the fatality rate of a zone based on these characteristics.

Jonkman and Vrijling (2005) (see also Jonkman, Gelder, and Vrijling [2002] and Jonkman and Asselman [2003]), concerned about potentially catastrophic flooding in Holland, present a flood fatality model that includes the evacuation effectiveness and the physical characteristics of the flood hazard. In this model, the size of the total population and the effectiveness of the evacuation determine the size of the exposed population. The number of fatalities is expressed as a fraction of the exposed population, which Jonkman terms flood mortality (otherwise referred to as the flood fatality rate in this paper).

To determine the relationship between the flood mortality and the flood characteristics, Jonkman divides the hazard region into three hazard zones: the breech zone, the rapidly rising water zone, and the remaining zone. Each zone is then subdivided into locations for which flood characteristics are assumed relatively homogeneous. Jonkman notes that these locations are about the size of villages.

The breech zone is characterized by high flow velocities that caused people to lose their stability and buildings to collapse. For locations within this region where the flood characteristics (flood height) (*h*) and flow velocity (*v*) meet the following two conditions

$$h \cdot v \geq 7\ m^2/s \qquad \text{and} \qquad v \geq 2\ m/s$$

it is assumed that all building collapse and that mortality equals 100 percent.

In the rapidly rising water zone, defined as $dh/dt \geq 0.5\ m/hour$, the flood fatality rate for a location is determined by the height of the water using the following equation

$$f(h)rise = e(h - 4.58)/0.69 \tag{11-1}$$

where the exponential function is assumed and the parameters are estimated from 15 data points from locations across three different floods (all during the 1950s).

While drowning is considered the main cause of death in the breech zone and rapidly rising water zone, indirect causes are assumed to dominant in the remaining zone. Again, the flood mortality is expressed as an exponential function of the height of the water,

$$f(h)remaining = e(h - 10.7)/1.59 \tag{11-2}$$

where the parameters are estimated from 90 data points representing five flood events.

Jonkman also discusses correction factors to account for the effects of warning and shelter, building collapse, and rescue actions. However, because a lack of available data, he does not attempt to quantify the effect of these factors.

Looking at loss-of-life modeling within a general context of risk analysis, Jonkman and Lentz (2005) propose three general steps in estimating loss-of-life:

1. Determine the physical hazard characteristics of the event;
2. Determine the number of people exposed to hazard; and
3. Determine the mortality for the exposed population.

To complete step 3, they write that “dose response curves model the human resistance to a certain level of effects,” thus specifying the relationship between the physical hazard characteristics and fatality rate of the exposed population. They describe two approaches to developing dose response relationships—one depends on physical laws while the other uses the historical data to infer statistical relationships.

In this context, Jonkman’s method for estimating the mortality of a flood event centers on three dose response relationships. Flood depth plays the dominant role in these relationships, but flow velocity and rate of rise are also important variables. Implicitly, the structural integrity of the building stock plays an important role when Jonkman states that all buildings are assumed to be destroyed when the conditions of the breech zone are met. This assumption may be appropriate for small nonengineered houses and structures, but it is likely not appropriate for larger, multistory, engineered buildings.

This article focuses on further specification of the dose-response relationship for populations exposed to floods. Jonkman's use of an exponential function is questioned, and we propose that an s-shaped function better relates the flood fatality rate to the flood depth. First, we develop the rationale for an s-shaped function based on basic principles. Then, we show that the s-shaped function provides a better fit to the available data than the exponential function.

Depth Only Flood Fatality Function

The derivation of the flood fatality function begins by considering a single individual standing in flood waters of depth d. Naturally, we would expect that the probability of drowning for the individual depends on the depth of water. In the most simplistic sense, we would expect the drowning probability function to be a single step function that goes from $p = 0$ for $d < d_c$ to $p = 1$ for $d \geq d_c$ where the critical depth, d_c, equals the height of the person's mouth. In other words, once the flood depth equals the height of the person's mouth, water enters the mouth and lungs and the individual drowns.

However, this simplistic model fails to account for a number of important processes related to survival or non-survival, most notably the possibility that the person may fall over or the possibility that the person will tread water or float. If a person falls over, water may enter the lungs before the water depth reaches the critical height, thus the probability of drowning is greater than zero for $d < d_c$. Likewise, if a person treads water or floats, water may not enter the lungs even though the water level is above head level, thus the probability of drowning is less than 1 for $d \geq d_c$. Still, the probability of drowning increases fastest as the water approaches and overcomes head level.

Indeed, these considerations suggest an s-shaped curve that relates the probability of drowning to the depth of water, as shown in Figure 1. In other words, as the water rises from zero to some moderate height (assume roughly equal to neck level for the time being), the probability of drowning rises roughly linearly with a slight slope. However, as the water rises from just below neck level to just above head level, the exposed individual faces a growing possibility of water entering the mouth and the probability of drowning increases rapidly. But, as the water continues to rise above head level the exposed individual implements personal protective actions to sustain life. As the water depth increases, the probability of drowning continues to increase but approaches an upper asymptote. Thus, we can think of the probability curve as consisting of a low probability region at low water depths, a transition region as the water depth approaches and becomes greater than head level, and a high probability region when the water depth is greater than head level. At this point it is worth noting, that we cannot assume that the probability of drowning will ever reach one. Rather, we must conceive of an unknown upper limit or asymptote.

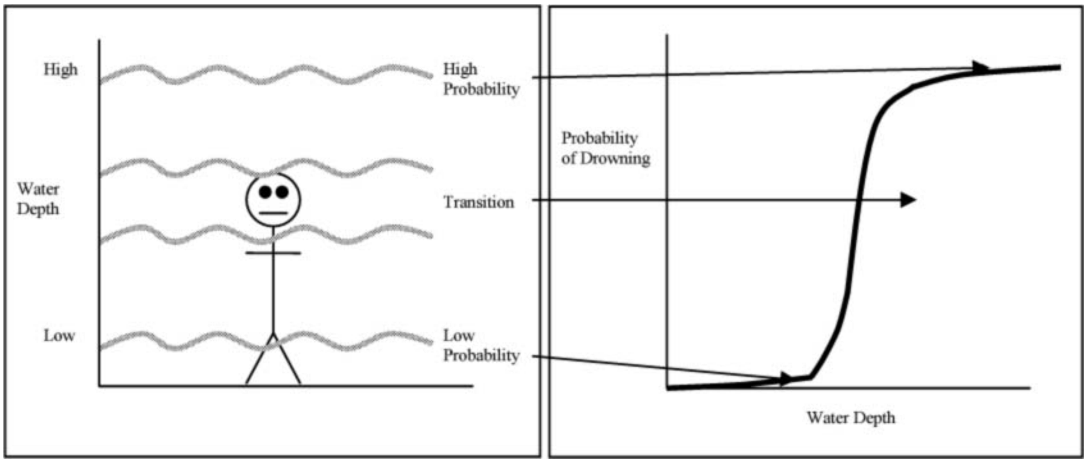

Fig. 11.1. S-shaped relationship between probability of an individual drowning and water depth

Thus, we see that for the i^{th} individual the probability of drowning is an s-shaped function of depth of water at the individual's location, d_i, which we will denote as $s(d_i)$. What about a group of individuals? How does the flood fatality rate, that is the number of drownings divided by the population exposed, relate to the depth of water?

In the most simplistic case, a group of N identical individuals is exposed to uniform flood depth, d. For each of these individuals, the probability of drowning is given by $p = s(d)$. Since the individuals are exposed to a uniform flood depth, d is equal for each of them, and since the individuals are identical, s is likewise identical for each of them. Based on the assumption that the probability of drowning is independent for each individual, the expected number of drownings, denoted n, is easily calculated using the binomial theorem,

$$n = p \text{ x } N = s(d) \text{ x } N. \ (i) \qquad (11\text{-}3)$$

Thus, the fatality rate, f, is given by

$$f = f(d) = n / N = s(d) \qquad (11\text{-}4)$$

So, for a population of identical individuals exposed to a uniform flood depth, the fatality rate for the population is equal to the probability of drowning of the i^{th} individual.

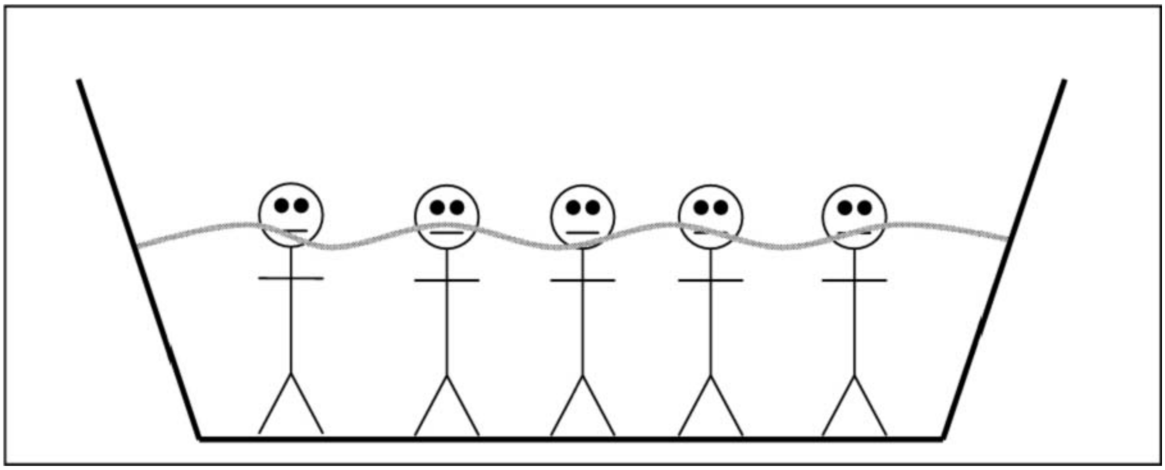

Fig. 11.2. Group of identical individuals exposed to uniform flood depth

This basic relationship provides the foundation for what have been termed homogenous base units (HBU). Typically, defined as an area of the flood region where the flood characteristics and population characteristics are homogenous, the HBU forms the most basic spatial element in flood fatality calculations. Naturally, the strict assumption of complete homogeneity over a region of any (significant) size is false; curbs, ditches, and mounds are everywhere. However, from the discussion above, we can qualify the definition of the HBU as a region where the flood and population characteristics display sufficient homogeneity such that the binomial theorem provides a reliable approximation.

