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The Protective Role of Natural and Engineered Defence Systems in Coastal Hazards

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Literature Review Report
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Executive Summary

This report reviews the role of vegetation and engineered defenses for protecting people against tsunamis, hurricanes, cyclones and typhoons.

A review of coastal vegetation for protecting human communities from tsunami forces and storm surges associated with hurricanes, cyclones and typhoons was conducted. For both types of hazards, tsunamis and storm surges, it was found that few quantitative field based studies have been conducted on the role of vegetation in protecting human communities from these events and many of these quantitative studies have come to conflicting conclusions. However, most of the theoretical studies found a clear role for vegetation, particularly mangroves, for buffering wave forces. Many biological and physical factors interact to influence the protective capacity of vegetation against such events, which makes the role of vegetation in isolation of other factors difficult to measure *in situ*, and also makes it difficult to compare across field based studies. It is clear from these studies that it is important to consider the ecological, geological, topographical and social context of a site in relation to its potential hazards to better understand the protective potential of vegetation in a specific area. Although, there is not a universal consensus on the role of vegetation for protecting human communities from tsunamis or storm surges, it is clear that coastal vegetation provides coastal communities with critical ecosystem services that may enhance their resilience to extreme events in the long-term.

The review of the role of coastal vegetation, including a review of sand dunes upon which much coastal vegetation grows, for protecting human communities from tsunami wave(s) focused on the quantitative studies that have been undertaken to assess the effectiveness of these natural defenses. The majority of this work has focused on mangroves. Due to the many interacting physical and biological factors that might influence the ability of a vegetation community to protect inland communities from the waves in combination with different methods and analytical techniques used to assess the tsunami buffering capacity of vegetation, many studies did not agree in their conclusions on the role of vegetation for protecting people from tsunamis. However, in the studies that did conclude that vegetation plays an important role in protecting humans from these events, it was shown that the ability of coastal vegetation, namely woody vegetation, to protect human communities from tsunamis depends upon the species, the stem diameter and the stem density. Ecological degradation, which may affect these attributes, can weaken the protective capacity of a vegetation community against tsunamis. Despite the lack of quantitative data on the role of coastal vegetation in mitigating against tsunami waves, there is considerable observational evidence supporting the importance of coastal vegetation, especially mangroves, in mitigating against tsunamis.

A review of the role of coastal vegetation in protecting against storm surges resulting from cyclones, hurricanes and typhoons was also conducted. Similar to the results found from the review on the role of mangroves and other coastal vegetation types for preventing against tsunamis, this review revealed a paucity of quantitative studies that

directly assessed the role of vegetation for protecting people against these coastal hazards, although, considerable work has been conducted on the ecological response to these hazards in isolation of the impacts on people. The studies reviewed showed that mangroves and native sand dune vegetation are consistently effective for mitigating against storm surges associated with coastal storms. Furthermore, the theoretical work done on coastal vegetation in relation to storm surges resulting from these hazards supports the considerable amount of anecdotal and observational data on the ability of coastal vegetation to mitigate against storm surges resulting from hurricanes, cyclones and typhoons.

In addition to the literature reviewed on the protective role of coastal vegetation, a review was conducted on the protective role and performance of coastal structures in reducing damage from coastal areas from tsunamis and storm surges resulting from cyclones, hurricanes and typhoons. Coastal protection is an applied discipline that is mainly conducted by coastal engineers, but which receives background support in the geological, oceanographic and to some degree even social sciences. The literature dealing with the design, performance, selection and effects of coastal protection works spans a vast disciplinary area where a lot of work has been done and much information is available. To focus the literature review only the performance of only those structural measures used to protect both human lives and assets from tsunamis, cyclones, hurricanes and storms surges are reviewed and in general structures used for coastal stabilization and erosion control were not included in the review, unless they also have a direct role in protecting human lives and assets against coastal areas.

The literature dealing with the role and performance of engineered structures in storm surges resulting from cyclones, hurricanes and typhoons was reviewed. Long-term studies of water-front structures evaluating their performance in coastal storms surges have shown that concrete seawalls are the most durable protection structure against various types of storm surges. Although their initial costs are relatively high, if they are well designed, their maintenance cost may be relatively low. Seawalls may often be used together with some system of beach control such as groins and beach nourishment because of their potential vulnerability to scour at toe. Seawalls are known for overtopping under storm conditions with high tides, large waves and an onshore winds where the largest waves hit the recurved concrete wall and send water and debris upward, filling streets and damaging houses behind the wall. Seawalls and jetties have also been criticized for inhibiting normal coastal processes, however, other studies have shown that local patterns of beach response and nourishment in storm surges are not very different when comparing seawalled beach sections with natural beaches.

In addition to seawalls, breakwater structures are commonly used to protect coastal areas by reducing hurricane, cyclone and typhoon storm surge heights. Breakwaters and shoreline structures require only moderate rock armour and low crest elevations in moderate wave climates. However, to cater for hurricane or cyclonic conditions and to prevent overtopping, artificial concrete units and substantially higher crest levels are required. Groins are thought to be inadequate as first line of defence against strong hurricanes, cyclones or typhoons, but coupled with seawalls, they may be considered protective on beach and property(Miller 1927). Nevertheless, groins are commonly used for beach protection with some desirable as well as unwanted effects. A combination of different natural and engineered protection systems might be the best alternative in some locations against hurricane, cyclone and typhoon storm surges. Integrated approaches to storm surge protection problems have included solutions such as the combination of seawalls with raising and widening the existing natural dune system. Another integrated systems solutions, applied to a typical coastal scenario of diminishing marshlands protected by shrinking barrier islands, can be strengthening barrier islands using vast quantities of sediment to reduce dangerous storm surge heights.

In the case of tsunami protection, seawalls are the most conventional engineered countermeasure and are used in many places around the world. Seawalls have demonstrated their usefulness even in cases where they were overtopped or had small (1-meter high) heights, as they effectively slow the wave and deflect its momentum, allowing in some cases structures behind them to survive. Reduction of tsunami height can also be achieved by means of offshore breakwaters which provide a solution for the protection of port areas from tsunami attacks. Breakwaters might be a preferable option to seawalls as a tsunami protection work in some instances. Seawalls hinder future development as they block access and separate port from city and the assets of the bay can not be protected sufficiently by seawalls in case of a great tsunami, and breakwaters are a more appropriate solution in these cases. The shape of the bay may also make breakwaters the only feasible option. For bays that are narrow and long, it would be necessary to construct long seawalls as tsunami protection works which would result in prohibitively high costs. A combination of engineered and natural defence systems maybe also be used in tandem to provide protection against tsunamis. Thus, non-structural measures, such as risk awareness and education, evacuation drills and preparation in combination with natural coastal protection can help prevent the loss of human lives.

Coastal protection works and procedures may affect the quality of daily life (inconvenience/ convenience), and efficiency of use of the waterfront. They also involve tradeoffs, and adjustments. They have risks and may be too costly. Some degree of risk that may be acceptable has to be decided on based on exposure to each coastal hazards and the capacities available for risk reduction. An integrated approach to coastal protection must consider social and economic tradeoffs as well as the relation between the effects of coastal structures on wave climate, beach morphology, and coastal ecology. Engineered defence systems, have morphological, ecological and socio-economic components, and the greater these relations are understood, the greater the coastal system's adaptive capacity to perturbations. Enhancing coastal resilience is increasingly viewed as a cost-effective way to prepare for uncertain future changes while maintaining opportunities for coastal development. A review of the literature related to the environmental and socio-economic impacts of coastal structures and the complex interaction among the coastal defence structures, the biological system and society is presented in this report.

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Chapter 1: Introduction

This report provides a broad literature review of historic and empirical evidence for a protective role of vegetation as a natural defence system against coastal hazards, here defined as tsunamis, hurricanes/cyclones/typhoons and storm surges. The background literature on various type of engineered defence systems designed to protect the coast against coastal hazards and their performance in historical cases are also reviewed. This report focuses on a review of the storm surge effects of hurricanes, cyclones and typhoons, rather than the wind effects.

When making decisions about selecting the most appropriate defence system or evaluating its performance during a coastal hazard, the dynamics and physical characteristics for each hazard type must be considered. The base physical processes governing tsunami, tropical cyclones (hurricanes and typhoons and storm surges are very different, as are the manifestation and the relative importance of each coastal hazard type. Whereas ordinary storm waves or swells break and dissipate most of their energy in a surf zone, tsunamis break at shore. Hence, they lose little energy as they approach a coast and can run up to heights an order of magnitude greater than storm waves (2001). Storm surges are commonly associated with tropical cyclones (hurricanes, typhoons), but are also associated with other severe storms, such as "northeasters" on the Atlantic coast of the USA, or storms with "hurricane strength winds" in the North Sea. Storm surges are not high on the Pacific Coast of the USA, owing to the relatively narrow or in some places non-existent continental shelf, which results in minimal attenuation of deep-water wave energy. "Wave set-up" or the increase in mean sea level caused by the "piling up" of water on the coastline by wind, is more important, and is often confused with storm surge (Wiegel 2007).

There are also significant differences in physical conditions between tsunami and other floods. For a typical tsunami, the flood water surface fluctuates near the shore with amplitude of several meters during a period of a few to tens of minutes. This timescale is intermediate between the hours to days typical of riverine floods, and the tens of seconds or less associated with cyclic loading of storm waves. This intermediate timescale makes tsunami behaviours and characteristics quite distinct from other coastal hazards(National Tsunami Hazard Mitigation Program March 2001). In comparison to a flooding that can be caused by a hurricane, tsunami inundation fluctuates faster, hence there is a higher potential to cause greater buoyant forces to be exerted on buildings. Unless, of course, as in the case of the floods in the aftermath of hurricane Katrina in New Orleans, breach of the levee results into hydrodynamic, surge and impact forces (Griffis 2007).

In addition to considering different physical processes behind each coastal hazard, the level of exposure along the coastal stretch for each hazard must be determined before a suitable defence system can be implemented or evaluated. The science behind modelling the hazard associated with tsunami, storm surges and hurricanes is not the focus of this literature review. However, in reviewing the role of engineered and natural defence systems, it is important that their performance be related to the level of hazard they experience. For example, estimation of tsunami hazard, given in terms of runup and extent of inundation, will depend on the recurrence period of the tsunami. Horikawa and Shuto (Horikawa and Shuto 1983) present an overview of the evaluation of recurrence periods on the basis of tsunami magnitude records and tsunamigenic earthquake records in Japan. One of the most important parameters that should be decided on in regard to the evaluation of the performance of any coastal protection measure in a tsunami is the runup and inundation that is most likely to occur(Wiegel 2006a). There have been many papers and reports on this topic. Nearly 300 source about Runup/Inundations (Flooding) and Drawdown; Tsunami Propagation Nearshore; and Induced Oscillations have been compiled in Wiegel's Tsunami Information Resources report(Wiegel 2006b). It should be noted that the terms tsunami runup and inundation are sometimes used differently in various publications. Bryant (Bryant 2001) presents a good overview on the treatment of tsunami runup, inland penetration, and depth and velocity at shore. Runup/Inundation maps and models exist for many locations, and are being developed for others.

Finally, the local site conditions should be examined when reviewing the performance of defence system at a particular locality. Backshore and offshore topography, geometry, sediment supply, and relative sea-level rise, among other factors vary between coasts and, indeed, along adjacent sections of coast (USACE 2006). Thus, great care should be taken in interpreting the results from historical or empirical cases which are cited and reviewed here, and applying them to larger contexts. For example the Japanese Sanriku coast where tsunami defence works have been constructed since 1960, exhibits seawalls along shore line high enough to have offered protection against the Chilean Tsunami of 1960, but not against great tsunamis such as the one that occurred in 1896 and 1933(Goto and Shuto 1983). Thus the performance of any coastal defence system should be evaluated on the basis of the level of the coastal hazard (e.g. recurrence interval) as well as site-specific parameters.

Given the preceding as a backdrop, it is clear that a specific shore-protection design on one coast will probably not translate directly to another coast and serve all functions. Thus, in selecting the response or combination of responses, it is vital that one be aware of the dynamics associated with each type of hazard, and only then judge the advantages and disadvantages of the response for coastal protection. The most appropriate solutions should be identified in terms of the intended function of the engineered systems as well as trade-offs to consider. Construction cost, effects on future development, assets at risk, geometry and topography of the coast, level of preparedness and capacity of the society to cope with the disaster, are all important factors to consider when choosing between a specific defence system(Wiegel 2006a). Good and Riddlington (Good and Riddlington 1992) discuss key points in the process of planning, designing and evaluating the performance of a shore protection project from the reconnaissance level, to the feasibility level, to how to select an optimal shore protection plan that accomplishes the design objectives, and management policies for the particular coast.

Chapter 2: Evidence for a Protective Role of Vegetation as a Natural Defence System

In this chapter literature addressing the role of vegetation as a natural defence against tsunamis, hurricanes/cyclones associated flooding is reviewed.

2.1 Methods

A keyword list was developed by scanning the literature available on this subject. Unless otherwise noted, the Web of Science database (1900-2007) was the database used for search with keywords. A combination of keywords associated with each coastal hazard was applied and the results of the search are provided in Table 1. The search was divided into tsunamis and hurricanes/cyclones. To begin each search, a coarse search of keywords "vegetation" and the hazard of interest were conducted. The searches were then increasingly refined, ending with a search of family or genus of vegetation types known to be highly abundant in coastal areas. Although numerous articles were found in each search, only articles and reports that specifically address the role of vegetation for protecting human communities were retained. Articles addressing ecological impacts of these events on vegetation without a mention of how this affected human communities were not deemed as useful for the purposes of this report. Thus, many of the papers for which results were returned were not included in the reference library or mentioned throughout the text. Additionally, the reference list of publications found using this keyword search was also used to find additional articles on each topic.

