Inundation of sea water in Andaman and Nicobar Islands and parts of Tamil Nadu coast during 2004 Sumatra tsunami

Earthquakes of large magnitude generally above *M* 7.0, occurring in shallow depths of seabed fault zones, cause rapid and vertical displacement of sea water. This results in the generation of tsunamis. The tsunamis in turn generate a series of deep ocean waves that have larger wavelengths, greater amplitude, period and velocity compared to normal waves. These waves with tremendous energy propagate in the deep sea at a speed of 750–900 km/h. When they encounter shallow waters of islands and landmass, their velocity decreases but change in total energy of the tsunami remains constant. At locations like open coast beaches, bays and harbours, due to shoaling effect, the height of the waves increases causing rise in sea level even to an extent of 30 m at the coast. Thereafter, the sea water penetrates the coast with high speed and causes extensive inundation, which is called run-up[1]. Run-up is usually expressed in metres above normal tide or mean sea level. Figure 1 shows a schematic representation of different aspects of inundation, including measurement of maximum run-up height. Run-up values can be used for determining the extent of vulnerability of human settlement, in coastal villages or towns and therefore they are useful in coastal land use planning. Run-up levels from the same tsunami within a coast or island vary depending on the geomorphology (shape) of the coast and land cover in the coastal areas. Tsunami waves travel far inside the land through estuaries and backwaters.

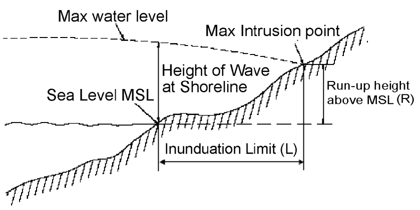

Figure 1. Schematic diagram showing measurement of run-up height[1].

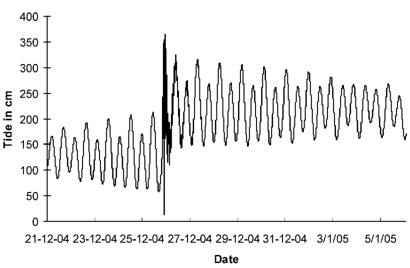

Figure 2. Sea water level recorded by NIOT tide gauge at Chattam Island, Andaman.

The National Geophysical Data Centre of the US National Oceanic and Atmospheric Administration is maintaining data on tsunamis that have occurred all around the world in the past. The data can be viewed from the website http:\\www.ngdc.noaa.gov. As indicated, in the tsunami run-up subsection of database for the Indian Ocean, 54 tsunami incidences were recorded between the years 1750 and 2004. Seven tsunamis have been reported in the Indian region. The run-up level data available for Andaman and Nicobar Islands and Tamil Nadu coast indicate 4 m in Port Blair (1868), 0.76 m in Car Nicobar (1881) and 1.22 m in Port Blair and Nagapattinam (1881).

The Andaman and Nicobar Islands (A&N) located in the subduction zone of Burma Plate are classified as seismic zone 5, indicating high level of risk due to earthquakes. A tsunami was generated on 26 December 2004 by an earthquake of magnitude *M* 9.0 that occurred off Sumatra Island of Indonesia with the epicentre located on the shallow depths of seabed (Source: USGS). Tsunami waves hit Indonesia, Andaman and Nicobar Islands, parts of East Coast of India, Thailand, Sri Lanka, Maldives and West and East Africa. These waves could be traced as far as New Zealand. Tsunami waves hit A&N within a few minutes. The Acoustic Tide Gauge (ATG) of the National Institute of Ocean Technology (NIOT), located inside the Port Blair bay (Chattam Island), which was set only for normal tidal variations, could record the sea water level up to 3.5 m on the day of tsunami. This is about 1.5 m more than normal tide level (Figure 2).

Run-up measurements at different sites along the A&N and Tamil Nadu coasts were made using Realtime Kinematic Global Positioning System (RTKGPS).