Building upon the simplistic model, we can consider a collection of homogenous base units, each populated with identical individuals. That is, we can consider a flood region that consists of sub-regions of identical individuals exposed to uniform flood depths. In this case, the total mortality is the sum of the mortality for each of the sub-regions and the overall mortality rate is determined by dividing the total mortality by the overall population. If the subscript *j* denotes j^{th} sub-region, we have

$$n = \sum_{j} n_j \qquad (11\text{-}5)$$

and

$$f = n / N = \sum_{j} n_j / N \qquad (11\text{-}6)$$

For the j^{th} HBU, the number of fatalities is determined from equation 11-6 above. Thus,

$$f = \sum_{j} s\left(d_j\right) x\, N_j \ / \ N f = \sum s(d_j)\, x\, N_j / N \qquad (11\text{-}7)$$

In other words, if the flood region consists of a set of HBUs each of which are characterized by a unique flood depth but identical drowning probability functions, the overall fatality rate for the region is just the average of the individual drowning probability function evaluated at the water depth value of the HBU weighted by the proportion of the exposed population in each HBU.

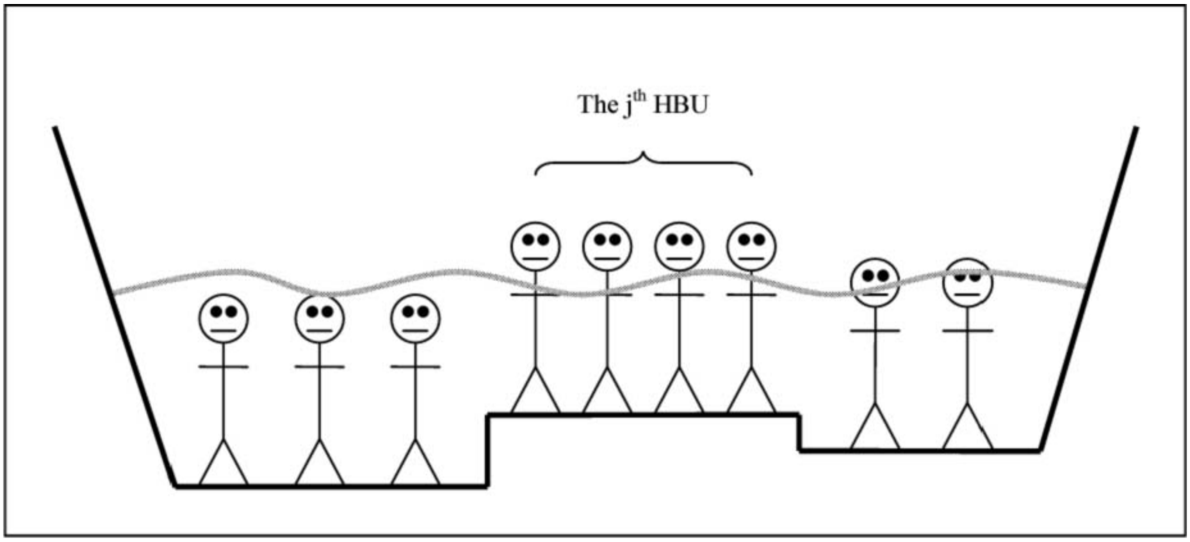

Fig. 11.3. Set of homogenous base units

With a minor transformation of variables, we can easily express *f* in terms of the maximum depth, d_m. Define the depth of region *j* in terms of its difference from the maximum depth, $d_j = d_m - \delta d_j$. This change of variables yields

$$\underset{j}{f} = \Sigma\, s(d_m - \delta d_j)\, x\, N_j \;/\; N \textstyle\sum s(d_m - \delta d_j)\, x\, N_j / N \qquad (11\text{-}8)$$

$$\underset{j}{f} = \Sigma\, (\, s(d_m) - \delta s_j\,)\, x\, N_j \;/\; N \qquad (11\text{-}9)$$

$$\underset{j}{f} = s(d_m) - \Sigma\, \delta s_j\, xN_j \;/\; N \qquad (11\text{-}10)$$

where δs_j is appropriately defined. Thus when we have a group of individuals characterized by a single drowning probability curve and varying flood depths, the value of the drowning probability curve assessed for the maximum observed depth provides a good first order approximation of the fatality rate. This approximation provides an analytic justification for the practice of using the maximum observed flood depth as the leading indicator of the magnitude of the flood event.

Evidence in Support of S-Shaped Flood Fatality Curve

This section compares the expectations of the previous sections with the available historical data from past storm surge flood events. The observed fatality rate is compared to the water depth for 20 locations from seven different flood events. The flood events consist of the 1953 storm surge in the Netherlands and England, the 1965 Hurricane Betsy that affected Southeast Louisiana, the

1969 Hurricane Camille that affected Coastal Mississippi, a 1959 flood event from Japan, and the 1991 Bangladeshi storm surge. The Dutch storm surge provided 12 data points, Hurricane Betsy provided three points, two data points were obtained from the Japanese event, and one data point each were obtained from the 1953 UK surge, the 1991 Bangladesh surge, and Hurricane Camille. Data from the Netherlands, England, and Japan flooding events were provided by Jonkman while the data the Bangladeshi storm is from Bern (1993). Data from Betsy and Camille was compiled through analysis of U.S. Census data, U.S. Army Corps of Engineers data, National Hurricane Center data, and evacuation estimates from local newspapers at the time of the event.

Jonkman presents a fit of the 1953 and 1959 flood data to an exponential function and obtains a reasonably good fit. Using the larger dataset, we compare the exponential function to the fit obtained using the logistic function. Actually, two logistic functions are used to fit the data—one with asymptote equal to one and another where the asymptote is an unknown parameter estimated through the fitting procedure. Statistical analysis was completed in the R statistical language using a non-linear least squared fitting procedure. The data along with the three best-fit curves are presented in Figure 11.4. Table 11.1 presents the best fit parameter estimates along with a basic measure of goodness of fit. The results indicate that the logistic with open asymptote provides the best fit to the 19 data points.

A comparison of the residual standard error, a basic indicator of goodness of fit for the nonlinear least squares fit, suggests that the logistic equation with unknown asymptote provides a slightly better goodness of fit than the other two models. When the sample consists of just the 12 points from the 1953 Holland storm, the strengths of the logistic curve with unknown asymptote becomes more apparent. The exponential model produces a residual standard error of 0.087, the logistic curve produces a residual standard error of 0.083, and the fit to the logistic with unknown asymptote produces a residual standard error of only 0.068. This preliminary finding provides empirical support for the principles described in the preceding section. However, at this stage, data analysis remains preliminary and future efforts will assess the robustness of this finding.

When the asymptote of the logistic equation was left as an unknown parameter to be estimated by the fitting procedure, it was estimated to be 0.34. This value implies that for populations exposed to the most extreme flood conditions, about one-third of the exposed persons will perish. Without commenting on this specific value, we can offer one explanation for why the fatality rate does not tend to reach 1 at large water depths. One basic empirical fact of flood events is that there are always survivors. Rarely, if ever, has the entire population exposed to the flood perish. Instead, even when the water is extremely deep people tend to find debris, trees, attics, roofs, and other ways to stay alive. Only under the most extreme situations would you expect the fatality rate to even approach unity. Even considering extreme flooding events such as the 2004 Asian Tsunami, many people survived under the most arduous of circumstances.