Keyword[1]	Database	Search Results
vegetation and tsunami*	Web of Science	42
tree* and tsunami*	Web of Science	18
mangrove* and tsunami*	Web of Science	27
casuarina* and tsunami*	Web of Science	1
palm* and tsunami	Web of Science	11[2]
vegetation and hurricane*	Web of Science	209
tree* and hurricane*	Web of Science	362
mangrove* and hurricane*	Web of Science	51
tree* and cyclone*	Web of Science	72
mangrove* and cyclone*	Web of Science	20
palm* and cyclone*	Web of Science	31[2]
palm* and hurricane*	Web of Science	65
casuarina* and hurricane*	Web of Science	0
casuarina* and cyclone*	Web of Science	0
vegetation* and typhoon*	Web of Science	25
tree* and typhoon*	Web of Science	59
mangrove* and typhoon*	Web of Science	5
palm* and typhoon*	Web of Science	2[3]
casuarina* and typhoon*	Web of Science	1
coco* and typhoon	Web of Science	1

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[1] Keyword used in abstract, title, or as a keyword used by the author
[2] None of these specifically addressed palm trees
[3] Only one of these references referred to palm trees

2.2 Protective Role Against Tsunamis

There are several different ways in which vegetation can provide a natural defence against tsunamis: by buffering communities against the force of the wave(s) or by providing a mechanism for escape via climbing (trees). Vegetation that is resistant or resilient to a tsunami may also provide valuable resources in the aftermath of the event such as fuel wood, food and drink (for example, from coconut milk). This report will primarily focus on regulating services (protective functions) rather than provisioning services (such as food, fuel wood, construction materials) of coastal vegetation in relation to tsunamis. Also, although many types of trees and vegetation have demonstrated resistance or resilience to tsunamis, this does not necessarily infer that they provided physical protection against the tsunami waves. This study has focused only on those trees or vegetation types that offered physical protection from the tsunami waves.

Most of the attention on the role of coastal vegetation in protecting human communities from tsunamis has focused on the role of mangroves following the Indian Ocean tsunami of 2004. Thus, since the majority of research and publications have focused on mangroves, they are the primary coastal vegetation type discussed throughout this section. Despite considerable focus and research on mangroves as a natural defence to coastal hazards, there is not a consensus amongst researchers on their ability to protect people from tsunamis. This section will review evidence for their protective features and the implications this may have for coastal hazard mitigation and some of the debates that have arisen around the role of this vegetation type as a natural defence against tsunamis. Other vegetation types will also be discussed throughout the section, where information was available.

2.2.1 Theoretical evidence of coastal vegetation as a natural defence against tsunamis

Theoretically, trees such as mangroves should be able to attenuate waves associated with a tsunami. Quartel et al. (2007) used field instrumentation to test the current velocity and water level at an open tidal flat, at the beginning of mangrove vegetation and inside the mangrove stand. Their results showed that the wave height reduction by mangroves was 5–7.5 times larger than by bottom friction only on beach plains, which they say clearly indicates the importance of the mangrove vegetation for coastal defence. Additionally, the dense network of trunks, branches and above ground roots of the mangrove vegetation caused a much higher drag force than in the other sites. However, they concluded that the drag force exerted by mangroves depends on species composition of the stand and the density of the vegetation. Similarly, Massel (1999) also found that the structural nature of a mangrove stand influences its ability to attenuate waves. They used numerical modelling and field observations in Australia and Japan, to show that the rate of wave energy attenuation by mangroves depends strongly on the density of stems in the forest, the diameter of mangrove roots and trunks, and on the spectral characteristics of the incident waves. Harada et al. (2002) conducted a hydraulic experiment to study the tsunami reduction effect of the coastal permeable structures using different models of mangroves, coastal forest, wave dissipating block, rock breakwater and houses. This work concluded that mangroves can be as effective as concrete seawall structures for reduction of tsunami effects on house damage behind the mangrove forest.

There is also much information on the hydraulic effects of tsunamis, hurricanes and storm surges and various modelling efforts (experimental and numerical) from the engineering literature. A preliminary review of this class of publications shows great potential in informing on how coastal engineering literature may be used in modelling the protective effects of coastal vegetation. For example, Goto and Shuto (1983) developed numerical simulations to show how large obstacles such as grouped houses or low seawalls are expected to be effective to some extent in reducing the inundation of tsunamis. In this work, grouped houses are taken as pillars and classified into three subregions; region of entry, the intermediate region and the last region. Coastal forests might be modelled as pillars with different spacing and geometries. The discharge and friction coefficients of these pillars can be expressed in terms of the Froude numbers or the ratio of contraction. Goto and Shuto (1983) compare their numerical simulations with hydraulic experiments for unsteady flow, and found that the coefficients can be easily taken into the numerical computations for unsteady flow through an equivalent roughness yields good agreement. While an exhaustive review of the modelling approaches does not fit the scope of this report, the modelling literature can be used in some cases to understand how coastal vegetation structures resist these forces. A presentation and synthesis of these methods and their application to coastal vegetation is not the focus of this report, but such work can be of great value to informing the modelling efforts on the protective role of coastal vegetation, and a vital and exciting topic for future research directions.

2.2.2 Empirical evidence on the role of vegetation as a natural defence against tsunamis

Despite the popular and widely accepted view that mangroves have protective capacities against coastal hazards, there is surprisingly little field data available to prove that hypothesis; most of the research has been observational and/or anecdotal (Kerr et al. 2006). Even some of the more quantitative field studies on the role of vegetation in mitigating against tsunamis have been questioned due to the statistics and analytical techniques used (see Dahdouh-Guebas, F. et al. (2005) and Kerr, Baird et al. (2006) for critiques of approaches used and discussed below).

In Sri Lanka Dahdouh-Guebas et al. (2005) used a semi-quantitative assessment technique to assess the protective capacity of mangroves against the tsunami. In January 2005, they conducted preliminary post-tsunami surveys in 24 mangrove lagoons and estuaries in Sri Lanka's coastal zones along the South-West, South and South-East coasts of the island. At each site they assessed: (A) the pre-tsunami extent of the front mangrove (the first 500m fringe); (B) the extent of mangroves already destroyed before the tsunami; (C) the 'naturalness' of the mangrove, in terms of the presence or absence of cutting activities and of cryptic ecological degradation; (D) tsunami damage to the front mangrove; and (E) tsunami damage to lives and properties in the back mangrove and behind the mangrove. They found that mangroves did indeed afford protection in sites where they occurred, but the degree of ecological degradation of mangrove stands was critically important in determining their ability to protect human communities. In the article they refer to cryptic degradation, in which species composition of mangrove stands changes throughout time to include less pure mangrove species. This would decrease the ability of the stand to function as a pure mangrove stand would against tsunamis. The key feature of damaged mangrove forests was a prominence of species not typical of natural mangrove forests. Mangrove sites with no cryptic ecological degradation, or those well protected by distance inland and by *Rhizophora* spp. fringes, all experienced a low destructive impact from the tsunami. The important lesson from this study is that, even though a coastal area might superficially seem to be protected by a mangrove forest, the stand could be cryptically degraded and not offer the desired storm protection.

In a fairly controversial study of 25-km of tsunami affected coastline in Parangipettai, Tamil Nadu, India, Kathiresan and Rajendran (2005) collected information on distance from shore, elevation, area of mangroves/coastal vegetation, number of deaths and per capital loss of life in 18 hamlets. There results showed a significant negative correlation between the human death toll and the distance of human habitation from sea (r^2=0.61, P<0.01), the elevation from mean sea level (r^2=0.63, P<0.01) and the area of mangrove and other coastal vegetation (r^2=0.58, P<0.01). However, their results were challenged by Kerr et al. (2006) who reanalysed their data using stepwise regressions after exponentially transforming data on mortality and loss of wealth rather than the simple linear regressions and non-transformed data used by Kathiresan and Rajendran (2005). Their results showed that distance from sea and elevation combined explained 87% of the variation of mortality in the area with vegetation contributing less than 1% increase in the explanatory power. Similarly, they found that distance from sea accounted for 61% of the variation in wealth lost with elevation and vegetation combined accounting for only 6.5% of the total variation. Vermaat et al. (2006) then challenged the approach taken by Kerr et al. (2006) by stating that a transformation of the data was not necessary and may have weakened the power of the test. They suggest that ANOVAs rather than regressions should be used for testing the effects of elevation, distance and vegetation with mortality and loss of wealth. Their re-analysis of the data using ANOVAs on untransformed data suggests that less lives and less property were lost from hamlets that were in the shelter of mangrove stands, even when they corrected for distance from the sea and elevation.

Tanaka et al. (2007) conducted field surveys across 29 sites in Thailand and Sri Lanka on the effectiveness of different species of trees/coastal vegetation in mitigating against the tsunami. The field surveys included assessments of vegetation types/classification, direction of the tsunami and height of waves. They also calculated the drag co-efficients of each species recorded which included (a) *Casuarina equisetifolia*, a representative tree that grows in beach sand, (b) *Anacardium occidentale*, a plantation species in the coastal zone, (c) *Cocos nucifera*, a plantation species in the coastal zone, (d) *Avicennia alba* or *Avicennia marina*, hereafter *A. alba*-type, representative mangrove species found in small tidal zones, (e) *Pandanus odoratissimus*, grows in beach sand, and (f)

Rhizophora apiculata (the dominant *Rhizophora spp.* on the western coast of Thailand) or *Rhizophora mucronata* (the dominant *Rhizophora spp.* on the southern coast of Sri Lanka), representative mangrove species in large tidal zones. Their results of field observations combined with modelling show that the ability to attenuate the tsunami wave is a trade-off between stem diameter and spacing of trees, (which is why mangroves are such effective defences because of high stem density in forest stands). For example, as stem diameter gets larger, the tree becomes more resilient to wave forces, but with an increased diameter there is less room for a higher number of stems and, so, stem density decreases. This problem was evident in *Casuarina equisetifolia* stands: when the stand is young, there is a high density of small stems which makes it effective at attenuating wave forces, but the stems break easily at this age because they are small; when the stems get bigger there is more space between the trees which lowers the ability to attenuate the wave. *C. nucifera*, despite how abundant it is throughout the tsunami zone, has too many spaces in between each stem to reduce wave force significantly. However, they suggest the proper spacing of vegetation throughout the coastal zone can maximize the potential benefits that different coastal tree species may offer with respect to tsunami protection, even if their functions are not directly related to wave attenuation (Figure 1). For example, a horizontal forest structure with small- and large-diameter trees is assumed to be effective because the densely populated small-diameter trees (d > 0.1) could reduce the velocity of the tsunami current, while the large-diameter trees (d > 0.3) could trap the broken branches and man-made debris. The vertical structure also provides an effective soft landing for people washed away by the tsunami or for climbing when the tsunami waves hit. In addition, creeks inside mangroves and gap structures inside the *C. equisetifolia* vegetation are assumed to be effective for trapping broken branches and reducing the water velocity.

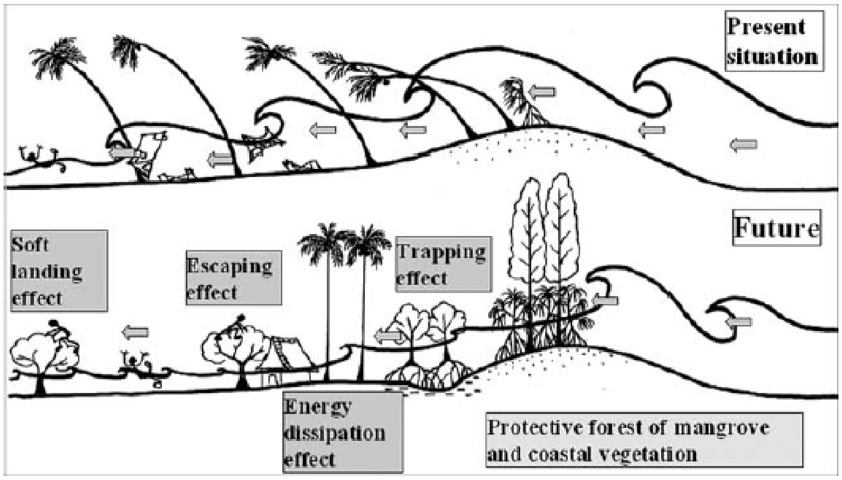


Figure 1. A schematic demonstrating the arrangement/zonation of different coastal tree species- with different drag co-efficients or functional responses to waves- may maximize the protective functions of different species as different effects become important (Tanaka 2007).

Danielsen et al. (2005) conducted a study of the role of vegetation in mitigating the impact of the tsunami along the tsunami affected coastline in the Cuddalore District in Tamil Nadu, India. The results of their analysis, using chi-square comparisons of damage in areas with different vegetation densities suggested that mangroves helped mitigate damage from the tsunami because the villages located behind the mangroves were not damaged compared to villages not behind mangroves. However, most of the villages located behind the mangroves were also a farther distance from the shore than villages that were not located behind mangroves (Figure 2).