Table 1. Run-up level of sea water during tsunami at selected locations in A&N along Tamil Nadu coast

Location	Maximum run-up level (m)	Distance of sea water inundation inland (m)
Andaman and Nicobar Islands		
South Andaman (Port Blair)		
JNRM College, Aberdeen	2.9	130
Bamboo Flat	3.5	250
New Wandoor	3.7	215
Wandoor	3.9	215
Chidiyatopu	4.5	130
Sippighat (Creek)	2.0	2000
North Andaman		
Diglipur	1.5	100
Rangat	1.5	200
Little Andaman		
Hut Bay	5.0	1200
Car Nicobar		
Malacca	7.0	1000
Great Nicobar		
Campbell Bay (Central)	3.0	300
Campbell Bay (North)	6.0	50
Tamil Nadu Coast		
Nagapattinam (lighthouse transect)	3.9	750
Chennai (Besant Nagar)	2.8	200
Chennai (Kattupalli)	1.8	190
Chennai (Kalanji)	1.4	45
Sathankuppam (Pulicat)	3.5	80

Transect run from sea water up to maximum inundation point was identified from (i) deposition of washed materials and/or (ii) degraded grass/vegetation or (iii) sea water level mark on external walls of buildings. These transects were drawn at each location representing characteristics of open coast with settlements and areas adjacent to inlet/backwater. All the levels taken along the transects were connected to GTS benchmark wherever available, and in other places the sea levels reported in tide table for the nearest location were taken as references. All run-up measurement levels were corrected to tide and reduced to mean sea level. The water point was measured in backwater/bay/inlet to minimize error in measuring the sea level. The highest point of inundation was also mapped along the identified signature using ARCPAD Differential Global Positioning System, where the inundation points were tracked using 'Polyline' feature, at an interval of 2 m. Locations where run-up level measurements were made are mentioned in Table 1. These measurements were made during January and February 2005 by the scientists of Integrated Coastal and Marine Area Management Project Directorate (ICMAMPD), Department of Ocean Development, Chennai in association with Andaman & Nicobar Centre for Ocean Science Technology, National Institute of Ocean Technology, Port Blair and Institute for Ocean Management, Anna University, Chennai.

In general, the extent of vertical run-up of sea water during tsunamis depends on earthquake parameters, geographical location, velocity of tsunami waves and their frequency, nearshore bathymetry, beach profile and land topography. Due to these parametric variations in A&N and Tamil Nadu coasts, the run-up levels and landward penetration characteristics of sea water were location-specific and varied within a location and even in an island (Figure 3; Table 1). In the case of A&N, in the North and South Andaman group of islands, the run-up levels varied from 1.5 to 4.5 m and the distance penetration from the coast ranged from 100 to 250 m (Table 1). Little Andaman recorded a run-up of 5 m, with the distance of penetration being 1200 m. In the two Nicobar islands, the run-up levels varied from 3 to 7 m, with distance of penetration ranging from 50 to 1000 m and with higher run-up levels and longer penetration noted in Car Nicobar (Table 1). The wide variation between Andaman and Nicobar Islands was primarily due to the above-mentioned parameters and also due to land subsidence caused by the earthquake. Similar types of diversified results were observed in 26 December 2004 tsunami-affected islands of Indonesia and Sri Lanka. Run-up levels varying from 0.3 to 32 m were recorded in Indonesia and from 2.5 to 10 m in Sri Lanka[2].

The coastal land-slope values were calculated based on RTKGPS data (Table 2). The data indicate penetration of sea water for a short distance in Andaman islands (except Little Andaman), compared to the Nicobar group. This may be due to the presence of elevated areas within short distance from the coasts in the North, Middle and South Andaman besides low velocity of tsunami waves. Little Andaman and Car Nicobar islands that had relatively gentle slopes along the coast compared to the South Andaman island, experienced farthest penetration of sea water (Figure 4). The slope value of 1 in 32 for Chidiyatopu in South Andaman compared to slope values of 1 in 325 for Little Andaman and 1 in 167 for Car Nicobar support this interpretation (Table 2). This clearly indicates the vulnerability of low-lying areas with gentle beaches/land-slopes to inundation of sea water during storms, tsunamis, etc. Low-lying areas adjoining the creeks, which facilitate travel of tsunami waves far inland are too vulnerable, as indicated by the landward penetration of sea water up to 2 km from the creek in Sippighat area, Port Blair (Table 1).