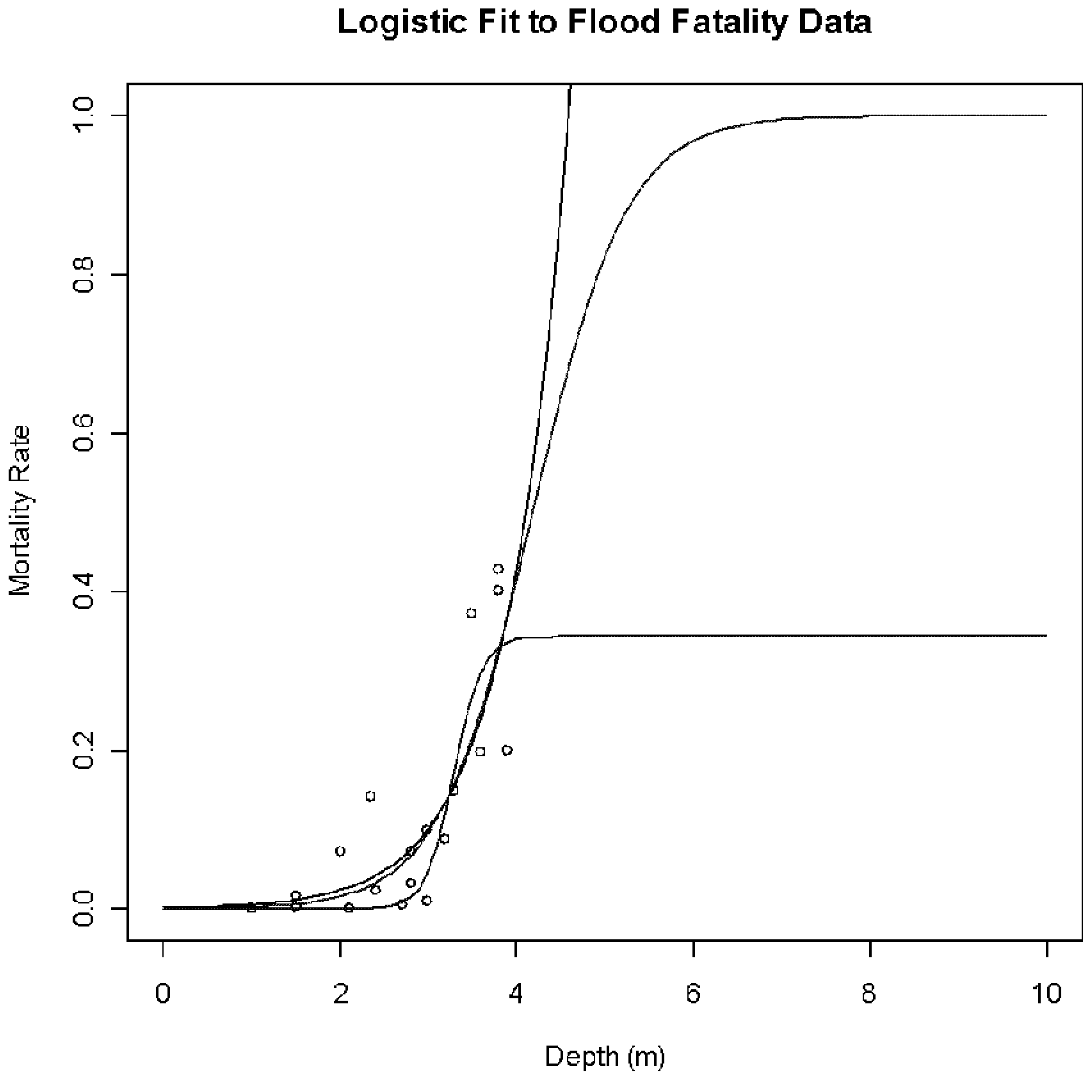

Fig. 11.4. Flood fatality rate versus depth, data, and three curve fits.

Table 11.1. Parameter Values and Basic Statistics (a linear fit is included in addition to the exponential and two logistic models).

Model	A	Signif-icance	B	Signif-icance	C	Signif-icance	Residual standard error
a + b*x	-0.21074	0.05	0.12066	0.00001			0.09824
exp((x - a)/b)	4.5862	0.00001	0.6902	0.00001			0.07873
1/(1 + exp(a + b * x))	7.9027	0.00001	-1.8886	0.00001			0.07711
c/(1 + exp(a + b * depth))	20.37252	0.1	- 6.18346	0.1	0.34383	0.00001	0.07440

Indeed, though highly preliminary, the observed value of the asymptote indicates that on average, about two-thirds of the population survives even when the water is more than 4 m deep. The qualifier "on average" needs to emphasized, meaning that an individual event characterized by flood depths greater than 4 m can have a fatality rate greater than one-third. For example, the fatality rate reached 0.43 at one location during the 1959 Japanese storm surge. Rather, the asymptotic value of one-third should be interpreted as the average for all events characterized by water depth greater than 4 m. It can be used as a rule-of-thumb upper limit when a rough estimate of potential flood fatalities is needed.

Conclusion

A review of the literature on loss of life models for floods demonstrates that a number of variables are important. In essence, estimating the number of fatalities for a flooding event requires two key numbers—the size of the exposed population and the fatality rate for this population. While measuring the size of the exposed population is relatively straightforward, estimating the fatality rate is very complicated. A number of factors influence this variable. Not only are the physical characteristics important, but the vulnerability characteristics also affects the fatality variable. Of the large list of variables, water depth of a location is identified as the dominant.

Jonkman's loss-of-life model assumes an exponential relationship between the fatality rate and depth of water. However, basic expectations of the flood fatality process suggest that an s-shaped function is more appropriate when modeling the flood fatality rate as a function of flood depth. Using data from six flood events, we find that a logistic with an unknown asymptote provides a better fit than an exponential function. However, data analysis remains preliminary, and we do not claim this result to be robust and generalizeable.

It is also important to note that this analysis excludes a number of other variables known to be important. These include the rate of rise, flow velocity, surface waves, and duration of flooding. The level of damage to buildings and the floor and roof heights of buildings relative to depth of floodwaters are also important factors relating to availability of vertical refuge. In addition, the vulnerability characteristics of the exposed population have an important influence over the fatality rate. Though precise numerical data remains limited, further research and analysis will attempt to quantify the effects of these factors and include them in the flood fatality estimation methodology.

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Chapter 12: Socio-Economic Effects of Tsunami on Bangladesh

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Abstract

Bangladesh has been spared any notable tsunami within living memory. As a result, we have to impute socio-economic effects by extrapolation from other countries and other disasters. In Bangladesh, cyclonic storm surges or tidal bores appear to be the closest counterparts. A survey of probable affected areas to assess awareness, preparedness, and concern of the people shows a gap between the worry evoked in foreign circles and the local population's hardy indifference. The economic damages indicated by the survey are also estimates and suggest that active measures to avoid tsunami damage will be hard to implement because tsunami are seen as low probability events. An examination of the orientation of fault lines in the Bay of Bengal suggests a low probability of tsunami in Bangladesh.

The paper surveys the historical evidence of tsunami in Hawaii, supplemented by evidence from the tsunami of 2005 in Indonesia, Sri Lanka, and India, to show the specific types of damage and the uncertain faith people have in many warnings. Unlike other countries, if a tsunami wave reaches the Bangladesh coast, it may travel far inland because of its extremely flat gradient, a dense network of estuaries, and the long and relatively flat continental shelf. Tsunami preparedness should be incorporated with existing disaster mitigation measures and use of current multi-purpose cyclone shelters. For those living within the danger zone, early warning systems and their acceptability is studied, again using Hawaii as a baseline.

As all estimates are based upon an uncertain induction from the past, the paper concludes by suggesting the implementation of any safety measures that can be included within current disaster mitigation practice. The most important short-term measures consist of ways to increase the lead time of the tsunami warning system, as well as the effectiveness of warnings through the training of volunteers. In the long run, surges can be effectively mitigated by a coastal green belt. Such belts are both cost-effective and environmentally sound.

Socio-Economic Effects of Tsunami on Bangladesh

The earliest recorded major tsunami that hit the shores around the Bay of Bengal originated in the Arakan Coast (Myanmar) in 1762 (ICZMP, 2005). This tsunami caused a water-level rise of 2 m in Kolkata port. Loss of lives and property because of the sudden water-level rise in the Buriganga River near Dhaka is also documented. A tsunami originated near the Car Nicobar Island in 1881 and traveled to the coasts of India and Sri Lanka. No tsunami was recorded in Myanmar. The 1883 volcanic eruption in Krakatoa, Indonesia, sent tsunami to the south-eastern coast of India and Sri Lanka. A water-level rise of 1.5 m was recorded in Chennai, India.

The 2004 (December 26) earthquake in Sumatra created one of the most devastating tsunami in history. The loss of human life caused by this tsunami is shown in Table 1. Infrastructure, fisheries, tourism, and the environment suffered major damages from the tsunami. This has led to the need to assess the socio-economic effects of a tsunami on Bangladesh. However, this is not an easy task. The infrequent occurrence of tsunami in the Indian subcontinent encourages the view that there is a definite event to assess that people can prepare for, but this is misleading. The socio-economic issues to address are ambiguous because tsunami are not identical events that keep repeating themselves. The experts carefully warn us that all tsunami should be considered as unique. Hence any reasonable answer requires that we distinguish between the different types of tsunami, their frequencies, and their probabilities of occurrence on the coast of Bangladesh.

How big of a tsunami and what kind are we preparing for? Meteors can cause *bolides* or mega tsunami, which generate waves estimated as being as large 3 miles high at impact and 300 ft. when 3,000 miles away (Dudley). If such an event were to happen, there is no preparation we can think of that would be effective, and we would have to revert to the advice of the old British India famine manuals, which told us just to accept cyclone storm surges as Acts of God and look to compassionate relief. What about tsunami caused by underwater landslides or volcanoes? These do occur and can be very destructive, but these events have not attracted attention and are among the least studied. Some idea of underwater volcanoes exist; however, no one seems to have a good grasp on potential sites for subsequent landslides.

So let us limit our attention to the recent Sumatra tsunami, which we will refer to as Aceh because its location was near Bandar Aceh. This tsunami was caused by the buckling of the earth's plates along well known geological fault lines. These are called the subduction tsunami, and their close link with the fault lines makes dealing with them a more calculable event than tsunami of other types. If an Aceh tsunami can occur just off the shores of Bangladesh at a distance similar to the one off Sumatra, then the potential damage is immense, and we have to cut funds and energy from other places to prepare for it. What is the probability of such an event? With very little definite guidance from scientists on this issue, should we really be moving money and energy away from issues directly affecting economic growth? Is it not better to plan for economic growth and then rely upon an informed and educated populace to take appropriate steps regarding tsunami?

In developing a policy decision in the current uncertainty, let us assume we are looking at an earthquake induced tsunami of the sort that occurred at Aceh, where the earth snaps back after being made to buckle by moving plates (subduction). What damage did it do in Bangladesh and surrounding areas and what measures were in place for warning and relief?

The December 26, 2004 tsunami created 5 to 6 ft. high waves in the coastal areas of Bangladesh. In addition, seiching (water-level oscillation in shallow water bodies caused by the earthquake) was reported throughout the country. Coinciding with a low tide minimized the tsunami's effects. There are also reports that the shore waterline receded by about 50 m at Saint Martin's island, and the water level fluctuated for about 3 hours (ICZMP 2005). Sudden recession and fluctuation of water level are typical signs of a tsunami. This can be expected to cause considerable damage to coastal shipping and fisheries. BIWTA water-level records show unusual fluctuation starting about 2.5 hours after the occurrence of the earthquake and continued through the day (see Figs. 1 and 2). The observed water level (peak) was about 0.4 m higher than the predicted level at Hiron Point. However, since these water levels were recorded half an hour apart, the actual peak may be missing from the records. Water levels recorded by an auto level recorder would more precisely show the peak and fluctuation. These records show only the mean level of the water surface; the local wave heights are not reflected.