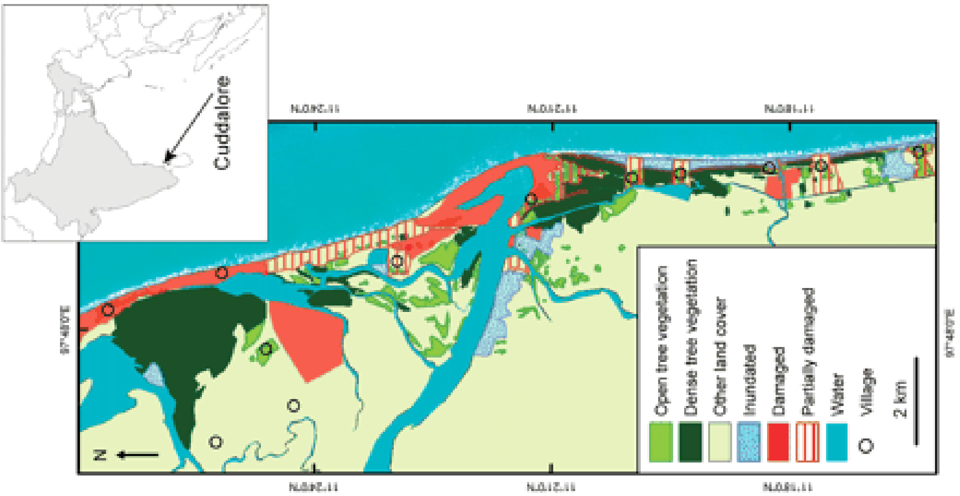


Figure 2. From Danielsen et al. (2005) based on satellite imagery, this map of the study area in Cuddalore, India shows the spatial distribution of vegetation types, villages and tsunami damaged areas.

They state, that villages on the coast were completely destroyed, whereas those behind the mangroves suffered no destruction even though the waves damaged areas unshielded by vegetation north and south of these villages. However, they do not account for distance from shore which has been shown to be an important factor influencing the degree of damage from the Indian Ocean tsunami in 2004 in other studies (Kerr et al. 2006, Vermatt et al. 2005, Dahdouh-Guebas and Koedam 2005). Danielsen et al. (2005) also showed that five villages located within *Casuarina* plantations experienced only partial damage which the authors interpret to mean that *Casuarina* plantations may afford considerable protection from the waves. However, the authors note a major caveat to their results (in the supplementary material and methods section): they do not know what the structure of the wave was like in this area or if it was completely uniform across the coastline, although they infer this by the relatively homogenous continental shelf proximate to the affected coastline.

Chatenuax et al. (2007) used a Geographic Information System (GIS) modelling technique and multiple regressions to assess the role of seagrass, coral reefs and mangroves for mitigating the impact of the tsunami in sites across Indonesia, Thailand, continental India, Sri Lanka and Maldives. Their results indicate the width of the flooded plain (the proxy for damage in this study) was strongly correlated with distance from the subduction fault line; the near-shore geomorphology, through average depth at 10 km and length of proximal slope; percentage of coral; and percentage of seagrass beds. These factors accounted for 65.5% of the variance in the width of the flood plain at 56 sites with a significance of $p<0.05$. The authors hypothesize that seagrass may help reduce the tsunami impact by mechanical influences that attenuate the wave; however, the authors state that the results could also be an artifact of the distribution of seagrasses that may only occur in areas where wave energy is lower. The authors were not sure which of these possibilities would be true. The authors found that damage was higher behind coral reefs. Areas where coral is growing are generally in shallow waters with small slopes, two conditions leading to higher waves. Although there are little doubts in the positive protecting role of coral from typical waves, caution should be kept, the authors warn, while rebuilding facilities in the shore zone; the geomorphology of areas where coral usually grow might be not a safe place for tsunami protection. The authors say they could not test for the effect of mangroves because they were only present in estuaries, areas sheltered by a stretch of coastline or in protected bays. However, this is contrary to the nature of the mangroves found in Tamil Nadu by Danielsen (2005), Kathiresan & Rajendran (2005) and Vermatt et al. (2006). They state that remaining mangroves forests were only identified in sheltered areas in the observed cases; it is, therefore, difficult to distinguish whether the areas covered by mangrove forests suffered less impact because of their intrinsic nature, or because they were sheltered by coastline or other physical protection. The authors also state that it is important to note that all this analysis was made on a single event, the tsunami of 26 December 2004 and a tsunami with a different magnitude and origin could result in drastically different wavelengths, and, thereby might induce different effects.

2.2.3 Negative Impacts of Coastal Vegetation on Human Lives

In the study by Kathiresan and Rajendran (2005) in Tamil Nadu, India, the researchers found that the majority of the death toll was due to a thorny plant species, *Prosopis spicifera*, which caused heavy wounding and damage to people. The authors suggest that the plant should be removed when it occurs in close proximity to the shore but should be allowed to grow densely in barren coastal wastelands, beyond 3 km from the shoreline because it is an important source of firewood. Furthermore, other types of coastal trees are thought to pose a physical threat to humans due to snapping and breaking during heavy winds, flooding and/or waves (http://www.fao.org/forestry/foris/webview/pageview.jsp?pageId=31843&langId=1).

2.2.4 Summary of the role of coastal vegetation in mitigating the impact of tsunamis

Although, many of the studies cited here differ in their results, there are a few broad conclusions that can be made. It is clear that the role of coastal vegetation in mitigating tsunami waves is dependent upon species composition (which is related to functional ability to attenuate waves through species specific root and stem structures), stem diameter and stem density in a stand. Thus, it is not surprising that cryptic degradation (which results species composition changes) has been shown to affect the ability of mangroves to protect shorelines from tsunami damage in Sri Lanka (Dahdouh-Guebas et al. 2005). Although many qualities of coastal vegetation have been demonstrated to be useful in preventing attenuating wave forces theoretically, these disaster resistant qualities have been less consistent in field based studies. The reason for the some of the disconnections between theoretical tests and field observations following a tsunami may be related to the many other non-biological factors, such as bathymetry, distance from epicentre, orientation of the coastline and depth of the sea floor that can influence the wave(s) and/or ability of the coastal vegetation to mitigate against tsunami forces. In addition different types of techniques and analyses have been used across studies meaning results are often not comparable.

Despite the lack of quantitative data on the role of coastal vegetation in mitigating against tsunami waves, upon which this review has focused, there are numerous articles that give anecdotal or observational evidence supporting the importance of coastal vegetation, especially mangroves, in mitigating against tsunami forces. Furthermore, coastal vegetation, such as mangroves and coconut trees to name a few, provide important goods (such as fisher grounds in mangrove habitats, fuel wood, food/drink from coconuts) and services (coastal erosion prevention, wind breaks) to coastal peoples that are critical for coastal livelihoods in general and in the days following a disaster such as a tsunami.

2.3 Protective Role against Hurricanes, Cyclones and Typhoons

Following recent major hurricanes, such as Hurricane Mitch and Hurricane Katrina, observations were made that loss of vegetation (Cockburn et al. 1999) and barrier islands (Fischetti 2005) increased vulnerability of human populations to the storms through landslides resulting from Hurricane Mitch and flooding associated with the storm surge in Hurricane Katrina. Similarly, in another non-quantitative piece of work, Willams et al. (Williams et al. 2007) state that mangroves were critical for preventing loss of life from Cyclone Larry that hit Queensland, Australia in March 2006, but they make a point of saying that good coastal planning and preparedness were also a key part of this. Despite numerous reports on the value of wetlands, mangroves, dunes and forests as defences against coastal storms and resultant flooding, there is very little quantitative evidence to support these commonly held beliefs. It has been well accepted that barrier islands, shoals, and wetlands can reduce storm surges and waves, but the full range of these effects is not well captured at present by most numerical models (Day et al. 2007). This section attempts to review quantitative studies on the role of vegetation for protecting people against storm surges associated with hurricanes, cyclones and typhoons but does not focus on wind damage associated with these events. The review does not include an exhaustive discussion of the ecological response of coastal vegetation to these events, a subject which many have addressed, unless the research also related this response to services or functions that directly affect its ability to protect human lives or prevent damage from the hazard.

2.3.1 *Common Coastal Vegetation for Defence against Hurricanes, Cyclones and Typhoons*

Although there are few numerical models on the role of natural defences such as vegetation in reducing storm surges, there are multiple projects globally in which vegetation and natural defences are being implemented as part of national coastal protection and management policies.

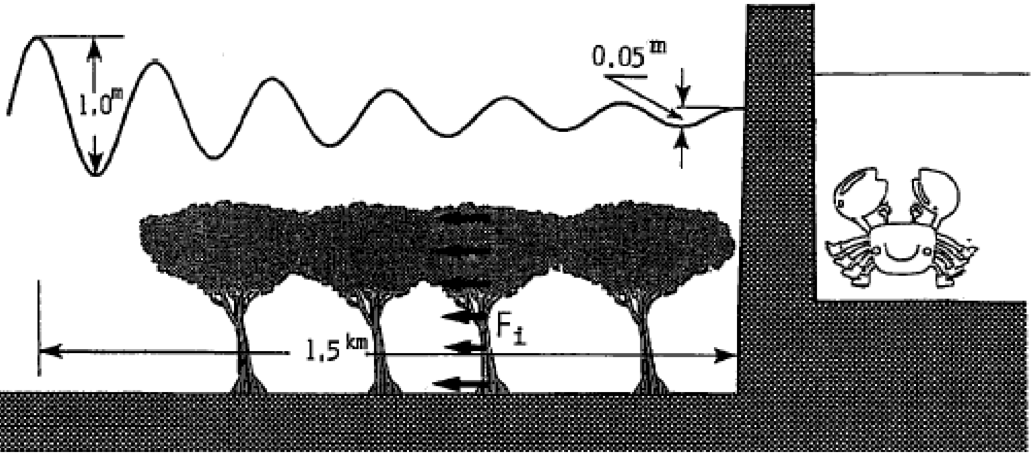
Bandyopadhyay (1997) reports that in Sagar Island, India several natural restoration schemes were initiated to prevent coastal hazards. Strip plantations of *Eucalyptus hybrid* and *Acacia nilotica* were planted along roads, canals and embankments on the island, but had little affect in controlling hazards such as shifting sands. However, they report that native vegetation unaffected by human impact is an effective way to stabilize dune systems. The species that proved to be most effective at dune stabilization were *Ipomea pes-caprae*, *Launaea sarmentosa, Cyperus exaltatus* and *Opuntia dillenii*, which are natural sand dune colonizers that stabilize dune systems. They stated that in an 1864 cyclone, dunes were quite effective at reducing storm surges on the island. Vegetation is an important part of dune systems generally; without vegetation sands become unstable and are easily eroded. The type of vegetation that colonizes dunes has a marked impact on their ability to exist as stable coastal defences. For example, in New Zealand, native dune vegetation such as Spinifex (*Spinifex sericeus*) and Pingao (*Desmoschoenus spiralis*, where present) are critical for restabilising dune sands after storms, while non-native plants that may also colonize sand dunes do not function as effectively as these native species.

The role of mangroves to attenuate waves associated with cyclones and hurricanes is thought to be as, if not more, important than their role in attenuating waves from tsunamis. Mazda *et al.* 1997 demonstrated through field measurements of water levels and current velocities in replanted mangrove stands of different ages (½ year old seedlings, 2-3 year old seedlings and 6 year old seedlings). They found that 6 year old mangrove stand 1.5km wide was effective at reducing 1m high waves at the open sea to 0.05m at the coast. However, the authors note that more research is needed on how dependent wave reduction is on species composition, spacing between trees, water depth, wave period and wave height.

Although there is sufficient scientific evidence suggesting that mangroves provide protective services from storms, there is a lack of ecological data on how loss of mangroves in specific locations will affect their ability to provide storm protection to neighbouring communities (Barbier 2007). Blasco *et al.* (1992) used satellite imagery to assess the impacts of flooding resulting from cyclonic activity in Bangladesh in the delatic complex of the Ganges. In mangrove forests, there was no sign of any kind of destructive effects by floods or winds, which the authors interpret to mean that these tidal forests are adapted for annual cyclones. The authors also note that a coastal afforestation programme carried out in the last 15 years, on the intertidal zone, had created a safety belt of trees, sufficiently thick to protect embankments facing open sea, which were undamaged. In India and the Philippines, fishermen have recognized the importance of intact mangroves in protecting against coastal hazards such as cyclones and flooding (Dahdouh-Guebas et al. 2005). In a study on the value of mangroves to a fishing community in the Philippines, more than 90% of all fishermen, regardless of where they fished, thought the mangroves provided protection from storms and typhoons and acted as a nursery site and should be protected. Those fishing only in the mangrove perceived more benefits from the mangrove forests and were prepared to pay more to protect it than those fishing outside (Walton et al. 2006). Some authors have argued that mangroves are more beneficial than built defence systems because they also offer provisioning services, such as fish and fuel wood, as well as providing storm protection whereas built systems only provide the latter (Tri et al. 1998).