Another major reason for inundation of sea water in South Andaman and Nicobar islands is land subsidence. Location specific observations made by ICMAM PD using ALHW data indicate 0.8 m around Port Blair and 1.3 m in Great Nicobar. Such land subsidence is evident from the high-tide water entering into paddy fields of Sippighat

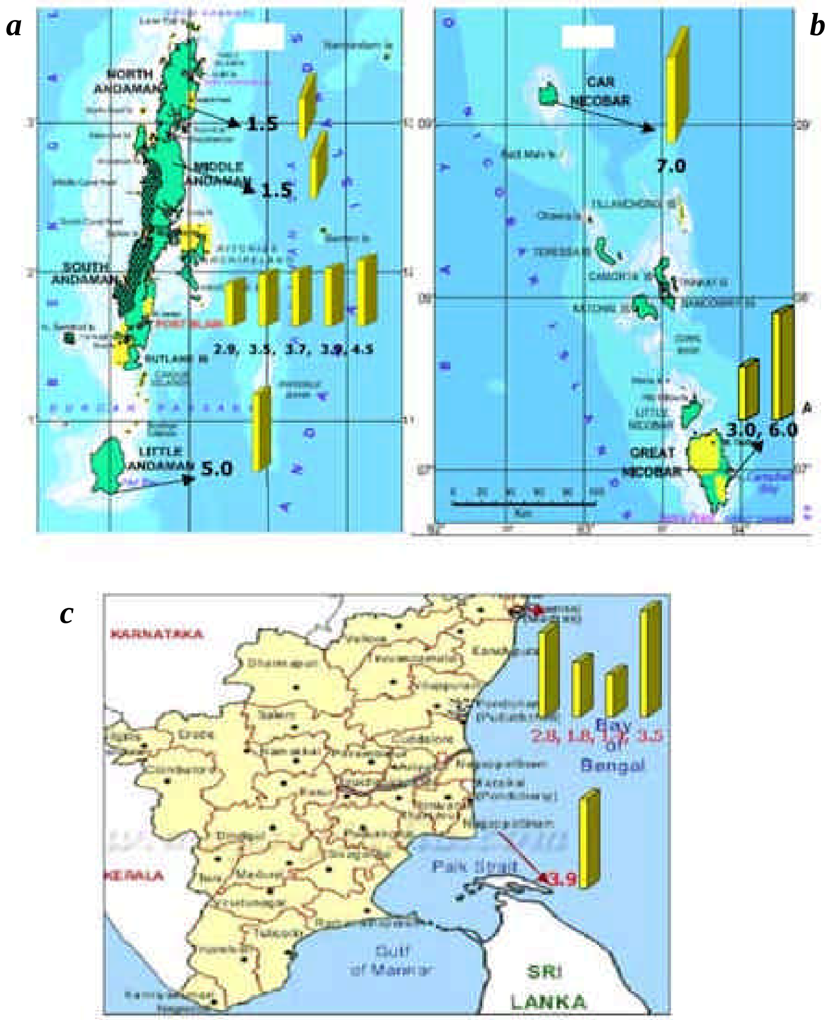

Figure 3. Run-up levels (in m) at selected locations in Andaman (***a***) and Nicobar (***b***) Islands and Tamil Nadu coast (***c***). (Names of locations are given in Table 1 against their run-up values.)