The Aceh tsunami actually caused very little damage in Bangladesh, hence any talk of estimating its effect is not meaningful because it did not really hit there. In two initial surveys undertaken to provide fresh data for this paper, we found that virtually no one knew about tsunami as such and were, therefore, quite reasonably, unconcerned about them. Hence we changed the focus of the paper from assessing the socio-economic effects of an unknown event—a tsunami—to extrapolating the socio-economic effects of a tsunami by using cyclonic storm surges as a benchmark. Translating the data from cyclonic storm surges to tsunami requires a template for the probable impact of an actual tsunami. This requires having a location where tsunami occur with some regularity, but the effects are small enough to make it reasonable to apply the data to Bangladesh. Hilo in Hawaii is the only place we found simply because Hilo has been well studied, and the tsunami there have caused extensive but not overwhelming damage. New scientific studies are needed to provide us with inundation mappings so we can make more educated guesses about Bangladesh, yet the scientists contacted were reluctant to provide specifics. Section 2 provides an extrapolated account of the probable damage if an Aceh tsunami were to hit Bangladesh. Section 3 inquires into the organized measures extant in Bangladesh for dealing with natural disasters that are relevant to tsunami. Section 4 then asks how the people can be expected to respond to the tsunami by using a survey that looks specifically at awareness and preparedness with regard to cyclonic storm surges. This section concludes with tentative recommendations and some suggested open questions.

Table 12.1. Death Toll Caused by Tsunami on December 26, 2004

Country	Deaths		Injured	Missing	Displaced
	Confirmed	Estimated			
Sri Lanka	38,195	38,195	15,686	23,000+	~573,000
India	10,744	16,413	-	5,669	380,000
Myanmar	59	2,500	45	7,000	3,200
Bangladesh	2	2	-	-	-
Source: *www.jorritdiepstraten.nl/~tqtsunami*					

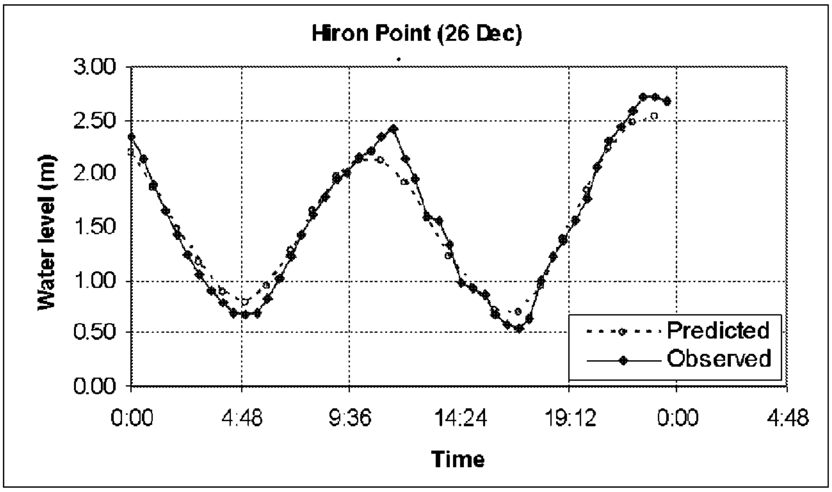

Fig. 12.1. Water-level fluctuation at Hiron Point

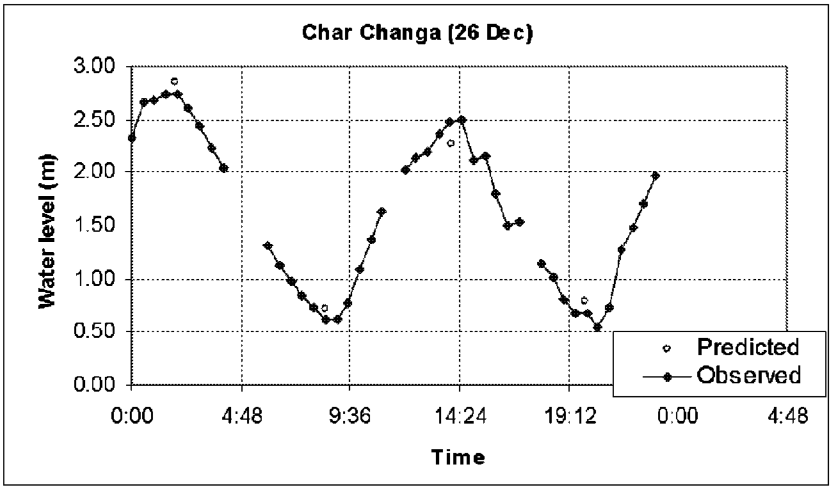

Fig.12.2. Water-level fluctuation at Char Changa

Preparedness: Focus or Fold in?

Most earthquakes do not cause tsunami because most plate movements seem to be lateral; hence, the vertical energy that causes waves is not created. Our primary reading for Bangladesh is as follows.

1. The fault lines appear to run north-south, so a subduction quake would cause waves to travel east-west directed toward Sri Lanka rather than Bangladesh.
2. Tsunami waves are vertical—due to the long shelf along Bangladesh coast, these waves would not have as much water to send ashore as they would with a deep-water coastline.
3. Shallow water waves are slower, so tsunami waves would not propagate as forcefully into Bangladesh.

This view makes the tsunami a secondary danger to Bangladesh. Because this assessment might induce complacency, we add the following caveats.

1. The estuarine nature of the southwest Bangladesh coast is the main reason to worry about an Aceh tsunami because it can cause tidal bores all along the southwest coast. These bores will enter deep inland and overflow as they spread, but this danger is perhaps balanced by the mangrove forests on the southwest coast.
2. There should be less reason to worry about the southeast Chittagong coast, (along Myanmar). How far Bangladesh is vulnerable depends upon a host of factors, such as the position of the plates, local coastal bathymetry, and such. Scholars never tire of reminding us how each earthquake can be different.
3. Computer models need quality bathymetric and topographic data sets to develop inundation maps. Inundation maps require maintenance and upgrades as better data becomes available and coastal changes occur. This is an urgent need.

More studies are needed for a better assessment of potential damage. While every scientific account of a tsunami refers to the height of the incoming waves, for economic purposes it is more significant to know how far inland the waves penetrated or the likely run-up. What do we think can happen with an Aceh nearer the coast of Bangladesh? NOAA provides a generic template for tsunami damages as follows: The material is appropriately titled: "Am I in Danger? Where Will the Water Reach?"

Tsunami waves can flood or inundate low lying coastal areas. Tsunami inundation is the horizontal, inland penetration of waves from the shoreline. Flooding can extend inland by 300 m (approximately 1,000 ft.) or more, covering large expanses of land with water and debris. Inundation distances can vary greatly along the shorelines, depending on the intensity of the tsunami waves, the undersea features, and the land topographic elevations. One coastal community may see no damaging wave activity, while another nearby community can be attacked by large and violent waves. When the tsunami reaches the coast and moves inland, the water level can rise many meters. The first wave may not be the largest in the series of waves.

Our first goal was to get expert opinion on this issue. According to Prasad Kumar Bhaskaran, Ph.D., assistant professor, Department of Ocean Engineering & Naval Architecture, Indian Institute of Technology, "In India the run-up was about 5 m and the land incursion was 1 to 2 km. The first and second crests were strong. Five crests were distinctly experienced and waves kept coming for 4 hours. The water level started rising with the first crest and remained high for quite some time. However considering the geomorphological and coastal ecosystem (due to mangroves), the run-up of tsunami affecting the Bangladesh coastline will be restricted within the near-shore belt before it makes an incursion into the land. One can expect a maximum incursion of about 1,000 meters inland."

To augment this guidance, here is a short table of information excerpted from the readable and valuable book, "Tsunami!" by Walter Dudley and Min Lee.

Table 12.1. Extent (page, location, height of waves in and extent of run-up)[1]

Location of Tsunami, Year	Height of Waves and Extent of Run-Up	Page Number
Kauai,1964	500 yd.	41
Hawaii,1868	430 yd.	57
Coconut Islands,1877	200 ft.	60
Lisbon Earthquake, 1755 at Tangier	50 ft. and 1.5 miles	64
Lituya bay, Alaska,1958	1,700 ft. to 3,600 ft.	78
Krakatau 1883, Telok Betong	30 ft. and 2 miles	86
Aletuian, 1946	30 ft. and 15 ft. a few miles apart	97
Chile, 1960	20 ft. and 1,600ft	142
Honolulu, 1960	10 ft. at the coast	144
"Large bays with gradually sloping bottoms can cause waves to build up to great heights. Furthermore the villages are mostly situated on lowlands at the head of these bays" 30' yet only coastal damage.		
Japan, Akita, 1983	400 ft. as bores	
E Java, Pancer, 1994	30 ft. and 2,500 ft.	266-7
Baudin, Australia	12 ft. and 1,000 ft.	

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[1] We are warned repeatedly about variability; "the actual inundation and flooding produced by a tsunami can vary greatly over only a short distance," p 97.

We may note that, even in the catastrophic tsunami off Chile, most damage was within .5 miles of the coast.

This evidence suggests a relatively simple, yet practical solution. If the tsunami run-up can be expected to be 1 km, then a solution is for the government to zone the land and prohibit normal habitation within 1 km of the coast. This area could be used as a green belt with playgrounds and specially prepared tourist areas—much as has been done in Hilo, Hawaii.

This conclusion is supported by past tsunami damage in Sri Lanka, which has never exceeded 400 m from the coast. In fact Sri Lanka initially passed a law prohibiting building within 200 m of the coast, but it may have to modify this due to commercial pressure.[2]

Thus, our first point is worth repeating: If tsunami are a real danger to an area, move human habitation inland or barring that move the tsunami shelters inland by 1 km.

Tsunami are principally linked with earthquakes, and the above conclusion is reinforced by considering of earthquake-induced damage. Kerry Sieh of Caltech writes via email, "In my judgment the greatest, most likely threat of tsunami damage to Bangladesh in the next few decades is rupture of the northward continuation of the megathrust that ruptured in December 2004. That active fault lies largely beneath the sea along the west coast of Myanmar. It and its continuation still farther north along the western flank of the Indo-Burman mountain range also pose a significant earthquake shaking hazard to Bangladesh. Earthquake shaking can be particularly hazardous to communities built on young sandy sediment because of the potential for shaking-induced liquefaction."[3]

The practical advice appears to be, the further we stay away from the sandy sediment of the coast, the better. Thus, rather than look specifically at tsunami preparedness, the goal should be to focus on multi-disaster awareness and preparedness. Many common sense points can be transferred from thinking about floods (APJE 2004).

