TSUNAMI PROTECTION BY NATURAL AND ARTIFICIAL BARRIERS

Dauji Saha[1], Kapilesh Bhargava[2], Kailash Agarwal[3], and Sekhar Basu[4]

[1] Scientific Officer, NRPSED, NRB, Bhabha Atomic Research Centre, Mumbai, INDIA (dauji_saha@yahoo.com)
[2] Assistant General Manager, NRPSED, NRB, Bhabha Atomic Research Centre, Anushaktinagar, Mumbai, INDIA
& Associate Professor, Homi Bhabha National Institute, Anushaktinagar, Mumbai, INDIA
[3] General Manager, NRPSED, NRB, Bhabha Atomic Research Centre, Mumbai, INDIA.
[4] Director, Bhabha Atomic Research Centre, Mumbai, INDIA.

Abstract

Tsunami may be defined as a series of long wavelength waves, having period from 30 minutes to a couple of hours, occurring due to displacement of a large volume of water in ocean or a big lake. The various initiating events would include earthquakes, volcanic eruptions, underwater explosions, underwater landslides, and meteorite impact. The 2004 Indian Ocean tsunami exemplified this hazard for the Indian coast, especially the eastern one. The Fukushima incident in 2011 drew fresh attention to tsunami analysis, early detection and tsunami protection among nuclear community. Tsunami protection may be in active form like seawall to resist the incoming wave. Investigators have also brought out the passive resistance offered by coastal features like sand dunes, mangroves, vegetation, coral reefs and artificial structures. The present paper brings together the information regarding passive tsunami protection, available in recent literature.

Introduction

Tsunami may be defined as a series of long wavelength waves, having period from 30 minutes to a couple of hours, occurring due to displacement of a large volume of water in ocean or a big lake. The various initiating events would include earthquakes, volcanic eruptions, underwater explosions, underwater landslides, and meteorite impact. An earthquake with magnitude of 9.3 in the Sumatra fault triggered one of the most destructive tsunamis in the Indian Ocean on 26 December 2004 and caused widespread inundation and extensive damage to lives and property along the coasts of several Asian countries. The eastern coastline in India including the Andaman and Nicobar group of Islands, Tamil Nadu, Andhra Pradesh as well as

Kerala on the western coast were among the severely affected. This exemplified the tsunami hazard for the Indian coast, especially the eastern one. The Fukushima incident in 2011 drew fresh attention to tsunami analysis, early detection and tsunami protection among nuclear community.

The threat posed by tsunami would include the destructive force of the wave train, as also the functional disruption due to run-up and inundation of the facilities. Rather than the forces exerted on the structures by the tsunami wave train, inundation of key facilities has been identified as the prime reason for the 2011 Fukushima incident in Japan. Tsunami protection may be in active form like seawall to resist the incoming waves. In literature, several studies have been reported pertaining to the efficiency of the passive tsunami protection offered by natural barriers like mangroves, coral reef, sand dunes and coastal forest, as well as artificial barriers. This paper presents a comprehensive overview of the findings of the earlier investigators.

Efficacy of Mangroves

After the December 2004 Indian Ocean tsunami, Kathiresan and Rajendran (2005) presented a study conducted along 25-km coastline at Parangipettai, Tamil Nadu, India which included 18 coastal hamlets and an estuarine complex made of two estuaries, namely, Vellar and Coleroon, and highlighted the importance of coastal mangrove vegetations and location characteristics of human inhabitation to protect lives and wealth from the fury of tsunami. From their analysis, the authors concluded that with increasing area of coastal vegetation, distance and elevation of human inhabitation from the sea, the death toll and loss of wealth decreased. It was suggested that human inhabitation should be encouraged more than 1 km from the shoreline in elevated places, preferably behind dense mangroves or other coastal vegetation. The suitable plant species for the muddy substrates in the sheltered shorelines was mangroves, and for the sandy substrates in close proximity to the shoreline were coconut, palm, casuarinas and sand-binding vegetation. It was noticed that post tsunami, most of the coastal vegetation was affected in the study area with shedding of leaves or browning of canopies, with only the mangroves surviving without any apparent damage. The suitability and importance of mangroves in mitigating the effects of mighty waves like tsunami was emphasized.