(a)

WITH MANGROVES



(b)

WITHOUT MANGROVES

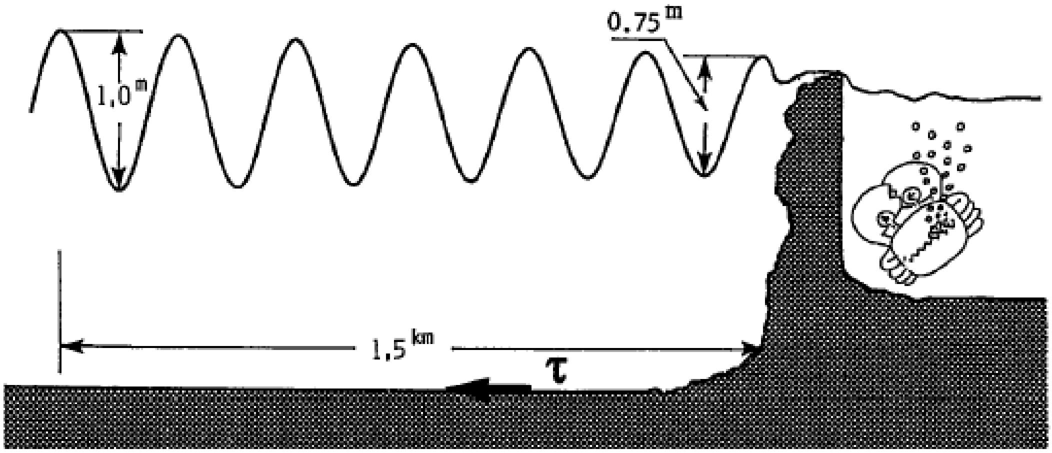


Figure 3 Differences in the effect of wave reduction (a) with mangroves and (b) without mangroves. In a, the drag force on the plants $\sum F_i$ occurs at the throughout the water depth. In b, the bottom friction only occurs on the sea floor. From Mazda et al.1997

In addition to dune vegetation and mangroves, tropical deciduous forests have also been shown to be effective at regulating floods associated with cyclones. In a long-term ecological study of tropical deciduous forests in the Chamela Region on the Pacific Coast of Mexico, Maass et al. (2005) report that, although the forest is deciduous, there is always a constant leaf litter layer in the forest floor that protects the soil from the direct impact of raindrops associated with the many cyclones that regularly hit the area (García- Oliva et al. 1995). The leaf litter on the forest floor acts to maintain high infiltration rates in the soil, avoiding runoff and soil erosion, thus reducing floods (Maass 1992, Cotler et al. 2002). When the forest is transformed into agriculture and pasture fields, soil cover decreases and infiltration rates diminish, resulting in soil erosion and sediment transport down the stream several orders of magnitude above the natural rates (up to 130 Mg-1 • ha-1 • yr-1; Maass et al. 1988).

Although, multiple studies have been conducted on the impact of hurricanes and cyclones on different types of forests, there is very little documentation on the role of different types of vegetative communities for offering direct protection to humans from coastal hazards.

2.3.2 Other natural defences against storm surges

Stone and McBride (1998) used historical shoreline change data to predict the rapid disintegration of a section of barrier island coast along central Louisiana (Isles Dernieres) and resultant increases in wave energy in the adjacent bays. Their results indicated that the bays adjacent to the Isles Dernieres could experience an increase in wave height of 700% if the barrier chain is reduced to shoals due to continual degradation.

2.3.3 Summary

Based on the studies reviewed, mangroves and native sand dune vegetation are consistently effective for mitigating against storm surges. In particular, mangroves reduce erosive waves associated with storm surges and also provide a windbreak from storms while the sand dune vegetation is important for stabilizing sand dunes, which provide an important physical buffer against flooding resulting from surges. Intact natural forests may also play important roles by moderating soil filtration rates and, thus, preventing runoff, erosion and flooding associated with cyclones and hurricanes. In addition, some tree species may provide a useful windbreak, but it is critical to select trees that can withstand high level winds and are not easily uprooted in sandy soils. Similar to the research gaps associated with assessing the role of mangroves and other coastal vegetation types for preventing against tsunamis, there remains a paucity of quantitative data directly quantifying the role of vegetation for mitigating against hazards during specific events. However, the theoretical work does support anecdotal and observational data on the ability of coastal vegetation to mitigate against storm surges resulting from hurricanes, cyclones and typhoons.

Chapter 3: Engineered Defence Systems against Coastal Hazards

3.1 Methods

In this chapter literature dealing with protective coastal structures and their performance in reducing damage from coastal hazards is reviewed. A keyword list was developed by scanning coastal hazards literature utilizing a set of databases provided in the Table below. A search on coastal structures and their protective role was conducted across multiple databases including, Web of Science, ScienceDirect, ASCE Civil Engineering Database, Georef, Water Resources Abstracts, and Oceanic Abstracts. The database that produced the greatest number of most relevant searches was found to be the combined Compendex®, Ei Backfile, Inspec®, Inspec Archive & NTIS™ and the Web of Science databases. These databases allowed for searching on the broadest disciplinary focus, covering the scientific, applied science, technical and engineering disciplines and included journal articles, proceedings, unclassified government reports, and more from 1884 to present. Additionally, several online information resources and collections such as Prof. Robert Wiegel's Tsunami Information Resources; The International Tsunami Information Center (ITIC) Library in Honolulu, Hawaii; TsuInfo at the Washington Department of Natural Resources; and the U.S Army Corps of Engineers online Database (see Appendix) were used to conduct the literature search.

Keywords	Database	Search Results
Coastal Structures	Compendex, EI, Inspec, NTIS	8967
Coastal Structures	ScienceDirect or WebofScience or Proquest or ASCE Civil Engineering Database	1369
Coastal Protection	Compendex, EI, Inspec, NTIS	7151
Coastal Structures and Protection	Compendex, EI, Inspec, NTIS	1437
Coastal Structures and Storms	Compendex, EI, Inspec, NTIS	679
Coastal Structures and Tsunami	Compendex, EI, Inspec, NTIS	126
Coastal Structures and Hurricane	Compendex, EI, Inspec, NTIS	196
Coastal Structures and Cyclones	Compendex, EI, Inspec, NTIS	234
Coastal Structures and Typhoon	Compendex, EI, Inspec, NTIS	28
Coastal Structures and Modelling	Compendex, EI, Inspec, NTIS	2956
Coastal Structures and Environment	Compendex, EI, Inspec, NTIS	1088
Coastal Structures and Environment	LexisNexis Environment	982
Coastal Structures and Economics	Web of Science, ScienceDirect	505
Coastal Structures and Policy	Web of Science, ScienceDirect	2133

Coastal protection is an applied discipline that is mainly conducted by coastal engineers, but which receives background support in the geological, oceanographic and to some degree social sciences. Almost 9000 publications exist on “coastal structures”, alone 71 of which are engineering handbooks and reference titles. Of these 9000 titles, almost 3000 comprise publications related numerical and quantitative (modelling) studies of coastal structures. When seen from the purview of coastal engineering, 1437 publications exist on coastal structures and their role in coastal protection against coastal hazards. Breaking up the mitigative effects of coastal structures on coastal hazards, 679 publications were found on storm surges and cyclones, 196 on hurricanes and 126 on tsunami. Searching across environment-related databases (e.g. LexisNexis Environmental), 1088 publications dealing with environmental studies of coastal protection have been uncovered. Additionally 2100 publications are available on coastal protection policy, and 500 publication deal with economics of coastal protection.

There is a prominent trend including increasing numbers of studies that analyze shoreline position, and steady flow of papers dealing with studies of coastal environmental impacts from shore protection structures. These trends reflect increasing awareness of natural erosion trends as well as those exacerbated by engineering works, including structures that are designed to mitigate erosion but which have unwanted effects. Also found are trends that evaluate the performance of shore protection efforts, such as beach replenishment, as well as introspection of cost-benefit analyses used to justify beach projects (Finkl 2002).

For the literature review conducted in this report, information was sought specifically on the effectiveness of engineered waterfront defence systems and their protective role during coastal hazards. As evidenced from the number of relevant publications uncovered, this is a vast disciplinary area where a lot of work has been done and much information is available. In general, the following five questions (based on comments in the NSF Tsunami Workshop in Hilo, 26-28 December 2006 by Wiegel (2006a) are used to classify and sort through the vast amount of information dealing with engineering solutions for coastal hazard mitigation.

1) What types of engineered structures are used to protect specifically against tsunamis, hurricanes, cyclones and storm surges?
2) What is the experience with engineered structures in past coastal hazards?
3) What factors should be used in the siting of engineered structures? (i.e. when and where does it make sense to use them)
4) What are the choices, risks and trade-offs associated with engineered systems? (i.e. how they may involve adjustments, cost-benefit analysis, etc.)
5) What is their social effect? (false sense of security, convenience/inconvenience factors)

In this section a brief review of various engineered defence systems is followed by the historical experience with these measures during coastal hazards. In addition, a discussion of factors to consider when selecting an engineered countermeasure for coastal protection and the trade offs that affect such decisions is provided based on the pertaining literature.

3.2 Types and Functions of Coastal Structures

Coastal structures are used in coastal defence schemes with the objective of preventing shoreline erosion and flooding of the hinterland. Other objectives include sheltering of harbour basins and harbour entrances against waves, stabilization of navigation channels at inlets, and protection of water intakes and outfalls. Coastal defences can be traced back to remote times. A panorama of the history of coastal protection is provided by Charlier, Chaineux et al. (2005). Coastal protection measures vary considerably in their function, cost, size, effectiveness and life span and there exists a vast body of knowledge on engineered coastal protection methods. There are a variety of “hard” and “soft” structural alternatives for protecting coastal areas. “Hard” protection works refers to measures that have sufficient structural integrity to withstand large waves and establish a fixed line of defence. Hard stabilization techniques are potentially applicable along both dune-backed and bluff-backed shorelines, and along shorelines with either high or low levels of development. Over a long period of time, however, hard protection measures can cause a loss of beach in front of the structures. A “soft” structure, such as a beach fill, is much more compliant as it will experience large displacements and possibly major erosion during a design event. Soft protection methods reduce potential risk to the coastline by enhancing the natural shoreline system. The techniques include fore-dune enhancement, beach nourishment and boulder berms, a form of dynamic revetment. Soft stabilization techniques are potentially applicable along both dune backed and bluff-backed shorelines with both high and low intensity land use.

In this report, the functional behaviour, and the performance only of those structural measures used to protect both human lives and assets from tsunami, cyclones, hurricanes and storm surges are reviewed. These are, in order of coverage, sea dikes, seawalls, bulkheads, revetments, breakwaters, storm surge barriers, scour protection, and combination structures. In general, structures used for coastal stabilization and erosion control are not included, unless they also have a direct role in protecting human lives and assets against coastal hazards.

The following is a brief summary of coastal structures used to protect against coastal hazards. Detailed and comprehensive description of various types of coastal defence structures, their construction and design are given in the Army Corps of Engineers Coastal Engineering Manual (USACE 1995) and (USACE 2006); and Coastal Engineering Handbook Series (Saczynski and Kulhawy 1982), (Hubbell and Kulhawy 1982a), and (Hubbell and Kulhawy 1982b) among other sources.

a. ***Sea dikes*****.** Sea dikes are onshore structures with the principal function of protecting low-lying areas against flooding. Sea dikes are usually built as a mound of fine materials like sand and clay with a gentle seaward slope in order to reduce the wave runup and the erodible effect of the waves. The surface of the dike is armoured with grass, asphalt, stones, or concrete slabs.

b. ***Seawalls*****.** Seawalls are onshore structures with the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind due to storm surges and waves. Seawalls are built parallel to the shoreline as a reinforcement of a part of the coastal profile. Quite often seawalls are used to protect promenades, roads, and houses placed seaward of the crest edge of the natural beach profile. In these cases a seawall structure protruding from the natural beach profile must be built. Seawalls range from vertical face structures such as massive gravity concrete walls, tied walls using steel or concrete piling, and stone-filled cribwork to sloping structures with typical surfaces being reinforced concrete slabs, concrete armour units, or stone rubble. Seawalls are differentiated based on the material type they are built with. Concrete seawalls are continuous, rigid structures, whose vertical or concave faces reflect wave energy upward, downward, and back out to sea and are commonly used to protect assets and sensitive coastal areas, such as stretches of loose fill or sand against wave attack. Some modern seawalls include a buffer zone behind the structure to prevent coastal inundation due to overtopping waves. Waves overtopping the front face of the seawall can permeate a buffer zone installed in front of the original seawall (Fujima et al. 2005). Detailed and comprehensive description of seawall types, their construction and design are given in the Army Corps of Engineers Coastal Engineering Manual (1995) and Coastal Engineering Handbook Series (1982) among other sources.

c. ***Bulkheads.*** Bulkhead is the term for structures primarily intended to retain or prevent sliding of the land, whereas protecting the hinterland against flooding and wave action is of secondary importance. Bulkheads are built as soil retaining structures, and in most cases as a vertical wall anchored with tie rods. The most common application of bulkheads is in the construction of mooring facilities in harbours and marinas where exposure to wave action is minimized. Some reference literature may not make a distinction between bulkheads and seawalls. The terms seawall, bulkhead, and retaining wall are often used interchangeably. To be more precise, a seawall provides stability against waves, a retaining wall provides geotechnical stability for a slope, and a bulkhead provides both functions.

d. ***Revetments.*** Riprap revetments are among the most commonly employed hard structures. It consists of several components: filter fabric or bedding layer, armour stones, toe trench, sand topping, beach grass and backshore drainage. A variety of concrete armour units are available as alternatives to stone. These units are employed in very large wave conditions, however, the availability of stone in a lot of coastal areas makes this the cost-effective alternative for typical revetments (Good and Riddlington 1992).

e. ***Breakwaters*****.** Breakwaters are built to reduce wave action in an area in the lee of the structure. Wave action is reduced through a combination of reflection and dissipation of incoming wave energy. When used for harbours, breakwaters are constructed to create sufficiently calm waters for safe mooring and loading operations, handling of ships, and protection of harbour facilities. Besides being built to improve manoeuvring conditions at harbour entrances, protection of water intakes for power stations and protection of coastlines against tsunami waves are other important applications of breakwaters.