If tsunami threats are real, we recommend extending zoning regulations to 1 km from the coast; however, the low probability of a destructive tsunami suggests that we incorporate measures dealing with tsunami into extant disaster measures, rather than focusing separately upon tsunami.

Current Measures in Bangladesh

In interviews several decades later, people in Chile, Hawaii, and Japan recall the tsunami triggered by a magnitude–9.5 earthquake that struck Chile in 1960. Their accounts contain lessons on tsunami survival:

- Many will survive the earthquake.
- Heed natural warnings.
- Heed official warnings.
- Expect many waves.
- Head for high ground and stay there.
- Abandon belongings.

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[2] Lareef Zubair of Columbia University provided us with the references for Sri Lanka.

[3] Prof Sieh is not an expert of the hydrodynamics of Tsunami, but he felt that the summary of tsunami danger listed at the beginning of this section may be incorrect. He referred us to two other experts, neither of whom, unfortunately, replied to our queries.

- Don't count on the roads.
- Go to an upper floor or roof of a building.
- Climb a tree.
- Climb onto something that floats.
- Expect the waves to leave debris.
- Expect quakes to lower coastal land.
- Expect company.

How much does Bangladesh need to learn from these guidelines, and what can be usefully implemented? Their preparedness for floods is high, and people are generally aware of the benefits of looking and planning ahead. The frequency of coastal cyclones (and floods) means that Bangladesh is somewhat in a permanent state of preparedness for natural disasters. However, tsunami are distinct in their impact, and it is principally these differences we need to address.

Lead Time

A cyclone usually takes 7 to 10 days from its genesis in the deep sea until its land fall on the coast. During this time, people become aware of the danger by visible change in the weather pattern. Meteorologists start to closely monitor the growth and track of the cyclone through satellites and land-based observations. Continuous warnings are given through radio, television, and volunteers. Therefore, people get enough time to prepare themselves, both physically and psychologically, for evacuation.

The lead time for tsunami is much shorter. With a cyclone people get 7 to10 days to prepare themselves; with tsunami, they get 6 hours at most. A tsunami starts with a tremor far away and the resultant waves propagate quickly. Although seismologists can sense the tremor through instruments, people are little aware of the impending danger because there are no visual weather signs. Additionally, tsunami are relatively rare in the Bangladesh coast. So people are less prepared psychologically for evacuation due to a tsunami than a storm surge.

Location of Shelter

The catchment area of a cyclone shelter (or killa) is the area people (or livestock) come from to take shelter during cyclonic storms and surges. If there are few shelters (or killas), the area may be quite extensive, but if there are several shelters (or killas) within close proximity, there may be considerable overlaps in their catchment areas.

The size and shape of a catchment area is determined by the following factors:

- the distance which most families were willing to move when winds pick up gale speed;
- the density of habitations, settlement pattern, and the number of people the shelter was designed to serve; and
- communication to the shelter.

For cyclone and associated storm surge shelters, it was estimated that people need 20 minutes of time for evacuation (MCSP 1993). Accordingly, shelters have been proposed at an average distance of 1.5 km from households. For tsunami, shelters need to be nearer because of the shorter lead time. In cases of cyclone and associated storm surge, MCSP (1993) observed that people usually move at the last moment due to a variety of reasons. These include security of household property, fatalism, inadequate facility in the shelter, unawareness of the dangers, signals received too late, incomprehensible warning signal, and inadequate transport facility. For tsunami, most of these causes will be magnified due to shorter lead time. It can be presumed that until people see the waves, they will not move. Therefore, there is a need for shelters at closer locations.

Shelter Amenities

Currently, there are 2,133 cyclone shelters covering only 30 percent of the coastal population (ICZMP 2005). The remaining population will gradually be brought under protection. This presents an opportunity to remodel the cyclone shelters so that they can also act as tsunami shelter. Because of the difference in characteristics in storm surge and tsunami waves, there is a need to reevaluate the requirements of shelter amenities. Cyclone shelters are usually aligned based on wind direction, but tsunami shelters should be aligned based on wave direction.

Tsunami shelters also require different amenities. Currently, the shelters are designed to accommodate people for 6 to12 hours, the duration of storm surge inundation. Therefore space requirement is less, only 4 sq. ft./person. For tsunami, there will be many aftershocks and people will be required to stay longer. Therefore, space requirement will be much higher. There may be a need to segregate males and females because of longer stay in case of tsunami. The requirement for other amenities such as drinking water and sanitation facilities will also be higher.

Currently there are about 21,000 volunteers working in the Cyclone Preparedness Program (CPP) of Red Crescent in the coast (CPP 2000). The volunteers are responsible for the following:

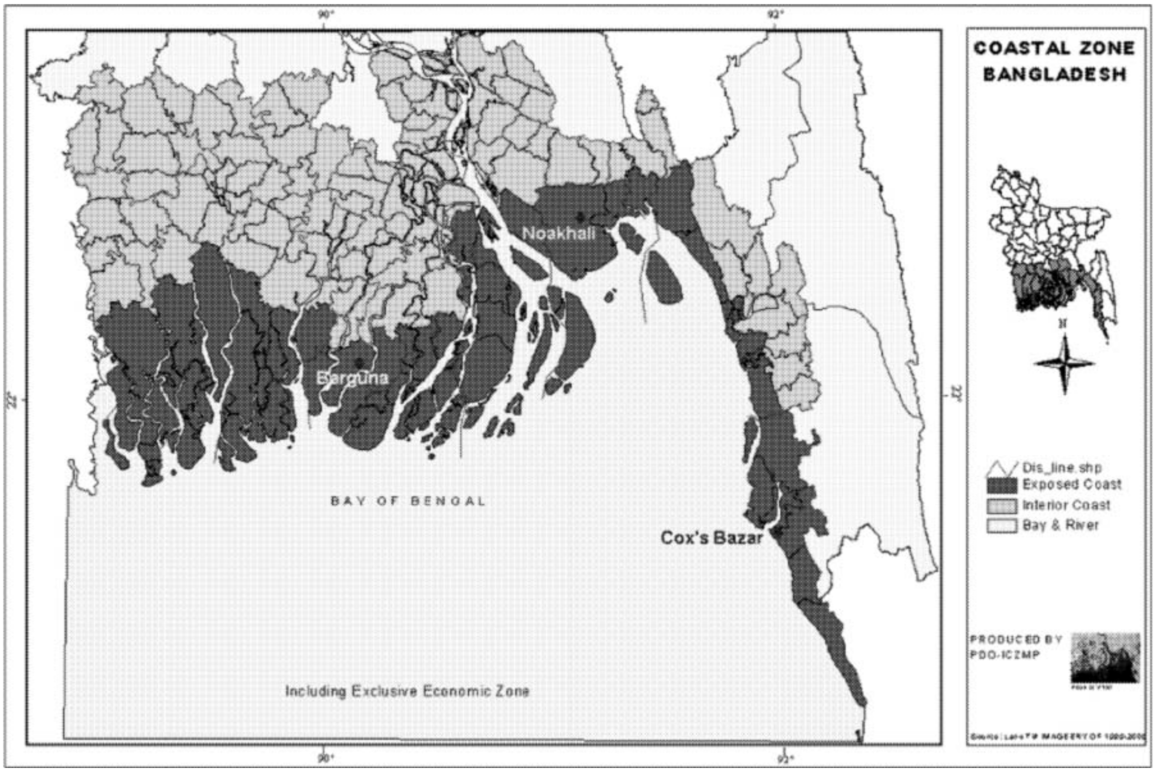
- alerting people by megaphones and mikes ('miking' is the local term);
- conducting house to house contact;
- raising the danger signal flag;
- arranging shelter for people and cattle, and security of other property;
- rescuing survivors;
- providing first aid to the wounded and post-cyclone security measures;
- distributing relief materials to the needy; and
- surveying damages caused by cyclones and reporting them to union headquarters.

The performance of the volunteers is well recognized. During the 1991 cyclone, the CPP volunteers alerted people by megaphones, hoisted great danger flags around the area, made house to house contact, evacuated people from low-lying areas, and helped people in taking shelter. They evacuated approximately 350,000 people to cyclone shelters and other safe places before the cyclone struck (MCSP 1993). During the process 23 volunteers lost their lives and 776 received serious injuries. Due to their experiences and noteworthy performance, CPP volunteers can be trained to be effectively engaged for tsunami evacuation. Tsunami evacuation are more difficult than cyclone evacuation because of shorter lead time and higher uncertainty regarding its occurrence.

People's Attitudes in Coastal Areas of Bangladesh

The coastal area of Bangladesh is vulnerable to three types of surges—cyclonic storm surges, tidal bores, and tsunami waves. The cyclonic surges are the most damaging. Tidal bores are more frequent but cause less damage. Tsunami waves are infrequent but may cause large-scale damage. The objective of this study was to learn about the socio-economic impacts of surges, more specifically the cyclonic storm surges, on the coastal population.

In this regard, a survey was conducted in three coastal sites—Patharghata of the Barguna District, Char Jabbar of Noakhali District, and Chokoria of Cox's Bazar District (Map 1). Patharghata is located in the Ganges Tidal Plain, and marine fishing is the principal livelihood. Char Jabbar is located in the Meghna Estuary Plain, and agriculture is the principal livelihood. Chokoria is located in Chittagong Coastal Plain, and shrimp farming is the predominant livelihood in this survey site.



Map 12.1. Location of survey sites

The survey was conducted through focus group discussions and key informant interviews. At each survey site, two focus groups and two key informant interviews were conducted. The issues discussed are as follows:

- awareness of cyclones/tsunami as a real threat and what level of preparedness they provide for themselves;
- their direct experience with such events—height, duration, and force of storm surge for example;
- who should accept primary responsibility for storm surges—the government or the people themselves; the appropriate role for government;
- the use and acceptance of the existing measures by the public—for example, multipurpose storm shelters;
- the extent of damage to different sectors; and
- how the population and economy have evolved since last storm surges.