Some possible drawbacks in the earlier study by Kathiresan and Rajendran (2005) were identified by Kerr et al. (2006). From independent analysis of the data of the previous study, it was shown that the vegetation area was weakly contributing to the tsunami mitigation effect, which was primarily governed by distance from the sea (~50%), followed by elevation (~35%). As the first wave in a wave train could clear much vegetation and enable the following waves to penetrate further than predicted on the basis of the wave height at the coast and the pre-existing vegetation, the overall effect of a series of waves could be significantly greater than the prediction on the basis of each wave arriving alone. Following the eruption of Krakatoa in 1883, tsunamis were estimated to have a wave height at the coast of 35 m and on the basis of wave height and vegetation roughness coefficient, penetration of around 2 km was predicted. The Tsunami Risks Project (2005) reported an actual penetration of up to 8 km inland through primary rainforest, almost four times the prediction. This effect should be factored in while assessing the protective capacity of vegetation, otherwise it might lead to a false sense of security and failure when a tsunami wave train actually arrives.

Vermaat and Thampanya (2006) threw further light on the potential tsunami mitigation effect of mangroves with statistical analysis like ANOVA-model with covariates, using the original data of Kathiresan and Rajendran (2005). The authors concluded that the original conclusion, though questioned by Kerr et al. (2006), held good. Mortality and property loss were found to be less behind mangroves, and literature existed which suggested that this could be generalized beyond the investigated area. Furthermore, the results indicated that mortality significantly reduced with increasing elevation above mean sea level, and property loss was governed by distance to the shore. However, it was mentioned that as relocation of human settlements 1 km inland may not be practical, and a combination of societal preparedness with early warning and disaster response systems would be more appropriate.

Among other factors, Alongi (2008) assessed the degree of resilience of mangrove forests to large, infrequent disturbance like tsunamis and their potential role in coastal protection. It was emphasized that mangroves had demonstrated considerable resilience over timescales commensurate with shoreline evolution and soil accretion rates in mangrove forests were keeping pace with mean sea level rise. Furthermore, the patterns of recovery of mangroves from natural disturbances like storms and hurricanes bore testimony to their resilience. In certain circumstances, mangroves could offer limited protection from tsunamis and some models using realistic forest variables suggested significant reduction in tsunami wave flow pressure for mangrove cover of width greater than 100m. The factors affecting the magnitude of energy absorption were mentioned as width of forest, slope of forest floor, tree density, tree diameter, proportion of above-ground biomass vested in roots, tree height, soil texture, forest location (open coast vs. lagoon), type of adjacent lowland vegetation and cover, presence of foreshore habitats (seagrass meadows, coral reefs, dunes), size and speed of tsunami, distance from tectonic event, and angle of tsunami incursion relative to the coastline.

Doubts have been cast over the possibility of survival of mangroves when impacted and inundated by tsunami wave train, and subsequently, on the protection that they may offer from tsunami waves. A study on this aspect was presented by Yanagisawa et al. (2009) using an integrated approach including satellite imagery analysis, field measurements, and numerical modeling. The authors investigated the damage to mangroves caused by the 2004 Indian Ocean tsunami at Pakarang Cape in Pang Nga Province, Thailand. From satellite imagery it was found that approximately 70% of the mangrove forest was destroyed by the tsunami. On field, it was noticed that the survival rate of mangroves increased with increasing stem diameter. For example, 72% of Rhizophora trees with a 25–30 cm stem diameter survived the tsunami impact, whereas only 19% with a 15–20 cm stem diameter survived. Based on the field measurements and numerical results, a fragility function, which was the relationship between the probability of damage and the bending stress, was proposed for the mangroves. Using the fragility function and numerical model based on the mangrove forest density, ground level, incident wave period, and inundation depth, it was shown that for the study area, mangrove cover reduced the inundation depth, with the reduction effect decreasing when the tsunami inundation depth exceeded 3 m, and was mostly lost when the tsunami inundation depth exceeded 6 m. Some limitations of the study were mentioned as the floating trees and debris load accounted in neither the force incident on the surviving mangroves, nor in the resistance offered to the flow. The fragility function would require further refinements to include varying stem diameter, different species, and variation in the region.