When used for shore protection, breakwaters are built in near shore waters and usually oriented parallel to the shore like detached breakwaters. They are typically 100 to 300 feet long, and usually placed somewhat farther offshore than the average width of the surf zone. The layout of breakwaters used to protect harbours is determined by the size and shape of the area to be protected as well as by the prevailing directions of storm waves, net direction of currents and littoral drift, and the manoeuvrability of the vessels using the harbour. The important concept is that the structure is separated or detached from the shoreline and hence, in principle, sediment can pass alongshore between it and the shoreline. The wave transmission coefficient of a breakwater, defined as the ratio of the height of the waves just seaward of the structure to the height of the wave on the landward side, determines the potential effectiveness of this device as a protection measure against coastal hazards. Breakwaters protecting harbours and channel entrances can be either detached or shore-connected. Detached breakwaters can be built alongshore in series, analogous to a field of groins, to protect a long stretch of shoreline. Such multiple detached breakwater systems are referred to as segmented detached breakwaters. The cost of breakwaters increases dramatically with water depth and wave climate severity. Also poor foundation conditions significantly increase costs. These three environmental factors heavily influence the design and positioning of the breakwaters and the harbour layout.

f. ***Storm surge barriers*****.** Storm surge barriers protect estuaries against storm surge flooding and related wave attack. These barriers also prevent excessive intrusion of salt-water wedges during high-water episodes. In most cases the barrier consists of a series of movable gates that normally stay open to let the flow pass but will be closed when storm surges exceed a certain level. The gates are sliding or rotating steel constructions supported in most cases by concrete structures on pile foundations. Scour protection on either side of the barrier sill is an important part of the structure because of high flow velocities over the sill.

g. ***Scour protection*****.** The function of scour protection of the seabed is to prevent instability of coastal structures with foundations that rely on stable seabed or beach levels. Both granular material and clay can be eroded by the action of waves and currents. Scour potential is especially enhanced by a combination of waves and currents. In most cases scour protection consists of a rock bed on stone or geotextile filter; however, several specially designed concrete block and mattress systems exist. Scour protection is commonly used at the toe of seawalls and dikes; and in some instances scour protection is needed at the toe of vertical-front breakwaters. Scour protection might also be needed along structures that cause concentration of currents, such as breakwaters extending from the shoreline. Highly reflective structures like impermeable vertical walls are much more susceptible to near-structure scour than sloping rubble-mound structures.

h. ***Integrated Defence Systems*****.** Consists of combination of different structural measures to reduce wave height and flow velocity. Alternatively, more modern approaches refer to integrated defence systems. Under such system, structural coastal protection measures such as revetments, sandy beaches and offshore breakwaters are arranged together with non-structural measures such as early warning systems in a protective configuration.

3.3 Performance of Coastal Structures

As stated already in Chapter 1, there are a number of factors that have to be considered when evaluating the performance of coastal structures and their protective role against hazards. Furthermore, it was stated that different coastal hazards are governed by different physical processes and dynamic characteristics. Thus, in this section, the performance of coastal structures will be looked at for storm surges, cyclones, hurricanes, and tsunamis separately. Here we review the performance from an engineering stand-point. In the next section, the social, economic and environmental impacts of coastal structures will be reviewed.

3.3.1 Coastal Storm Surges

The effectiveness of coastal structures during coastal storm surges is influenced by (a) level of exposure of the site to wave attack, (b) the presence and geometry of a protective beach, (c) the resistance of the sea cliff or bluff to erosion, (d) the presence or absence of a supporting bedrock platform beneath the beach as well as the specific design, (e) construction quality and dimensions of the structures (Fulton-Bennett and Griggs 1986).

Long-term studies of water-front structures evaluating their performance in coastal storms have shown that concrete seawalls are the most durable protection structure against storm surges. Although their initial costs are relatively high, if they are well designed, their maintenance cost may be relatively low. Seawalls require regular maintenance as flaking and cracking present long-term hazards to concrete walls and their steel reinforcing. Abrasion by cobbles has been a significant problem for some British seawalls. Damaged portions of concrete walls must be grouted or repaired to prevent saltwater seepage from weakening materials or causing piping of fill. Most concrete walls suffer from other problems, however, before their strength has been significantly reduced by degradation of concrete (Fulton-Bennett and Griggs 1986). There are several circumstances under which the selection of a seawall may be the most appropriate structural alternative: (1) There is insufficient space between the zone line and structures on the property to install a sloped revetment; (2) the bluffs behind the seawalls are unstable and susceptible to slope failure or landslides; and, (3) the developer wants to extend the lot seaward by filling behind the seawall (USACE 1995).

The causes of failure for concrete seawalls typically fall into the following categories: loss of foundation support; inadequate penetration; scour at toe; outflanking; and inadequate height. Erosion of the beach profile landward of a seawall might be stopped or at least reduced. However, erosion of the seabed immediately in front of the structure will in most cases be enhanced due to increased wave reflection caused by the seawall. This results in a steeper seabed profile, which subsequently allows larger waves to reach the structure. As a consequence, seawalls are in danger of instability caused by erosion of the seabed at the toe of the structure, and by an increase in wave slamming, run-up, and overtopping. Because of their potential vulnerability to toe scour, seawalls are often used together with some system of beach control such as groins and beach nourishment. Exceptions include cases of stable rock foreshores and cases where the potential for future erosion is limited and can be accommodated in the design of the seawall (USACE 2006). Loss of fill behind walls due to piping (the subsurface removal of loose sediment, soil or fill due to water flowing through voids or holes, gullying and/or undermining are also prevalent causes of seawall failure (Fulton-Bennett and Griggs 1986). According to the Shore Protection Manual (USACE 2006) failure of rigid seawalls is most likely to be catastrophic, however there are studies which show that seawalls are endangered by a gradual removal of fill over several days or storm periods (Fulton-Bennett and Griggs 1986).

There is a general belief that concave-faced concrete walls will prevent or greatly reduce overtopping and damage by wave splash. Recurved seawalls, which have an overhanging section at their top, may reduce overtopping, if properly designed with respect to still water levels and maximum wave heights. Under moderate-size waves and no wind, spray does not travel as far inland behind concave walls as behind straight vertical walls. However, under storm conditions, with high tides, large waves and an onshore wind, Fitzgerald (1981) observed the largest waves hitting a recurved concrete wall sent 50 foot high jets of water and debris upward, filling streets and damaging houses behind the wall. These near vertical jets have been observed in front of almost all vertical seawalls when high tides and low sand levels allow waves to reach them. These jets may reach heights perhaps two to three times the height of the original wave and will allow spray and splash to overtop almost any structure, if blown inland by strong winds (Fulton-Bennett and Griggs 1986). The Army Corps of Engineers (2006) acknowledges the problem of overtopping during onshore winds, and suggests that rip rap at the base of the wall will reduce it. Fitzgerald (1981) observed that after rip rap was placed at the base of a concave wall, overtopping due to high waves without wind became more frequent, but that the spray and gravel did not appear to be thrown with as much force. Where erodable material is exposed to wave action, the force of the spray may not be as critical in causing erosion as its volume and persistence. Where this is the case, overtopping with rip rap in place still causes serious erosion (Fulton-Bennett and Griggs 1986). A wide concrete apron shoreward of the wall and oversized drainage holes will help reduce damage or erosion caused by this overtopping, and will reduce pounding. However, careful design, inspection and maintenance are necessary to insure that piping does not undermine paved areas behind concrete walls. Such undermining may be virtually undetectable from the surface.

Diversity of seawall designs and assumptions used in such designs greatly complicated determination of overtopping rates. While equations have been developed for simple designs (1995), physical model tests are typically required for more complex geometries. Ward and Ahrens (1992) present a comprehensive report where they discuss methods for calculating overtopping rates for common seawalls using regression analysis of physical models. These models incorporate information on wave conditions, structure height and water level in determination of overtopping rates for a variety of seawall types.

3.3.2 Hurricanes, Cyclones and Typhoons

Within a hurricane's path, there are patterns of performance in design, construction and materials of various structures that can contribute useful data and guidelines for future coastal protection projects (Taylor 1991). Some of the factors responsible for increasing storm damage include: notching of dunes, removal of forests, narrowing beaches with seawalls or jetties and by siting development in low elevation. On the other hand, factors such as; wide beaches, undisturbed dunes and forests, construction at high elevation and building setbacks can lessen damage to the build environment in the hinterlands (Thieler et al. 1989).

Seawalls – Many publications are available on the design and construction of seawalls and their patterns of performance and damage during strong hurricanes(Miller 1927, Noyes 1939, Kriebel 1987, Sayre 1987, Heimbaugh et al. 1988, Lillycrop et al. 1988, Gaythwaite et al. 1989, Mossa and Nakashima 1989, Thieler et al. 1989, Wuensche 2001). Construction of seawalls and jetties have often been criticized for inhibiting normal coastal processes. Comparison of seawalled beach sections with natural beaches has revealed that local patterns of beach response and nourishment to hurricanes storm surges are not very different and that statistically there is no difference in erosion rates (Jones and Basco 1997). Hurricane Gilbert caused about 70% of the sediment loss on both the seawall-stabilized and the natural shorelines over a three-year period from 1985 to 1988 along sections of a rapidly eroding coast at the Bayou Lafourche headland, Louisiana (Mossa and Nakashima 1989). Following Hurricane Elena, beach profiles were monitored at Clearwater Beach, Florida, to document the modes and rate of natural post-storm beach recovery. In general, it was found that following hurricanes, the presence of an exposed seawall did not hinder swash bar development as the rates and modes of beach recovery were nearly identical on seawalled versus non-seawalled profiles (Kriebel 1987).

Breakwaters – Breakwater structures are commonly used to protect coastal areas by reducing hurricane storm surge heights. Details on design and performance of breakwaters during hurricane attacks on coastal areas around the world are given in numerous publications (Bremner et al. 1981, Hashimoto 1984, Penland and Suter 1984, Balloffet and Horton 1987, Nakashima et al. 1987, Cox 1989, Taylor 1991, Rogers and Houston 1998, Sloop et al. 2002, Jordan and Paulius 2007). These efforts include damage assessments, breakwater design and construction, wave hindcasting, numerical modelling, and physical modelling. Breakwaters may be used in combination with others protection measures, such as a system in Nevis, West Indies, consisting of a segmented, low-crested breakwater, buried revetments, and a renourished beach (Sloop et al. 2002). Breakwaters and shoreline structures require only moderate rock armour and low crest elevations in moderate wave climates. However, to cater for hurricane or cyclonic conditions and to prevent overtopping, artificial concrete units and substantially higher crest levels are required. The failure of the Rosslyn Bay breakwater during cyclone David resulted in a submerged breakwater over which wave breaking occurred, thus still providing substantial protection to inshore structures. This has led to a design concept of using dual breakwaters of relatively small size stone in which the offshore structure is designed to fail and act as a submerged breakwater. The design concept, its application to Townsville Harbour and the economic advantages over conventional breakwaters are discussed in Bremner (1981).

Groins – External groin fields or inlets are sometimes constructed as hurricane storm-protection projects (Miller 1927, Anon 1976, Hou and Liaw 1984, Meyer-Arendt 1993, Nersesian et al. 1993, Leatherman 1999). Groins are thought to be inadequate as first line of defence against strong hurricanes and cyclones, but coupled with seawalls, they may be considered protective on beach and property (Miller 1927). Nevertheless, groins are commonly used for beach protection with some desirable as well as unwanted effects. At Westhampton Beach, New York, where groin construction work has stopped since 1970, substantial portions of the groin field have been filled naturally by trapping of sediment that moves alongshore with a net rate directed to the west. However, the shore area downdrift of the last westerly groin in the unconstructed increment of work has experienced inordinate recession because of insufficient bypassing of sediment to this area. Neresian et al. (1993) describe the functioning of the groin field, examining both extreme downdrift recession and the equally dramatic accretion and beach build up in the groin field, drawing lessons on groin functional design from the historic hurricane storm-protection project. Spencer and Terchunian (1996) argue that the artificial interruption of the natural sand transport through groin field construction projects at West Hampton beach are responsible for almost two-thirds of the erosion on Fire Island. They show how erosion moves west in a series of propagating erosion waves that are well documented by existing aerial photography, ground surveys, and beach profiles.