About 50 percent of the coastal population, which consists mainly of island and near coast/river habitants, fishers, and large farmers, has a high level of awareness. About 30 percent of the coastal population, consisting of medium farmers, businessman, and mainland habitants, has a medium level of awareness. A low level of awareness persists among the remaining 20 percent of the population, which comprises mainly rich town dwellers and poor laborers, who have very little to lose.

It is estimated that 5 percent (Patharghata) to 20 percent (Cox's Bazar) of the population will move to a cyclone shelter in case of a storm surge. These are mostly the people living near the shelter and the local influentials. About 15 percent (Patharghata) to 50 percent (Cox's Bazar) of the population, primarily poor people with relatively less property, will move to a distant safe place. About 20 percent of the population in Patharghata, again poor people with relatively less property, expressed their intention of moving to a relative's place at a safer distance. About 20 percent (Cox's bazaar) to 60 percent (Patharghata) of the population, those who have relatively more property, report they will stay in their own house or take shelter in trees.

In the fisheries sector, loss of lives from boats capsizing during a surge is a major problem. Additionally, trawler/nets are damaged. Fish cultivators lose almost all their fish, which escape with the surge. Additionally, for next couple of years, they are not able to restart fish cultivation due to the damage to the fish ponds.

In the agriculture sector, damage to standing crops is total. Land loses fertility due to saline intrusion, and good harvests are not possible for next 2 to 3 years.

In infrastructure sector, houses are damaged, and it takes 2 to 3 years to rebuild. Sea dykes are also extensively damaged.

In the tourism sector, tourists do not return for 3 to 4 months after the surge. Hotels are physically damaged, and theft/hijacking and such rises because of the difficulties faced by the local population. As a result, there is a further drop in tourism.

Respondents consider the followings as the main government responsibilities:.
- distributing food, medicine, clothing, and other relief items;
- shifting marooned people from shelters, trees, and such to safer places; and
- strengthening the program of warning people through radio.

The responsibility of the public is to follow government guidelines. Those who have some property often try to stay in their homes even after receiving a signal to evacuate and seek shelter. They should leave their homes and shift to a safer place. Mosque Imams and other local elites should motivate local people to move to safety.

The role of the government after the storm surge should be distributing relief material:
- assistance for home building;
- credit for power tiller/livestock, etc.;
- credit without interest for seed, fertilizer, pesticide, etc.;
- loans for fishermen to buy trawler/nets, etc. ;
- water purifying tablets; and
- mobile health clinics.

In the past, the government has taken many steps, which include:

- providing dry food, clothing;
- building cyclone shelters/killas;
- broadcasting warnings via radio;
- constructing sea dykes;
- miking through Red Crescent; and
- afforestation.

The public has taken the following steps:

- Wealthy people have constructed concrete buildings after the 1991 cyclone.
- People have purchased radios to listen to the warnings.
- The wealthy have arranged miking of the warning signal.

There have been many changes in social and economic structure of the coastal zone since the last major surge in 1991. The population has increased, but the growth rate has declined. It appears that people have become more financially solvent due to the following factors:

- In the past there was only one crop, aman. Now the local population also plants boro and rabi.
- They have implemented better agronomic practices and now use HYV seeds.
- The number of fishermen has increased, and their income is higher.
- Business has improved through boat/trawler communication.

There have been significant infrastructure developments in the coastal zone. Developments in road communication have made the vulnerable population safer along with improvements in telephone and electrical connections. Education has improved through increases in educational institutions.

The level of preparedness for next surge, however, lacks socio-economic development. There are not enough cyclone shelters, and sea dykes will protect only up to a 5 to 6 ft. surge height. Fishermen get radio warnings when at deep sea but frequently get lost on the way back because there are too few light houses.

Summary

In coastal areas, the population has increased even as the economy has diversified and expanded. As a result, vulnerability to both lives and property has increased. The following are needed to reduce the vulnerability of the coastal population from storm surges:

- more cyclone shelters;
- stronger and higher sea dykes;
- more roads and bridges;
- additional light houses;
- mobile communication between trawler and coast; and
- more land under afforestation to reduce the impact of surge.

Our survey clearly shows that people who live in risky environments adapt their lifestyles. There is already considerable achievement in this regard. Tsunami may occur, but instead of a separate warning and preparedness program, it is most effective to adopt a multi-hazard approach, recognizing the similarities of many sensible human responses to natural disasters.

Conclusion and Recommendations

In economic terms, we can summarize the socio-economic impact of disasters as follows. If the country was growing before the disaster, it will continue to do so after the disaster. If the country was not growing before the disaster, it will not do so afterwards. In short, natural disasters reveal the preparedness and spirit of a people. From the cyclone warning systems, cyclone shelters, and especially the model volunteer program, it seems that Bangladesh has a satisfactory initial level of preparedness. Cyclone shelters, which have been long used in the coastal areas of Bangladesh, can become the primary policy to save lives from impending tsunami. This can be linked with more scientific studies, the afforestaion of the coastal belt, and placing zoning limits on building near the coast to form the primary long-term policy measures for hazard mitigation and to support economic growth.

The main caveat to the view that disasters can be overcome by prepared populations lies in the possibility of nonlinear effects (Hallegate 2000). Hallegate notes, "The production losses caused by extreme events depend, with strong non-linearity, both on the changes in the extreme distribution and on the ability to fund the rehabilitation after each disaster." Thus, to spell out what non-linear means in economic terms, since we do not allow people to function with negative net wealth, the threat of bankruptcy changes everything. In human terms, it means that starvation and death are irreversible events. The policy imperative then is to ensure that there is preparedness to avoid catastrophe and the means to provide immediate relief. As we saw earlier, Bangladesh is perhaps in the forefront of countries with both its cyclone shelters and its volunteer program. Because zoning restrictions on coastal development would hurt tourism and be strongly resisted, it is worth speculating on alternative ways to retain disaster preparedness with economic promise.

Two curious facts arise from reports of earlier tsunami disasters. First, the earthquake of Lisbon wiped out the stately stone cathedrals but left many wooden bordellos standing. Secondly, in Hilo in 1945, one of the few structures unaffected on the beach was a wooden hotel. These events suggest that native materials—wood and bamboo—appropriately fashioned and structured—may be able to withstand earthquake and water surges even close to the coast. Such a possibility deserves scientific investigation, especially because in Bangladesh women who did not want to mix with the men have sheltered in wooden homes—and survived.[4]

Secondly, we note how the cyclone shelters have functioned effectively as shelters, but also that they have limited promise because even though they are community shelters, there are no communities around them. As a result, maintenance is an ongoing problem. The solution is perhaps to build larger urban conglomerations about 1 to 2 km inland, which will simultaneously provide urban space, markets, community, and shelter.

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[4] EBF, the Environmental Bamboo Foundation, based in Nyuh Kuning, Bali, was founded in 1993 with the mission of protecting tropical forests in Indonesia by promoting conservation and demonstrating the sustainable utilization of bamboo and its various economic and environmental benefits. In the wake of the destruction caused by the tsunami, EBF is working to advance the use of bamboo for reconstruction efforts. As a part of its efforts, EBF is organizing a workshop on earthquake resistant bamboo construction. EBF's project represents a long-term response to the devastating tsunami by concentrating on the preparedness of coastal. Information kindly provided by Dr Bhaskaran.

Acknowledgements

Special thanks are due to Prof. Walter Dudley of Hawaii for his constant advice and access to latest information.

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Chapter 13: Twenty-Five Years of Caribbean Hurricane Disaster Mitigation

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Abstract

The damage to buildings and infrastructure during the 2004 (Hurricane Ivan) and 2005 (Hurricane Wilma) hurricane seasons has highlighted the vulnerability of the populations and socioeconomic fabric of the Caribbean. Annual damage losses continue to accrue despite existing mitigation strategies and lessons learned from post-disaster assessments. The questions now facing Caribbean states are which of these strategies have succeeded and how can the results be applied to benefit other regions susceptible to the hurricane damage.

This paper explores these disaster mitigation issues in further detail by reviewing major efforts implemented by scientists, researchers, and planners in the Caribbean region during the past 25 years. The objectives and outcomes of previous mitigation studies are examined to identify the components of successful strategies. The failures of past approaches are also identified and a methodology is proposed for identifying future research needs and initiatives that will have the greatest impact and chance of minimizing future losses.

Current needs include practical solutions and investigations to identify and correct systemic weaknesses in existing infrastructure as well as strengthen the institutions that oversee them. In addition, approaches to establish public policy based on the latest scientific and engineering research and integrate communications technologies into Caribbean disaster management and public policy and planning are especially needed. Other recommended improvements are research studies similar to those conducted in the United States that examine ground-level wind speed monitoring and provide full-scale measurements of wind loads on residential structures. This paper proposes a research program of field-instrumented houses and installed wind anemometer towers to monitor and collect data on wind load and wind velocities during storms.

Introduction

The Caribbean region is susceptible to the onslaught of devastating hurricanes: More than 2,000 storms have passed through the region in the last 100 years. Extreme winds, storm surge, inland flooding, and landslides result in major damage to existing infrastructure. Significant loss of life and property damage has occurred during the past quarter century, prompting island governments and regional and international agencies to respond with disaster mitigation plans and fundamental research. Despite these efforts, Caribbean societies and infrastructure remain highly vulnerable to the hurricane hazards of storm surge, wind damage, and landslides.

From the decades of the 1930s through the 1980s, hurricane frequency in the Lesser Antilles, which includes the islands stretching from Trinidad to the south and including all islands southeast of Puerto Rico, fell by 66 percent (Reading 1990). Consequently, an entire generation has grown up without personally experiencing major hurricanes on an annual basis. This may account for the hesitant adoption of designing hurricane-resistant buildings. However, since 1991, there has been an alarming rise in both hurricane strength and frequency. Improved forecasting has reduced the loss of life from hurricanes, but the potential for catastrophic damage still exists.