Efficacy of Sand Dunes and Coastal Forests

Mascarenhas and Jayakumar (2008) presented the results of field investigations along Tamil Nadu seaside, which revealed that the 2004 Indian Ocean tsunami had demolished dwellings within strips ranging from 6 to 132m (average width, 41 m) from the dune, and flooded up to a distance of 862m (average, 247 m) from the shore. The destruction was evident in damaged sand dunes, ripped dune vegetation, and shattered high value assets. In contrast, uprooting of trees of the casuarinas forest was limited to a strip ranging from 5 to 25m (average width, 14 m) nearest to the shore where the maximum wave run-up was 6.5m above sea level. Also noted were negligible over-wash along belts characterized by high dune complexes, intactness of villages shielded by dense forests as well as sand dunes, whereas maximum destruction was noticed on open beach front influenced by human activity. From the foregoing discussion, the authors concluded that sand dunes in general, and casuarina forests in particular, had displayed an innate capacity to dissipate even the powerful waves like tsunamis. It was suggested that a coastal hazards policy comprising of adaptation, dune restoration and forested buffer zones, could be a sustainable long-term option for Indian coasts.

A fresh analysis of the field survey results of 2004 Indian Ocean tsunami was presented by Patnaik et al. (2012) with focus on the tsunami run-up heights and inundation. It was observed that the Andhra coast was largely affected by the tsunami and in general the intensity of the tsunami decreased with run-up heights of 4.5m in the south to around 2m in the north with the distance of inundation varying from 60m to 900m. The authors identified the interdependency between the tsunami run-up height and inundation with the physical setup of the shoreline and the width of continental shelf. The vital role of local features such as dunes, vegetation and steepness of beaches in reducing the impact of tsunami was also mentioned. It was noted that the orientation of offshore depth contours had a significant influence in tsunami propagation and inundation. Beach slope was identified as another crucial parameter influencing the tsunami run-up and inundation. Coastal Characteristic Index (CCI) was proposed to represent the dependency of run-up heights and inundation on the independent tsunami parameters like shape factor and slope of the coast, length and width of mangrove/vegetation cover, coastal construction, and good correlation could be obtained between CCI and run-up as well as inundation. The average CCI was found to be inversely related to inundation, implying that coasts with lower value of CCI would be more vulnerable to tsunami inundation and thus, CCI was could be an effective parameter for assessing the tsunami hazard of any coast.

Efficacy of Coral Reefs

Fernando et al. (2008) investigated the effect of coral reefs on tsunami impact on the coast, and the influence of channels existing between reefs, with laboratory experiments. From the observations in Sri Lanka after the 2004 Indian Ocean tsunami which indicated significantly enhanced wave heights and water inundations in areas where coral poaching had been prevalent, it was postulated that low-resistance paths created by coral removal would lead to water jetting through them, while simultaneously reducing flow speeds in nearby coral-laden areas that offer higher bottom resistance to the flow. For the simulation of corals, a submerged porous barrier made of a uniform array of rods was used. Measurements of the flow velocities due to a solitary wave packet on a slope in presence and absence of the simulated uniform coral cover, and also with an opening, were taken. From the analysis it could be noticed that the coral canopy decreased the flow velocity substantially, due to increase in the bottom drag coefficient, which in turn was a strongly influenced by the canopy porosity. Jetting flow was observed in the case with gap in the simulated coral canopy, as the exit flow velocity from the gap became significantly greater than the surroundings. The factors governing the jetting effect included coral porosity, wave characteristics, features of coral canopy, water depth and gap size. It was concluded that during isolated wave events like tsunamis, the partial removal of natural barriers may cause local flow intensification, whereas intact barriers could have a buffering effect in reducing the tsunami wave height, velocity, run-up and inundation.

An investigation on the buffering effect of coral reefs and embayments on tsunami wave heights, inundation distances, and velocities was conducted by Gelfenbaum et al. (2011) using a numerical model of tsunami inundation, Delft3D, which had been validated for the 29 September 2009 tsunami in Tutuila, American Samoa. The study included the response of tsunamis to reefs of varying widths, depths, and roughness, the effects of channels incised in the reef and also the focusing effect of embayments. In place of the exact Tutuila conditions, simplified model simulations which were uniform in the alongshore, were performed. It was observed that for narrow reefs (width <200 m), the shoaling owing to shallow water depths over the fringing reef dominated, inducing greater wave heights onshore and farther inundation inland. With increasing reef width, wave dissipation through bottom friction began to dominate and both tsunami wave heights and inundation came down. Furthermore, it was noted that the amount of wave amplification or decay and the inundation distance were dependent on the shape and height of the tsunami waves, the tide height at the time the tsunami impacts land, and the shape and condition of the fringing reef. It was also suggested that smoother reefs were likely to increase the onshore velocity in comparison to rougher reefs. The effect of incised channels and embayments on tsunami inundation was investigated, and such features were found to allow larger waves to penetrate farther inland. As can be understood, wider embayments would induce comparatively less tsunami amplification than narrowing embayments. Though further work would be required for better understanding, the authors concluded from their simulations that healthy, rough, high and wide coral reefs, and without unnecessary channels would offer the greatest protection from destructive tsunamis.