Integrated Systems – A combination of different natural and engineered protection systems might be the best alternative in some locations. Various steps taken to strengthen the hurricane defence systems in the North American continent (Kosowatz and Illia 2005). An analysis completed by the U.S. Army Corps of Engineers to determine the extent of cost and benefits for the construction of a protection system, concluded that the most practical solution to the beach erosion control and hurricane protection problem at a location in Virginia Beach, Virginia, would be a combination of solutions that included approximately 4 miles of stepped face seawall and 2 miles of raising and widening the existing natural dune system. The basis for design and a description of the selected seawall are presented in Gaythwaite, Pezza et al. (1989). Another example of an integrated coastal defence work is the historic Galveston Seawall and Grade Raising project, constructed after the 1900 Galveston Hurricane. The seawall is presently 10 miles long. It is approximately 17 feet high, and 16 feet thick at its base. Although the structure proved a formidable barrier against the tide and waves and has never been overtopped, it protected only the seaward side of the island and waves from hurricane storms surges have caused considerable damage to buildings that line Seawall Boulevard. To protect the city from rising storm surges, the engineers suggested raising the entire city. Approximately 12 million cu yd (9.2 million m³) of fill was used to raise the city. In most residential areas the grade was raised approximately 8 ft (2.4 m). But near the seawall, it was raised 16 ft 7 in. (5 m). The seawall and the grade raising cost approximately $3.5 million; it proved to be money well spent. On August 15, 1915—five years after the second project was completed— Galveston took another direct hit from a hurricane. That event, too, was a tragedy, but the death toll—275—was much lower. Most of the seawall is still in use today. During the 20th century it was extended horizontally and vertically, and portions of it have been covered to accommodate roadways and other facets of infrastructure resulting from the city's growth (Hansen 2007). Another integrated systems solution, applied to a typical coastal scenario of diminishing marshlands protected by shrinking barrier islands, was an ambitious engineering project of strengthening barrier islands by re-creating immense surfaces of marshlands using vast quantities of sediment to reduce dangerous storm surge heights. A 65 km (40 mile) long stretch of coast, south of New Orleans at Terrebonne Bay was the site of this integrated defence system which was completed at a cost of $500 million (Otten et al. 2006). Integrating tools and models that predict the intensity of storm surges and where they will land, with engineered or natural protection measures is becoming a more common feature of integrated defence systems. The University of Central Florida's Coastal Hydroscience Analysis, Modelling and Predictive Simulations Laboratory and others are working with the National Weather Service to produce an improved storm surge modelling tool than can be used for real-time forecasting (Kosowatz and Illia 2005).

Rubble Mound Structures - A synthesis of existing models and formulas is made to compute the virtual performance of rubble mound structures in shallow water under combined storm surge and breaking waves for sequences of hurricanes. The computed wave overtopping rate and volume during the entire duration of storms with different recurrence intervals are analyzed to assess the severity of flooding hazards. In this study it is found that the computed progression of damage to the armor layer is caused episodically by several major storms but slows down as the structure ages. The computed results are also used to quantify the equivalent duration of the peak of a storm that yields the same overtopping water volume and damage increment as those computed for the entire storm duration (Kobayashi et al. 2003).

3.3.3 Tsunamis

***Seawalls* -** Seawalls are the most conventional engineered countermeasure to protect against tsunamis and are used in many places around the world. Experience in the Indian Ocean (Sumatra) tsunami of 26 December 2004 has demonstrated the usefulness of seawalls for protection from the tsunami, even where they were overtopped (Dalrymple and Kriebel 2005). High seawalls were shown to effectively slow the wave and deflect its horizontal momentum vertically. Investigators from ASCE's Coasts, Oceans, Ports and Rivers Institute (COPRI) reconnaissance team surveyed five beaches in Sri Lanka, India and Thailand and found that seawall wave-deflection greatly reduced the speed and force with which the wave struck buildings, allowing them to survive structurally. This study shows that even small seawalls (1-meter high), presumably to protect against high perigean tides and storm surges, proved highly effective in reducing damage and deaths by diverting the horizontal force of the wave vertically, reducing the forces on the landward structures. Shepard, Macdonald and Cox (1950) comment on the value of the strongly built concrete seawall at the Puu Maile Hospital in Hilo, HI during the 1 April 1946 tsunami, where the wave rose about 20 feet, flooding over the wall. They say: "The wall itself was undamaged, and buildings sheltered by it were undisturbed except for minor damage by flooding." Seawalls have been used in Japan for many decades and many reports look at the utility of seawalls as effective tsunami countermeasures in Japan (Togashi 1981, Horikawa and Shuto 1983, Miyoshi 1983, Kawaguchi et al. 1995).

Seawalls must be well designed, constructed, and maintained; they should be long and the crest (top) of the seawall must be high enough (i.e. correspond to the expected tsunami recurrence level at the site) to prevent overflow of tsunami. High seawalls require access gates or regularly spaced opening for pedestrian access to the beach. COPRI Investigators found that damage to inland shops appeared to correlate to these openings of the seawall along the business district of Patong Beach (Dalrymple and Kriebel 2005). Scour of the beach berm also appeared to be related to these openings, probably because of the draining of the receding tsunami floodwaters seaward through the openings. If access had been provided by cross-over access paths over the wall, instead of openings in the wall, the constant wall elevation along the beach would presumably have reduced damage significantly. In the Maldives, on Male’ Island, seawalls were effective to reduce tsunami flooding, because the tsunami did not come at high tide. Had the tide level at the moment of the tsunami arrival been higher, the seawall would have been overtopped and flooding may have been more severe (Fujima et al. 2005).

As with seawalls designed to protect against storm surges, the vertical or concave seaward design of seawalls is important. COPRI Investigators found that at the north end of Patong Beach, in Thailand the design of a masonry seawall created a problem. Rather than having a vertical seaward face, the wall sloped inland, creating a ramp for the tsunami run-up jet that essentially launched the water into the attic of the building the wall was supposed to protect (Dalrymple and Kriebel 2005).

Breakwaters – Reduction of tsunami height can also be achieved by means of offshore breakwaters which provide a solution for the protection of port areas from tsunami attacks. After the severe damages resulting from the 1960 Chilean earthquake, Japan has started to construct breakwaters to protect its ports and harbours from violent tsunamis. Matsumoto and Suzuki (1983) have published on the design and construction of the first breakwater in Japan, completed 7 years after the Chilean earthquake tsunami of 1967. There are also many numerical computation methods available on the effect of breakwaters in dissipating tsunami energy. One such method applied to the 1968 Tokachi-oki earthquake tsunami in Japan and can be used to demonstrate that a tsunami breakwater would have reduced the tsunami height by one half had it been constructed as a countermeasure to the 1968 tsunami (Tanimoto 1983).

Breakwaters might be a preferable option to seawalls as a tsunami protection work in some instances. In the case of Ohfanto Bay, where the first Japanese breakwater was installed, Matsumoto and Suzuki (1983) describe the following advantages of breakwater to seawall: (1) Seawalls might hinder future development as they block access and separate port from city; (2) The assets of the bay can not be protected sufficiently by seawalls in case of a great tsunami; (3) In the case of Ohfunato City, the shape of the bay being narrow and long and the position of the city, being located on hilly or mountainous terrain, makes breakwaters the only feasible option. For bays that are narrow and long, it would be necessary to construct long seawalls as tsunami protection works which would result in prohibitively high costs.

Breakwaters reduce the velocity of the tsunami flowing in toward the protected area, except in the vicinity of the entrance. This reduction of velocity in itself has the effect of delaying the tsunami arrival in the city and port, providing more evacuation options.
Breakwaters are also effective in reducing the tsunami height and a parameter used to measure this reduction is referred to as the “peakcut effect” of a breakwater. Problems to consider in constructing breakwaters, include such items as volume of permeating water through the rubble mounds, resonant oscillation and influence on other places outside and in the vicinity of the breakwater (Matsumoto and Suzuki 1983).

Rigid houses and Buildings - Large obstacles such as grouped houses are expected to be effective to some extent in reducing the inundation of tsunamis. Buildings can be effective measures to reduce tsunami damage behind them as they work like breakwaters on the land. These are numerous cases where rigid coastal houses contributed to reduction of the tsunami behind them. Records show that when the 1960 Chilean Tsunami hit Kushiro city, Hokkaido, Japan the horizontal distance of tsunami inundation was only 20m in areas dense with residential structures, but more than 100m along wide boulevards (Fukushima 1961). Similarly, in the southwest of Sri Lanka, the tsunami trace height was 4.8m behind completely collapsed houses along the coast. On the other hand, it was 3.2m behind the houses with little damage (Dalrymple and Kriebel 2005). A numerical simulation method which examines the reproduction of the tsunami inundation reduction effect through large obstacles is presented by Goto and Shuto (Goto and Shuto 1983). Combination of seawall and rigid buildings as protection measures require some careful considerations. Dalrymple and Kriebel (2005) show in buildings they surveyed after the Indian Ocean Tsunami in five beaches of Sri Lanka, Thailand and India, while elevated buildings behind seawalls survive because the brunt of the force goes underneath the main structure, those buildings whose foundations were at the same height as the top of existing seawalls were completely destroyed.

Substantially constructed buildings of concrete, masonry, and heavy steel frames are likely to perform fairly well in a tsunami unless compromised by earthquake shaking. Wood-frame buildings, manufactured housing, and light steel-frame structures at lower elevations close the shoreline are likely to fare poorly in a tsunami (National Tsunami Hazard Mitigation Program March 2001). This was also confirmed by experience in the Indian Ocean tsunami , where the collapsed houses were primarily masonry one-story buildings with thin walls, while buildings with two stories or higher resisted the hydrostatic and hydrodynamic pressures imposed by the tsunami well due to stronger first story built with reinforced concrete frames and added resistance capacity of the taller and heavier structures (Dias, Dissanayake et al. 2006; Khazai, Franco et al. 2006

(Dias et al. 2006, Khazai et al. 2006). It is also in agreement with the experience in 1993 Hokkaido-Nansei-Oki Earthquake Tsunami (Shuto and Matsutomi 1995) and April 1946 tsunami in Hawaii (Shepard et al. 1950). Additionally, in Alaska during the 27 March 1964 tsunami, Wilson and Torum (Wilson and Torum 1968) found that the few concrete-block and reinforced concrete structures (most buildings were wood frame) withstood tsunami waves rather well, and cited examples. They recommend: "Sound reinforced-concrete construction with deep embedded foundations or solid raft foundations (foundation mats) capable of resisting scour; shear walls are desirable." Dalrymple and Kriebel (Dalrymple and Kriebel 2005) drew some very clear conclusions based on their observation of post-tsunami damage about structural design in a tsunami-prone regions.

1. Most of the well designed, reinforced concrete buildings with good foundations survived the wave attack.
2. The survival rate was even higher for buildings that were elevated, allowing the water to flow under the structure.
3. In addition, if the structure was constructed so water could flow through the first floor, structural damage was minimized, despite the loss of interior contents.

Distributed throughout many reports and papers are comments and recommendations for designing for tsunami hazards. Building codes have been developed, and promulgated. The Tsunami Hazard Mitigation Program (NOAA, USGS, FEMA, NSF, Alaska, California, Hawaii, Oregon, and Washington) has set forward “Seven Principles for Planning and Designing for Tsunami Hazards” (National Tsunami Hazard Mitigation Program March 2001). This publication was considered at the NSF workshop at Hilo, Hawaii in December 2006 and recommendations were made (Wiegel 2006a). Valuable information on loads and design for tsunami have been collected in reports such as Yeh, Reobertson and Preuss (Yeh et al. 2005); Coastal Engineering Manual (FEMA 2000); Dames and More Engineering Consultants (Dames&Moore 1980); Camfield’s Tsunami Engineering (Camfield 1980).

Besides designing houses according to tsunami resistant standards, new hotels in coastal areas, typically multi-level concrete frame structures, can be designed to withstand tsunami and earthquake forces and allow waves to pass through the ground floor parking, lobby and service spaces, leaving upper level rooms undamaged (Lowe 1971, Wiegel 2006a). This was actually part of the (accidental) design of many resorts in Thailand, which had reinforced concrete buildings that contained resort apartments with sliding glass doors facing the sea and the backs of the buildings. These buildings suffered little structural damage as the force of the tsunami broke through all of the doors and windows, thus reducing the force of the water on the building itself. By contrast, concrete buildings with solid masonry in-fill walls and no flow-through capability often experienced destruction of the walls and, in many cases, damage to the load-bearing structural frame (Dalrymple and Kriebel 2005).

Integrated System – A combination of engineered and natural defence systems maybe used in tandem to provide protection against tsunamis. Structural measures can provide protection for levels of tsunami hazards for which they were designed for. However, for the hazards exceeding the specified level, the structural measures are not effective in preventing damages. Thus, non-structural measures, such as risk awareness and education, evacuation drills and preparation in combination with natural coastal protection can help prevent the loss of human lives. For example, Okushiri island a technologically-advanced integrated defence system has been set up against tsunami. Here, in the event of a tsunami earthquake, a network of sensors will automatically set off an alarm in each resident’s house, and four flood gates will close to prevent waves from surging upriver. 22 escape routes whose entrances are lit by solar-powered sign-boards will enable residents to get to higher ground. At the port, a 50,000 square-foot evacuation terrace raised 20 feet can provide refuge to workers.

3.4 Impact and Tradeoffs of Coastal Structures

Today, nations with coasts exposed to threats of tsunami, hurricanes, cyclones and storm surges are trying to decide whether to allow new construction on the coast. In many places, such as in Hawaii, and in California, it is difficult or nearly impossible to obtain a permit to build a new seawall for example (Eversole and Norcoss-Nu'u 2006). In Japan, efforts are under way, at great cost and expense, to ensure that ports are tsunami-proof and that populations living near the sea are protected through appropriate construction and alerted through warning systems. For example, on Okushiri Island, a seawall 4.5 meters high was built to protect the Aonae peninsula. Yet this wall was overtopped by a tsunami in 1993, and more than 185 people were killed. Since then, a new seawall ranging between 10 to 16 meters and the island was rebuilt at the cost of 1.5 million yen. There is an ongoing debate about the wisdom of the seawall, which is so high now it obstructs the view of the sea and was extremely expensive to build (Onishi 2006). Coastal protection works and procedures may affect the quality of daily life (inconvenience/ convenience), and efficiency of use of the waterfront. They also involve tradeoffs, and adjustments. They have risks and may be too costly. Some degree of risk that may be acceptable has to be decided on based on exposure to each coastal hazards and the capacities available for risk reduction (Wiegel 2006a).