The limited extent of hurricane-damage research in the Caribbean states has reduced the potential benefits of post-disaster surveys for those island nations. While the spatial extent, nature, and underlying causes of the damage is often documented in post-disaster reconnaissance exercises, an in-depth engineering analysis has not been conducted to determine the causes of structural failure in buildings. Disseminating this information would improve housing construction practices before the next major event. Therefore, the primary objectives of this paper are as follows: (1) to catalog major hurricane research and mitigation efforts undertaken during the past 25 years, (2) to document successful research or mitigation projects, and (3) to identify areas where additional research is still needed. Because there has not yet been a systematic attempt to compile hurricane data and results for the entire Caribbean region, this paper will focus on data available for individual Caribbean countries for which prior mitigation research has been performed. This will be used to identify trends that can be beneficial to these island communities. Recommendations are also provided for improving the dissemination of research and for concrete efforts to increase our understanding of wind-induced building failures.

The Caribbean Region

The Caribbean islands form a sub-regional grouping of 25 countries along the eastern edge of the Caribbean basin extending from the Bahamas to Trinidad, which is located 7 miles off the coast of Venezuela. Hurricanes are likely to occur during the North Atlantic tropical cyclone season from June 1 through November 30. At the time of this writing, the 2006 season is not expected to be as ferocious as recent seasons, still it is estimated that 17 named storms will form in the Atlantic basin, (Klotzbach et al. 2005), and nine of these may strengthen into hurricanes.

For a number of historical, political, and socioeconomic reasons, many of the state capitals and densely populated urban areas in the Caribbean are located on low-lying coastal areas or along exposed hillsides, which are subject to greater hurricane risks. Coastal examples include Port-of-Spain, Trinidad, (Fig. 13.1) and Bridgetown, Barbados, while hilly areas such as Petit Martinique in the Grenadines are prone to the acceleration of upslope winds. Low-lying regions such as St. Georges, Grenada, and the Seven Mile Beach area of Grand Cayman Island have been damaged by flooding from storm surges. Hillside regions such as those in the Grenadines also suffer from landslides and topographic acceleration of upsloping winds.

Caribbean Building Performance in Hurricanes

Recent post-hurricane studies reveal that buildings and infrastructure in the Caribbean remain extremely susceptible to hurricane damage. The damage sustained from the 2004 and 2005 hurricane seasons in the Caribbean was extensive, affecting many islands. For example, an 8-ft. storm surge hitting the Grand Cayman Islands' commercial district destroyed about 15 percent of the island's structures, while another 20 percent suffered major structural damage. As a result, the local tourism industry was severely disrupted for many months (Frederick 2004).

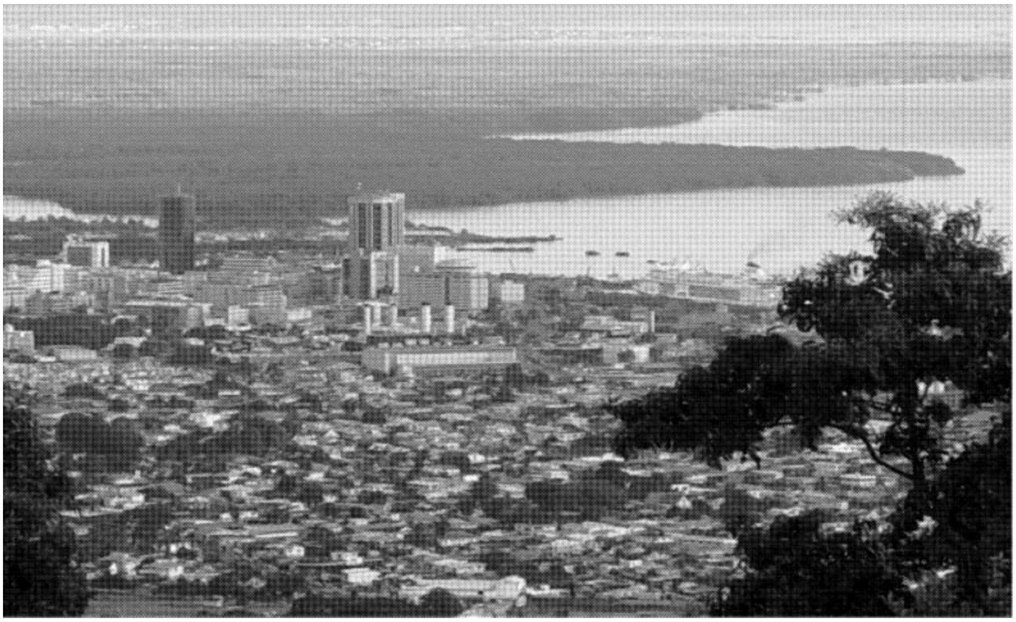

Fig. 13.1. Port-of-Spain, Trinidad (Photo Credit: David Prevatt)

In Jamaica, the heavy rains, strong winds, and storm surge damage from the 2004 Hurricane Ivan caused a loss of 8 percent of the gross domestic product (Mortley 2004). In Grenada, damage estimates from this storm indicate that approximately 80 percent of residential structures and numerous health facilities were damaged (Gibbs 2004). A year later Hurricane Emily tore the roof off of a newly constructed hospital and destroyed the recently rebuilt roof of the only hospital on the neighboring island of Cariacou (Bascombe 2005).

The impact on buildings is not limited to their outright destruction. When the Bahamas was struck by three consecutive hurricanes in 2004 (Frances, Ivan, and Jeanne), most buildings retained their structural integrity. Nonetheless, the triple impact of these storms damaged the building envelope components of most structures (roof coverings, windows, and wall cladding) (Dean 2004), with a loss of approximately US$230 million to that nation's economy in the form of destroyed infrastructure and repair costs.

Caribbean islanders do not typically have the option to evacuate or flee inland from a hurricane. Therefore, access to adequate shelters is critical. The damage to 96 percent of the schools on Grenada by Hurricane Ivan illustrates that, in regions where building codes are not enforced, schools are equally vulnerable to damage as other buildings. A notable contrast was observed in Grand Cayman where, due to the strict enforcement of building codes, only 69 percent of schools sustained damage. These results clearly indicate that adopting and enforcing building codes saves lives and reduces hurricane damage and its adverse economic impact. Unfortunately, these construction deficiencies are long standing.

The pattern of damage throughout the islands reveals an interesting trend. Housing construction in southerly islands, such as Grenada, that experienced infrequent hurricanes recently performed far worse than those with more recent hurricane experience. Conversely, islands experiencing frequent hurricanes had incorporated improved engineering design into their construction codes, which resulted in markedly less structural damage compared with similar structures in Grenada. In addition to this experiential advantage (see next section for more detail), the northerly and central islands of the Bahamas and the Cayman Islands adopted more building codes (Metropolitan Dade County 1997, SBCCI 1997), including the hurricane-resistant design requirements established for the U.S. construction market. A major benefit of these new standards was that most structures in the Bahamas and the Caymans were subject to mandatory inspections during the construction phase, thus increasing building code compliance. However, the Southern Building Code International (SBCCI) provisions reflect construction practices that are substantially different from traditional practices in the Caribbean. As such, these codes must be modified to be integrated successfully in the Caribbean construction industry.

Relationship Between Construction Practice and Hurricane Recurrence

In the past, researchers have documented the vulnerability of Caribbean infrastructure and housing in post-hurricane damage surveys (Chin 1989, Gibbs 1996a, Godoy et al. 1996, and Berlianu and Barnaud 1990). The relationship between the structural vulnerability of buildings and the frequency of hurricanes was demonstrated by Prevatt (1994). That paper documented results of a 1992 survey of housing construction, which showed a direct relationship between construction traditions and the frequency of hurricane exposure. Islands with higher exposure showed a greater awareness of expected forces and better construction practices, which in turn resulted in less damage during hurricane landfall. The survey also determined that inadequate construction methods were fully integrated into the existing housing stock and that most of the roofing systems were constructed without structural diaphragms or waterproofing underlayments in the houses surveyed. This state of construction is still present today.

For example, the last major hurricane landfalling in Grenada was Hurricane Flora in 1963. With the exception of Hurricane Ivan in 2004, only 14 Category 2 or less storms have passed within 50 km of Grenada since 1886 (Gibbs 1996b). Low exposure to extremely high wind events, coupled with the lack of institutional enforcement, has resulted in a very relaxed approach to structural integrity in Grenadian building designs. This translated to the substantial damage observed during the 2004 and 2005 hurricane seasons as compared with other islands to the north (Fig. 13.2).

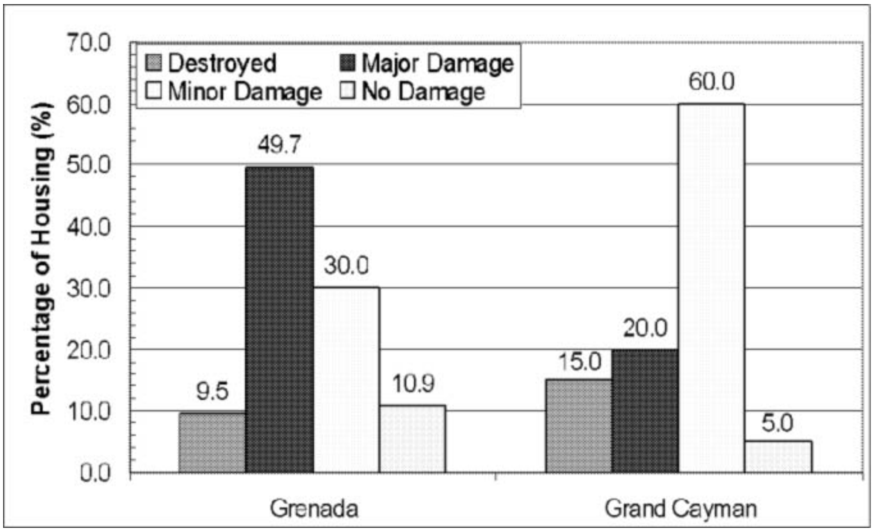

Fig. 13.2. Comparison of hurricane damage to Grenada and the Grand Caymans during Hurricane Ivan 2004

It should be noted that for most of the 20th century hurricanes formed and tracked across the northernmost part of the development region in the North Atlantic Ocean affected the islands of the eastern Caribbean and Greater Antilles. As a new era of increased activity began in the late 1990s, this pattern changed. While the active 2001 season was notable for two southerly hurricanes and extension of the season into December, the 2004 season highlighted Caribbean housing vulnerability in a new way. Tropical storm Bonnie and Hurricanes Charley, Frances, and Ivan spawned under very warm sea surface temperatures, low wind shear, and strong high pressure ridging over eastern North America that prevented their recurvature.