Another study by McAdoo et al. (2011) in the same area also discussed the effect of coral reef on tsunami run-up and inundation. The coral reef bordering the coastline of Samoa affected by the 29 September 2009 tsunami and possibility of the wide lagoon reducing the onshore wave height was explored. The scale of reef damage observed varied from severe with piles of freshly-killed coral fragments and mortality, to areas showing little impact, despite being overrun by the tsunami. Many coral colonies were found to be impacted by tsunami entrained coral debris, while some of the large surface area tabular coral were found to be damaged from the high tsunami velocity when it funneled through the channels. In the lagoon on the south coast with its steep topography, coral colonies were found to be damaged by backwash tsunami-generated debris from onshore. Although algal cover was higher with the increased nutrients mobilized by the tsunami, live coral cover was unchanged despite the destruction caused by the tsunami, indicating that the coral reefs would recover fast after tsunami. From the study, it was also observed that the lagoon provided a degree of physical buffering against the tsunami, and the buffering effect would increase with wider lagoons, with less number of channels in between.

Efficacy of Coastal Ecosystem

The 2004 Indian Ocean Tsunami stimulated a debate about the role played by coastal ecosystems such as mangrove forests and coral reefs in protecting low-lying coastal areas with some observers confident that these ecosystems would play an important role, and others skeptical about their effectiveness. Cochard et al. (2008) reviewed the role of coastal ecosystems in mitigating sea wave hazards, particularly the influence of coastal vegetation in severely affected parts of Aceh and Southern Thailand during the 2004 tsunami, with two field observation sets during 2006. They found the influence of coral reefs on tsunami waves to be complex with closed, intact reefs providing some protection, and fragmented reefs accelerating water through channels, causing greater destruction on land. Though more data was felt necessary for quantification of the effect, seagrass beds appeared to provide a more consistent buffering against tsunamis. While in places away from the tsunami source, mangroves and other coastal vegetation apparently provided some protection, at other locations, however, vegetation could even have increased the hazard by contributing to flow debris, or by channelizing the water flows. The factors influencing the degree of protection offered by vegetation were mentioned as stand size, density, species composition, structure and homogeneity. It was felt that realistic modeling and visualization of vegetation protection would require more detailed spatial and hydro-dynamic analyses. It was emphasized that tsunami greenbelts should not be treated as alternatives to early warning systems, but as an economical and multi-functional means to provide relative hazard protection for material assets.

Efficacy of Artificial Barriers

After the 2011 Great East Japan tsunami, damage to embankments and forests along the coast of the northeast Japan was observed at twenty-five locations along 340 km length. Nandasena et al. (2012) assessed the tsunami mitigation effect of the artificial and natural structures and coastal vegetation at two coastal sites, Misawa, a site with vegetated dune, and Hachinohe, a site with seawall with a modified two-dimensional depth-integrated shallow water model. Additionally, some hypothetical cases were tested with alternative arrangements of these structures to identify their contribution towards tsunami mitigation. From the numerical results, the authors concluded that the vegetated dune in Misawa contributed to the mitigation of the tsunami and indicated the effect of the shape of access roads, straight or crooked, through the vegetation to the coast, on the variation of flow velocity increment. At Hachinohe, the vegetation behind the seawall was undamaged while those not shielded from the seawall was severely damaged. As found from the numerical model study, the diversion of the tsunami flow by the seawall enhanced the moment experienced by the un-shielded vegetation (4–2 kN-m) compared to those behind the seawall (< 0.2 kN-m), thus causing higher damage in the former. The actual Froude number of the wave front at the Sendai Plain calculated from video footage were comparable with the maximum Froude number obtained for Misawa and Hachinohe from the numerical model, thus validating the analysis.

Concluding Remarks

In the paper, some recent studies on the efficacy of the natural and artificial barriers in providing protection from tsunamis have been reviewed. Though numerous scientific studies are available regarding role of coastal ecosystems as protection against normal and extreme wind-driven waves including cyclonic storm surges, similar studies for protection against tsunamis are less and are limited in scope for generalization over large geographic areas or diverse conditions. Factors like the high variability in the energy and speed of tsunami waves along different coastline stretches, the spatial patterns of impact like flow diversion and channelizing due to hydraulic resistance, and the effects of tree breaking and flow debris have not been adequately studied.