An integrated approach to coastal protection must consider social and economic tradeoffs as well as the relation between the effects of coastal structures on wave climate, beach morphology, coastal ecology, etc. Engineered defence systems, have morphological, ecological and socio-economic components, and the greater these relations are understood, the greater the coastal system's adaptive capacity to perturbations. Enhancing coastal resilience is increasingly viewed as a cost-effective way to prepare for uncertain future changes while maintaining opportunities for coastal development (Klein et al. 1998). The Netherlands has known a long tradition of controlling natural coastal processes by stringent dune management and building hard coastal defence structures. However, both socio-economic and natural adaptive processes have become constrained owing to the limited availability of land and the diminished coastal resilience that has resulted from technological solutions and legal provisions. A recent study “Growing with the Sea” proposes to restore natural coastal processes along the Dutch coast and let natural and socio-economic systems interact more dynamically. It explores possibilities of enhancing coastal resilience in The

Netherlands by allowing managed retreat in areas where it is environmentally acceptable and reclaiming land in other areas (Klein et al. 1998).

A project aimed to promote effective and environmentally compatible design of low crested coastal defence structures through a multi-disciplinary approach, is the DELOS project in Spain (Mediterranean Sea), Italy (Adriatic Sea) and UK (English Channel and Atlantic Ocean) (Caceres et al. 2005, Lamberti 2005, Lamberti et al. 2005, Martin et al. 2005, Martinelli et al. 2006, Zanuttigh and Lamberti 2006, Davidson et al. 2007), which integrates research on hydrodynamics, beach morphology, engineering design, structure and dynamics of coastal assemblages of animals and plants, cost-benefit analysis as well as assessment of societal and economic impacts (recreational benefits, swimming safety, beach quality). From a socio-economical point of view, the DELOS project provides an up-to-date inventory of coastal environment valuation methods (Hanemann and Strand 1993), the analysis of the possibility of transferring benefit quantifications from one country to another (Ahearn et al. 1998) extending significantly the base on which local quantifications can be made.

Guidelines have been drafted (Burcharth and Lamberti 2004) to be appropriate throughout the European Union taking into regard current European Commission policy and directives to promote sustainable development and integrated coastal zone management. The target audience for these guidelines consists of engineers and local authorities promoting coastal protection schemes. It is also of relevance in providing a briefing of current best practice for local and national planning authorities, statutory agencies and other stakeholders in the coastal zone. In the following section, a review of the literature related to the environmental and socio-economic impact of coastal structures and the complex interaction among the coastal defence structures, the biological system and society is presented.

3.4.1 Economic Impacts

Cost of Construction - Well-engineered concrete seawalls, which extend both high enough to prevent significant overtopping from storm surges and deep enough such that they are not endangered by scour, are relatively expensive to build. The total costs for one concrete seawall fronted with rip rap built in Monterey Bay in 1983 reached over $6000 per linear foot at present day costs. At another location in central California a concrete sheet pile seawall was completed in 1985 for $1500 per linear foot at present day costs. In comparison, a concrete seawall completed in San Francisco in 1929 was $8000 per linear foot at a total cost of $6.5 million when adjusted for inflation (Fulton-Bennett and Griggs 1986). In the United States, the U.S. Army Corps of Engineers' (USACE) shoreline protection program covers 8 percent of the nation's 2,700 miles of critically eroding shoreline and consists of 82 specifically authorized projects. Total actual expenditures, including periodic nourishment, for these 82 projects from 1950 to 1995 have been $731 million. When updated to 2007 dollars this expenditure becomes $2,180 million (Hillyer et al. 1997). Construction costs for seawalls or breakwaters for protection against great tsunami is even significantly higher, because the tsunami run-up is much higher than storm surges and the protection works are accordingly costlier, especially when the frequency of an extreme tsunami is taken into consideration. The first breakwater that was constructed in Japan three years after the 1963 Chilean earthquake took four years to complete at the cost of 1.9 billion yens at that time (Matsumoto and Suzuki 1983). Tanimoto (1983) argues that the severity of great tsunami damages removes any doubt against the necessity of tsunami protection works, even if they are very costly. Hillyer and others (Hillyer et al. 1997) have performed cost-benefit analyses to evaluate whether the "estimated" benefits of coastal protection works will converge on the "actual" or measured benefits (and costs). The key to the benefit-cost analysis is that the benefits are estimated based on a probabilistic assumption that, over the period of analysis (generally 50 years), a comparable sequence of events will occur as in the past, causing a comparable level of property damages. In another cost-benefit study, King (1991) performed an analysis of the economic benefits of hurricane and storm damage reduction. According to the methodology used for computing the benefits of hurricane and storm damage reduction, the composite damage reduction method, benefits of a project for hurricane and storm damage protection equal the amount of hurricane damages without the proposed project minus the amount of hurricane damages with the project. Benefits may also be realized from increased recreation, land enhancement, lost land reduction, and reduced maintenance of infrastructure. Furthermore, this methodology considers damages to structures from inundation, waves, storm-induced recession and long-term erosion. The economic model will also take into account other factors such as rebuilding constraints and structural impediments to erosion.

Cost of Maintenance - In addition to cost of construction, maintenance of existing shoreline structures is becoming more important with increasing coastal population. The cost of maintaining the existing coastal infrastructure is high and methods for reducing these costs are being developed and employed (Houston 1996). One present focus on reducing the costs of coastal structures is by employing the concept of life cycle efficiency as opposed to the historical perspective of "no damage" for the design storm. Life cycle efficiency means that a shore protection structure has a certain service life. Typically, engineers think in terms of a 20 to 25 year life for a coastal protection structure. The argument is that on a rapidly eroding coastline, any protective structure built to withstand direct wave attack will probably fail eventually. Even a well-designed structure is likely to fail once its design life has been exceeded, and especially if it has not been properly maintained (Fulton-Bennet). Research and development work is underway to provide tools for life-cycle, risk and reliability analysis techniques in both planning and design studies in order to develop more efficient designs. One research centre that is actively pursuing this work is the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program of the US Corps of Engineers.

Influence on Development - One item of specific concern with regards to the US Army Corps of Engineers protection works is that of induced development, i.e., do shore protection projects lead to more growth and development in protected areas, and hence, ultimately to increases in storm damages rather than a reduction in damages. Three specific economic analyses were applied during the course of the study to determine whether USACE shore protection projects induce development in the areas they protect. Hillyer et al. (1997), carried out three complementary studies were to investigate this: (1)

a survey of beachfront community residents; (2) an econometric model of beachfront development; and (3) an econometric analysis of beachfront housing prices. None of these approaches could verify that there is a measurable induced development link. The analyses demonstrated that the primary determinant of development of beachfront communities is growth in beachfront demand based on rising income and employment in non-coastal areas, rather than the presence or absence of a shore protection project. In fact, there is limited public awareness of the Federal shore protection program, where Federal projects currently exist, and of the involvement of the USACE in reducing risks through project construction (Hillyer et al. 1997).

3.4.2 Social Impacts

Beach Access - Beach access may pose limitations for seawall construction. Concrete seawalls are usually built along straight, low-lying stretches of coast and houses, roads, or other improvements are often built on the fill behind the wall. Although some small concrete seawalls have been built in front of cliffed pocket beach areas, the access required for construction is often a major limitation. Seawalls used to protect against tsunamis are much higher than sea walls used to protect against storm surges and can reach crest heights of 16 meters and above. For high seawalls, on-land gates are additionally necessary to access coasts and harbours. The construction of high seawalls along the waterline of a port area, however, causes hindrance and inconvenience for daily port operation and the community in the hinterland. Additionally, arguments have been made that by blocking the view of the sea by high seawalls, overtime it could reduce the communities' ability to understand the sea and give them an indication of when to flee (Onishi 2005).

False Sense of Security – The blocking of view and access to the sea by seawalls has consequences not just on the tourism industry which claim that seawalls repel tourists, but upon the risk perception of the local community as well instilling a false sense of security. One case where critics say engineering protection works may have lead to instilling a false sense of security is in Okushiri Island. This small island in Japan which suffered severe damage by the 1993 Hokkaido Nansei-oki Earthquake Tsunami, was rebuilt at a cost of 1.3 million yen at the peak of Japan's public works spending of the late 1990s. After the tsunami, 9 miles of the 52 miles of the island's perimeter, including almost all coastal stretches inhabited by its 3,700 people were protected with high seawalls ranging in height from 18 to 38 feet which restricted access and view to the beach. As a result of the fortressing effect of the great seawall structure, indeed many islanders said they did not bother taking part in regular evacuation drills. Interestingly, it is Okushiri island that has set up a technologically-advanced integrated defence system against tsunami discussed earlier in this section (Fujima et al. 2005). The potential lack of awareness of the community due to false sense of security, may work against the resiliency that the integrated tsunami defence system is intending to provide. In fact statistics on risk reduction activities by the general public in Japan demonstrate people's preference for immediate warning systems, rather than advance preparation (Hani 2007).

Evacuation – Evacuation inland ('horizontal evacuation') is the traditional method of saving life in areas forecast as the site of hurricane landfall. Even though, 'High Confidence' warning time for hurricanes is about 12 hours, and even less for tsunamis, some coastal areas are now so densely populated that twice that time is required for evacuation. The alternative of vertical evacuation (going upstairs in hurricane-proof buildings) is resisted by planners who are concerned that its risks are too high and that partial acceptance of the concept would vitiate compliance with the horizontal component. But in some areas there may no longer be a choice (Salmon 1984). Horikawa and Shuto (1983) maintain that based on past experience with tsunami protection measures in Japan, "it is quite dangerous to believe that a violent tsunami attack can be completely prevented by man-made structures, and suggest that evacuation to a safe area before a tsunami attack is the best resource for the inhabitants." In some regions however, the tsunami generating source is so close that almost no time is available for evacuation. In some area, both tsunami and direct earthquake effects (shaking, subsidence/uplift, ground-breaking, liquefaction and landslides) occur nearly simultaneously. Effective integration of both vertical and horizontal evacuation will require development of new plans and policies (Salmon 1984). Besides developing an accurate early warning system and educating communities on how to respond to such a system by conducting evacuation training, a successful evacuation campaign also relies on much pre-planning including the construction of well-marked escape routes, and strategically located evacuation towers, evacuation terraces or high and rigid buildings that can be used as evacuation shelters (Fujima et al. 2005). It is important also that evacuation measures consider the varied needs and resources of the particular community they are serving. For example, after the tsunami damage suffered by Okushiri Island during the1993 Hokkaido Nansei-oki Earthquake, a new terrace was constructed which serves both as a tsunami evacuation measure as well as a port that is used for fishery activities. The fishery port was purposefully left out of the seawall to keep the fishery functions active and an multi-use evacuation plan was chosen as the mitigation option instead (Fujima et al. 2005). Structures to be designed as vertical evacuation shelters must have sufficient structural integrity to resist expected tsunami forces and earthquake ground shaking for tsunamis originating locally. Building codes and design standards for these structures should go beyond the minimum life safety requirements of most locally adopted codes (Wiegel 2006a). Yeh, Robertson and Preuss (Yeh et al. 2005) have developed a set of design guidelines for structures that serve as tsunami vertical evacuation sites.

Relocation – Relocation, or moving existing resources, such as residences, commercial buildings and roads, landward to maintain a certain minimum distance between the resource and the location of the coast segment at risk, might be a viable trade-off in some cases (Good and Riddlington 1992). However, relocation can have complex social and economic consequences that should be considered before it is used as a planning and risk mitigation tool. Buffer zones or set back lines as policy to implement relocation can give disproportionate attention to reducing exposure to future extreme event and, subsequently, may not address the critical social, economic and institutional factors that influenced sensitivity to the hazard in the first place (Ingram et al. 2006)

3.4.3 Environmental Impacts

A strict relation among coastal protection works and beach erosion, habitat changes and beach value exists. Results obtained in Lido di Dante, Italy, by Lamberti and Zanuttigh (2005), suggests the necessity of integrated approaches and thus the relevance of design guidelines covering: structure stability and construction problems, hydro- and morpho-dynamic effects, and environmental effects. A project aimed to promote effective and environmentally compatible design of low crested coastal protection structures through a multi-disciplinary approach, is the DELOS project in Spain (Mediterranean Sea), Italy (Adriatic Sea) and UK (English Channel and Atlantic Ocean) (Caceres et al. 2005, Lamberti 2005, Lamberti et al. 2005, Martin et al. 2005, Martinelli et al. 2006, Zanuttigh and Lamberti 2006, Davidson et al. 2007), which integrates research on hydrodynamics, beach morphology, engineering design, structure and dynamics of coastal assemblages of animals and plants, cost-benefit analysis as well as assessment of social consequences.