Research on Caribbean Hurricane-Resistant Construction (with Special Reference to Low-Income Housing)

In 1979 the Building Research Establishment (a U.K. government development research institution) initiated one of the first studies on hurricane-resistant residential construction in the Caribbean (Eaton 1980). Located on the island of St. Vincent, this project facilitated the construction of model low-income houses that incorporated engineering principles and applied hurricane-resistant connections using simple, economical techniques for hurricane resistance. It emphasized improving the connections between structural members and utilizing indigenous construction techniques.

A second construction improvement program was conducted by the Construction Resources Development Centre (CRDC) in Jamaica in 1988 (McLeod 2001). After Hurricane Gilbert damaged large swaths of the housing stock, the Jamaican government implemented an emergency hurricane mitigation program focusing on retrofitting roofs. It was found that, despite the poor performance of the roofs during the storm, most of the subsequent repairs still lacked hurricane-resistant connections. To address this problem, the CRDC with United States Agency for International Development (USAID) funds implemented a project to inspect damaged roofs and provide training to carpenters to retrofit existing roof structures. In three years, the CRDC helped 1,500 homeowners strengthen their roofs with hurricane-resistant construction.

In the early 1990s, researchers at the University of the West Indies in St. Augustine, Trinidad, researched the mitigation of hurricane damage. Many civil engineering faculty there studied hurricane effects on housing under the auspices of the Cyclone-Resistant Housing (Caribbean) Project, initiated through the International Development and Research Corporation (Canada) (Osborne et al. 1992). The researchers found that the homes of low-income people suffered most from hurricanes because their traditional low-cost houses lacked appropriate construction methods to resist the wind forces. While post-disaster studies have provided general solutions to mitigate the damage, specific solutions suitable for self-help and affordable construction using sustainable construction methods are still not widely available. Wind-tunnel testing at the University of Waterloo was conducted on six common house shapes to determine wind loads. The study found that the major construction weakness was a lack of structural ties between members that result in brittle failures at relatively low wind speeds.

A structural assessment survey of low-income housing conducted on seven islands identified four common roof types (gable, hip, monoslope, and double-lean-to) (Prevatt 1994). Most of these had low-pitched roof slopes (less than 3 in 12) with large eaves, typically ranging from 0.6 m to 1.2 m. Furthermore, structural calculations revealed that most of the structural systems used in the houses were under-designed for the design wind uplift forces characteristic of hurricane-strength events. Unfortunately, these four roof designs were the most susceptible to wind damage, due to their inherent shapes and lack of structural ties to the building walls.

The roof geometries make these Caribbean houses susceptible to wind damage because high pressure areas are created at the double-lean-to roof and along the edges. Moreover, wind design data may not be applicable to some of these houses because previous wind tunnel tests did not consider their unique shapes to determine wind load. Another factor that contributes to their vulnerability is the large eaves and roof overhangs used, even at the ridgeline of the double lean-to house (Figure 13.3). These eaves can span as much as 1.2 m (4 ft.).

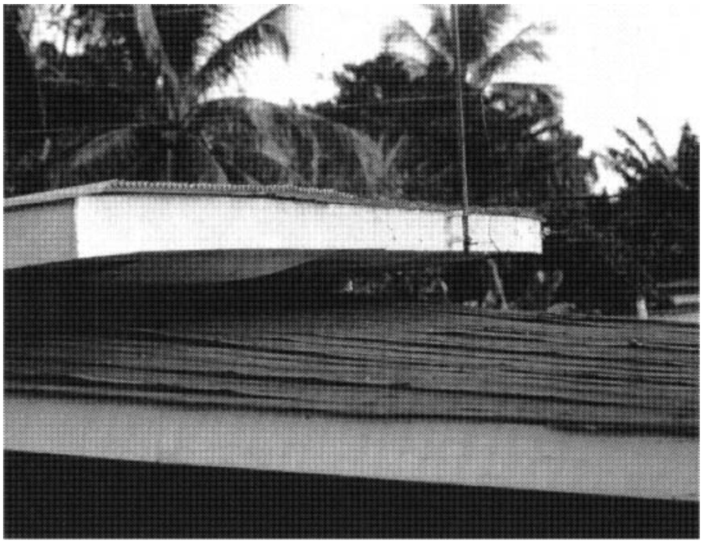

Figure 13.3. Example of a 1.2 m wide cantilever eave beyond the ridge line of a double-lean-to roof, Trinidad.

Compounding these deficiencies is the location of many typical low-income Caribbean neighborhoods along elevated and exposed hillsides that are both susceptible to funneling and acceleration of upsloping winds as well as landslides during heavy rainfall.

Caribbean Disaster Mitigation Planning and Implementation

One successful disaster mitigation project in the Caribbean has been the Caribbean Disaster Mitigation Project (CDMP). The CDMP was a six-year project (1993–1998) funded through the Organization of American States (OAS) and a US$5 million grant from USAID, (Ford and Vermeiren 1996), which made significant progress in disaster mitigation in the Caribbean. The CDMP now provides a well documented database of online information through its Web site, which serves as a repository of disaster mitigation information for the region (*www.oas.org/cdmp*).

The main organization currently directing the implementation of research and collaborations for hurricane research is the Caribbean Disaster Emergency Response Agency (CDERA). CDERA, a Caribbean Community (CARICOM) agency, has provided the leadership and clearinghouse for international cooperation on disaster mitigation. Such information is provided by the Caribbean Hazard Mitigation Capacity Building Program (CHAMP) (see *www.cdera.org/projects/champ*).

The urgency now is to continue developing and disseminating reliable research data on hurricane retrofit of housing and to improve the information disseminated to eliminate the propagation of anecdotal opinion as fact. The goal is to use research results and engineering analysis as the basis for shaping policy in the region. Research and collaboration within Caribbean educational institutions will no doubt strengthen the benefits of hurricane-resistant construction knowledge at present.

Linguistic and cultural barriers continue to hamper an efficient exchange of information. For example, although extensive hurricane research has been conducted by the University of Puerto Rico at Mayaguez (Genock et al. 2002, Godoy et al. 1996), the dissemination of these findings has be limited by linguistic and networking challenges.

Discussion

This paper highlights the research and knowledge gaps present in mitigating housing structural damage by hurricanes in the Caribbean. It reveals an urgent need to improve scientific and engineering research in support of policy changes and planning objectives in the Caribbean region. One approach advocated here is the information and communications technology (ICT) program (Richards 2004). This framework—parts of which are being implemented—identified areas of need, including enhanced information access, improved national and regional ICT infrastructures, approaches to make ICT more effective in disaster management, disaster mitigation, and post-reconstruction. A unique theme of this proposal is the implementation of scientific research and training within the Caribbean to improve regional decision-making.

The Caribbean Constellation Project Proposal

A complement to the ICT is a second proposed framework, which calls for an increase in research collaborations and technical exchanges among U.S. and Caribbean researchers. The United Sates has a longer history of research on wind engineering and hurricane mitigation than the Caribbean region. In particular, U.S. universities are currently involved in studies on the fundamental interactions of wind with residential structures (Gurley et al. 2005, Liu et al. 2005). Near real-time wind speed data is provided through its Web site *(http://users.ce.ufl.edu/~fcmp)*, and in addition, the research collects data on wind loads needed for future analysis. This project benefits the Caribbean because the threat of catastrophic damage to buildings is ever present. Research is needed to overcome the institutional inertia to adopt mitigative strategies and reduce damage. Wind load studies on unique building shapes and hillside wind speedup is recommended.

Recommendations

Although the overall impact of disaster mitigation effort in the Caribbean may appear incomplete, the region has made comprehensive strides to address the seasonal hurricane threat confronting it, especially through basin-wide agencies such as the CDMP and CDERA. It is important to distinguish between the benefits of engineering interventions (such as improvements to building codes), which are still lacking in places, versus policy interventions aimed at improving the overall regional planning and infrastructure support. While engineering interventions are likely to have a more immediate impact on repaired or retrofitted structures, it often takes decades to fully realize the full positive impact of policy interventions.

What seems to be missing is a collaborative approach and support for fundamental research to better understand the wind-structure interaction and to improve the implementation of this knowledge. Because of the very limited implementation and enforcement of building codes around the Caribbean to mitigate hurricane damage, these societies remain dangerously vulnerable to hurricanes despite recent efforts. Policy changes are needed in addition to engineering improvements to effect lasting changes in construction. In addition, fundamental research is needed to support policy-making decisions with real data from the region. Linguistic challenges, cultural barriers, and the lack of national resources all serve to hinder a coordinated effort to address the potential annual exposure to hurricane impacts. Conducting research at universities and education can result in lasting and widespread construction improvements.

Researchers and Caribbean engineering professionals must increase collaboration to create a knowledge base for uniform construction guidelines to reduce hurricane damage. Examining current practices will provide a clearer understanding of where inherent weaknesses lie and where improvement is needed. A proposal to incorporate the U.S. model for collaborative research among Caribbean universities is also suggested. This project would include data collection of meteorological data from future hurricanes and measuring wind loads and structural capacities of Caribbean houses. In addition research is needed to better integrate communications technologies into disaster management, as proposed by the international community. The introduction of the ICT network to the region will have many beneficial features for the global Caribbean disaster mitigation scheme.

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