However, it may be concluded that coastal sand dunes, and vegetation like causarina forests would help in mitigation of the damage potential of tsunami waves. Protection offered by mangrove belts, especially the ones with thicker stems, and having width more than 100m, should also be considered. Coral reefs, of width more than 200m would help reduce the velocity, run-up, and inundation of tsunami, and they should be maintained in intact condition. When partially damaged or removed, the channelizing effect and higher water velocity should be considered in evaluation of the tsunami hazard for the coast. Seagrass belts were mentioned to provide a consistent buffering against tsunami. Artificial structures like seawall may provide protection to the shielded area, but the aggravated damage to the adjoining area has to be taken into account while planning them. The information summarized here would be useful in developing passive tsunami protection systems for important structures like nuclear facilities, subjected to tsunami threat. Finally, till more detailed knowledge regarding the passive tsunami protection systems are acquired and better confidence is developed, the greenbelt solutions should not be considered as replacement of tsunami early warning systems and disaster preparedness, but as complementary to them.

References

Alongi, D. M. (2008). “Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change,” *Estuarine, Coastal and Shelf Science,* 76, 1-13.

Cochard, R., Ranamukhaarachchi, S. L., Shivakoti, G. P., Shipin, O. P., Edwards, P. J., and Seeland, K. T. (2008). “The 2004 tsunami in Aceh and Southern Thailand: A review on coastal ecosystems, wave hazards and vulnerability," *Perspectives in Plant Ecology, Evolution and Systematics,* 10, 3–40.

Fernando, H. J. S., Samarawickrama, S. P., Balasubramanian, S., Hettiarachchi, S. S. L., and Voropayev S. (2008). "Effects of porous barriers such as coral reefs on coastal wave propagation," *Journal of Hydro-environment Research,* 1, 187-194.

Gelfenbaum, G., Apotsos, A., Stevens, A. W., and Jaffe, B. (2011). "Effects of fringing reefs on tsunami inundation: American Samoa," *Earth-Science Reviews,* 107, 12–22.

Kathiresan, K. and Rajendran N. (2005). "Coastal mangrove forests mitigated tsunami," *Estuarine, Coastal and Shelf Science*, 65, 601-606.

Kerr, A. M., Baird, A. H., and Campbell, S. J. (2006). "Comments on „„Coastal mangrove forests mitigated tsunami‟‟‟‟by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601-606]," *Estuarine, Coastal and Shelf Science,* 67, 539-541.

Mascarenhas, A., and Jayakumar, S. (2008). "An environmental perspective of the post-tsunami scenario along the coast of Tamil Nadu, India: Role of sand dunes and forests," *Journal of Environmental Management,* 89, 24–34.

McAdoo, B. G., Ah-Leong, J. S., Bell, L., Ifopo, P., Ward, J., Lovell, E., and Skelton, P. (2011). "Coral reefs as buffers during the 2009 South Pacific tsunami, Upolu Island, Samoa," *Earth-Science Reviews,* 107, 147–155.

Nandasena, N. A. K., Sasaki, Y., and Tanaka, N. (2012). "Modeling field observations of the 2011 Great East Japan tsunami: Efficacy of artificial and natural structures on tsunami mitigation," *Coastal Engineering,* 67, 1–13.

Patnaik, K.V.K.R.K., Kumar, S.V.V. A., Ramu, C. V., and Prasad K.V.S.R. (2012). "Observational analysis on the run-up height and inundation along the Andhra coast during December 26, 2004 Indian Ocean tsunami," *Journal of Asian Earth Sciences,* 45, 239–246.

The Tsunami Risks Project, 2005. <http://www.nerc-bas.ac.uk/tsunami-risks/html/Phy3Impact.htm> (accessed September 2012).

Vermaat, J. E., and Thampanya, U. (2006). "Mangroves mitigate tsunami damage: A further response," *Estuarine, Coastal and Shelf Science,* 69, 1-3.

Yanagisawa, H., Koshimura, S., Goto, K., Miyagi, T., Imamura, F., Ruangrassamee, A., Tanavud, C. (2009). "The reduction effects of mangrove forest on a tsunami based on field surveys at Pakarang Cape, Thailand and numerical analysis," *Estuarine, Coastal and Shelf Science,* 81, 27–37.