In the United States, between the periods of 1950-1995, the coastal protection works program has also shifted from primarily "hard" structures (groins, seawalls, breakwaters, etc.) to primarily "soft" beach restoration and nourishment through placement of sand. Beach restoration and nourishment is also the most environmentally compatible shore protection measure. The projects receive intense preconstruction coordination with environmental agencies to assure no long term adverse environmental impacts result from the projects. Over this same time period, a set of policies has led the program to shift from primarily recreation oriented to one of protection for storm damage reduction (Hillyer et al. 1997).

Erosion – There are many examples of properly planned, designed, constructed, and maintained coastal defence structures, such as seawalls and revetments, that have prevented further retreat of the shoreline and provided a high level of protection of the property backing the structure, but beaches sometimes have been lost as a result. Thus, their effects on adjacent shores must be carefully evaluated (Committee on Coastal Erosion Zone Management 1990). The problem is that many of these rigid structures may induce beach erosion by depriving the downdrift areas of natural sand supply. Efforts to protect certain segments of shoreline can in some circumstances induce increased erosion on nearby unprotected shorelines. Location of a seawall relative to the shoreline is an important parameter in determining its potential effects on erosion (Weggel 1988). An overview of the effects of seawall on beaches is given in Kraus (1987, 1988), (Griggs et al. 1997) and an edited collection of papers on this topic is contained in Kraus and Pilkey (1988). In a survey of 70 technical papers and reports on the effects of seawalls on beaches (Kraus, 1987), followed by a more extensive study with an additional 30 references, led Kraus (1988) to conclude: beach changes near seawalls, both in magnitude and variation, is similar to that on beaches without seawalls, if a sediment supply exists. Sediment volumes eroded by storms at beaches with and without seawalls are comparable, as are post-storm recovery rates. In addition, the shape of the beach profile after construction of a seawall is similar to the preconstruction shape if a sediment supply exists, showing the same number of bars with approximately the same volumes of relative locations. The form of the erosional response to storms at seawalls is typically different. Limited evidence indicates that the subaqueous nearshore profile on a sediment-deficient coast with seawalls does not steepen indefinitely, but approaches an equilibrium configuration compatible with the coarser-grained particles comprising the bottom sediment.

The universal effect is that sand impounded behind the structure cannot participate in bar development during storms. The formation during storms of a large breakpoint bar (built from material from the upper profile) is the usual storm response of the beach. In front of a seawall or revetment, sand to develop a bar may come from unprotected properties adjacent to the structure. Therefore, the structure may increase erosion on adjacent properties. This has been observed in the laboratory and after hurricanes on the Gulf coast (Walton and Sensabaugh 1978; McDougal et al. 1987). However, other efforts, such as a five-year program monitoring revetments and seawalls in Oregon, do not support this observation (Good 1994). A seawall or revetment reduces or eliminates toe erosion and also reduces winnowing of the bluff face. Some of this benefit extends to the adjacent unprotected properties. Preliminary field results suggest that this stabilizing effect is more important than the demand for sand for bar development during storms (Good and Riddlington 1992). Griggs et al. (1991) discuss the results of a four-year seawall monitoring program along a pocket beach in southern California. Komar and McDougal (1988) describe observation of seawall and beach interaction on the Oregon coast.

Griggs et al. (1997) identified three potential impacts of protection structures: (a) impoundment or placement loss, (b) passive erosion, and (c) active erosion. The third of these impacts has been the subject of considerable discussion and debate, but until recently, has not been systematically investigated in the field. In a survey that presents 7 years of biweekly to monthly monitoring of beaches adjacent to seawalls along the central California coast, Griggs et al. (1997) investigate:

a) How do beaches backed by seawalls change seasonally in response to changing wave climate compared to adjacent beaches without seawalls?
b) What bearing does seawall design have on beach response?
c) Does the position of a seawall on the beach profile exert any effect on the seasonal beach changes?
d) Do seawalls exert alongshore control on beach development, crossshore control, or both? and;
e) Are there any long-term effects of seawalls on fronting or adjacent beaches?

These surveys have allowed evaluation of both the seasonal beach changes due to the presence of seawalls as well as any longer term effects. Although active erosion during winter months has been documented at seawalls in this study, erosion has been seasonal and temporary in nature. A comparison of summer and winter beach profiles on beaches with seawalls and on adjacent control beaches reveals no significant long-term effects or impacts of seawalls in this location during this 7-year period. Results from this survey indicate that although beach width decreased in front of the seawall due to passive erosion, active erosion, even under storm conditions, was minimal and did not produce any long-term effects.

Degradation of Natural Landforms – Coastal structures might compromise neighbouring natural and engineered defence system if they are not correctly designed or placed. Remote sensing studies of aerial imagery between 1955 and 1995 of the coastal zone in southwest Taiwan bounded by the Pei-Kang and Tseng-Wen rivers, have shown that inappropriately designed or misplaced coastal engineering structures destroy or reduce the effectiveness of neighbouring natural defence systems (i.e. muddy tidal flats, offshore bars, spits, lagoons and coastal sand dunes) leading to storm damage, flooding and encroachment by the sea (Lin 1996). There is a need for a coordinated coastal management program to regulate on-shore activities.

Colonization of Structure - Hydrodynamics strongly affects barrier colonisation by conditioning feeding process and removing organisms under extreme conditions. Ecological models integrate biological and hydrodynamic data to evaluate different impact scenarios (Martin et al. 2005); these scenarios allow to identify characteristics (including breakwater morphology, size, location and distance between the structures) which minimise disruption to coastal assemblages and maximise benefits in terms of production of economically relevant species and/or protection of exploited or endangered species (Airoldi et al. 2005, Moschella et al. 2005). So far, the complex interactions between physical and biological processes on and around artificial coastal structures are poorly identified, and the quantification of how the outcomes of such interactions vary in response to environmental changes at a range of spatial and temporal scales (Miller 1999) are still missing. Few quantitative data are available about colonisation processes, life-histories and food web dynamics of species associated with artificial structures, and even less information is available about linkages with surrounding natural habitats and large scale impacts (either positive or negative) of structures on regional biodiversity and population dynamics (Boshnsack 1985). The rocky barrier of the low crest coastal protection works in Lido di Dante, Italy, provides support for active and rich biological assemblage, which enhances water filtration, and induces a change of assemblages in the area, increasing biodiversity of the littoral zone (Lamberti and Zanuttigh 2005). A degradation of water quality in a bay might be anticipated after the construction of coastal structures such as breakwaters as they can lead to decreasing the exchange rate of seawater. However, in a study by Tomonari et al. (Tomonari et al. 2001), which used concentration of dissolved oxygen as an index of water quality deterioration to examine the effect of tsunami protection breakwater in Kamaishi bay in Japan, a long-term trend of dissolved oxygen concentration change was not detected.

Marine Life - In another study, Guidetti et al. (2005) show that coastal protection works may significantly affect predatory fishes in artificial rocky habitats and that coastal defence structures such as breakwaters, can represent a potential tool for fish population recovery and enhancement of local fisheries.

Complementary Information Resources

Sharepoint Site
All electronic publications are stored on the SIG sharepoint site and are available for download. Currently, there is about 90 MB of content which is sorted in six categories: Bibliographic Indices, Historical Case Reports, General Mitigation, Engineering Solution, Coastal Landforms and Coastal Vegetation. Where relevant, paper copies have been scanned and added to the electronic repository of the sharepoint site. Access to this site is created by submitting a request directly to Teresa Trueman-Madriaga.

Del.icio.us Site
A book-marking website has been created to store and tag all information resources, portals and publications that are available online. Free access to this information is available by following link below. We ask that you use and help contribute to the collection of bookmarks and use the relevant tags to sort the websites.

http://del.icio.us/SIG_Tsunami

Tsunami Information Sources – Professor Robert Wiegel

Professor Robert Wiegel at UC Berkeley's Department of Civil and Environmental Engineering has compiled a series of 3 reports, classifying and about 3500 tsunami information sources (reports, articles and papers) on tsunami-related information.

Reference to reports of tsunami information sources by Robert L. Wiegel, are available at
http://www.lib.berkeley.edu/WRCA/tsunamis.html

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ITIC
The International Tsunami Information Center (ITIC), Library in Honolulu, Hawaii houses a large compilation of tsunami information resources. A Technical Review of the ITIC content was performed in 1997 by Dr. Denger of Humboldt State University (online reference). She found that in comparison to other collections, made via Internet

searches of major library electronic card catalogs and databases, the ITIC library with approximately over 3000 books and documents appears to have the highest number and concentration of books about tsunamis known. As of the date of her assessment, most of the material at the ITIC pertains to Tsunami science and only “perhaps 10 percent” applies to tsunami mitigation.

International Tsunami Information Center
Box 50027
Honolulu, Hawaii 96850-4993
Telephone: (808) 541-1657 or 1658
Fax: (808) 541-1678
E-mail: itic.tsunami@noaa.gov

ITIC Online Library Search URL
http://ioc3.unesco.org/itic/contents.php?id=281

TsuInfo

TsuInfo is headquartered at the Washington Department of Natural Resources, Division of Geology and Earth Resources (DGER) library. They have been intensively collecting reports about tsunamis in that library since 1994 and have issued two bibliographies to aid tsunami mitigation in Washington (Manson 1994; Manson and Walkling, 1998). Funding from the national program allows them to expand their tsunami mitigation collection and to provide copies of these materials to emergency managers and decision makers in the at-risk communities of the Pacific states. Dr. Bijan Khazai is a subscriber of the TsuInfo program and has been in contact with the TsuInfo librarian, Ms. Walking, who has generously mailed and scanned rare publications and has made them available to us.

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Additional Resources

Coastal Structures

A series of comprehensive handbooks 0prepared on Coastal Structures for the New York Sea Grant Institute, by the Geotechnical Engineering Group at Cornell University. These manuals provide an in-depth background on the construction, design and performance of waterfront structures. Three of the handbooks are most relevant: A handbook that deals with analysis, design and construction of coastal structures (Ehrlich and Hubbell 1982), (Saczynski and Kulhawy 1982); a handbook that deals with the performance of waterfront structure in coastal regimes during various loading conditions, including waves, winds, tides and earthquakes (Hubbell and Kulhawy 1982a); and a handbook that deals with the evaluation and use of different materials in building waterfront structures (Hubbell and Kulhawy 1982b).

Ehrlich, L., A. and W. Hubbell, D. (1982). Coastal Structures Handbook Series - Breakwaters, Jetties and Groins, New York Sea Grant Institute: 376.

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The Coastal Engineering Manual (CEM) provides a single, comprehensive technical document that incorporates tools and procedures to plan, design, construct, and maintain coastal projects. Included in this engineering manual and relevant to this report are chapters on the basic principles of coastal processes, coastal protection types, functions, planning and design and guidance on how to formulate and conduct studies in support of coastal shore protection.

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Case histories for USACE-maintained coastal structures were reported in a series of nine reports prepared under the USACE Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program (Bottin 1988a, and 1988b, Sargent 1988, Sargent and Bottin 1989a, 1989b, and 1989c, Sargent et al. 1988, Smith 1988, and Ward 1988). The more than 500 structures discussed in these reports have a total aggregate length of more than 500 km. Over 90 percent of these structures are large rubble mound breakwaters and jetties. Most of these structures were originally built in the early 1900's and have been extended and rehabilitated many times.

1. *Case Histories of Corps Breakwater and Jetty Structures - South Pacific Division - Report 1 (Technical Report REMR-CO-3) - A case history from the South Pacific Division which encompasses 28 projects along the California coastline.*
2. *Case Histories of Corps Breakwater and Jetty Structures - South Atlantic Division - Report 2 (*Technical Report REMR-CO-3) *- From the South Atlantic Division. There are 32 projects that are located from Wilmington DE to Mobile AL*
3. *Case Histories of Corps Breakwater and Jetty Structures - North Central Division - Report 3 (Technical Report REMR-CO-3) - A case history from the North Central Division and covers 107 projects in three areas of management. The report has been separated into five parts.*
4. *Case Histories of Corps Breakwater and Jetty Structures - Pacific Ocean Division - Report 4 (*Technical Report REMR-CO-3) *- A case history from the Pacific Ocean Division and encompasses 14 stuructures on the the Islands of Hawaii, Guam, and in the Samoan Island chain.*
5. *Case Histories of Corps Breakwater and Jetty Structures - North Atlantic Division - Report 5 (*Technical Report REMR-CO-3) *- A case history from the North Atlantic Division and encompasses 58 projects from New York City to Norfolk VA.*
6. *Case Histories of Corps Breakwater and Jetty Structures - North Pacific Division - Report 6 (Technical Report REMR-COS) - A case history of the North pacific Division and encompases 48 projects, comprised of 68 breakwaters and 35 jetties. They are located between Portland, Oregon and Nome, Alaska.*
7. *Case Histories of Corps Breakwater and Jetty Structures - New England Division - Report 7 (*Technical Report REMR-CO-3) *- A case study from the New England Division and encompasses 52 project located Western Conneticut and Northern Maine.*
8. *Case Histories of Corps Breakwater and Jetty Structures - Lower Mississippi Valley Division - Report 8 (Technical Report REMR-CO-3) - A case historyy from the Lower Mississippi Valley Division and encompasses 10 projects located of the Gulf of Mexico. Eight of these projects are located at the mouth of the Mississippi River.*
9. *Case Histories of Corps Breakwater and Jetty Structures - Southwestern*

*Division - Report 9 (*Technical Report REMR-CO-3*)* *- This report is a case history from the Southwest Division and encompasses 12 projects. They are located within the Galveston District and are located on the Texas Gulf Coast.*

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