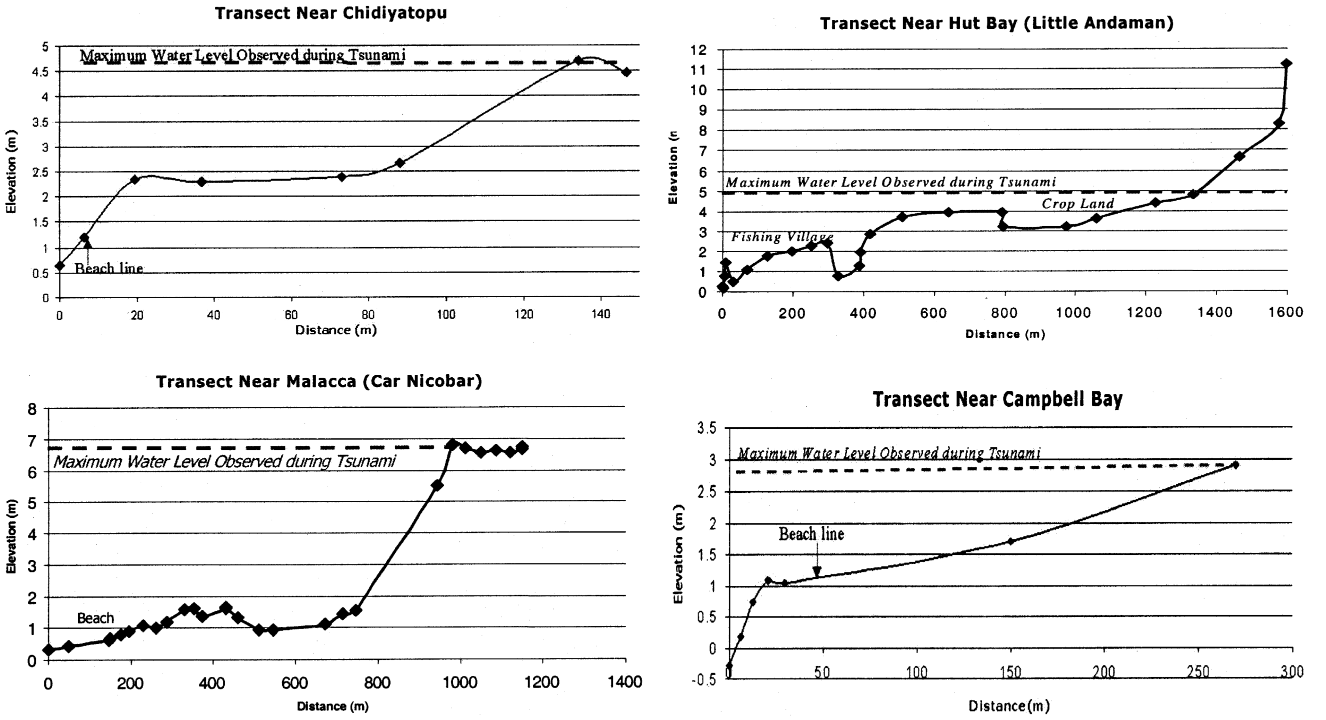

Figure 4. Coastal land profile at Chidiyatopu (South Andaman), Hut Bay (Little Andaman), Malacca (Car Nicobar) and Campbell Bay (Great Nicobar).

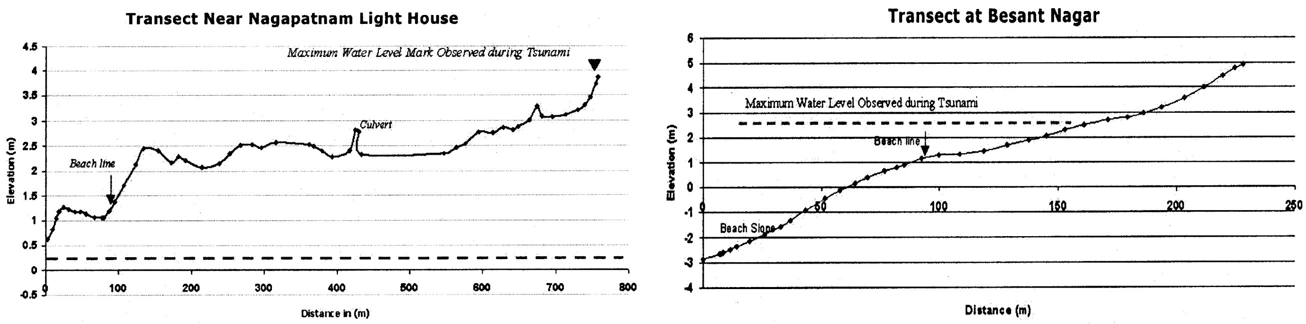

Figure 5. Coastal land profile at Nagapattinam and Chennai (Besant Nagar).

area that registered penetration of sea water up to 2 km during the tsunami. Inundation of inland low-lying areas during high-tide has become a cause for concern to the local population as their houses are marooned in sea water. The concern is likely to get aggravated during monsoon months, when rain-water antagonizes movement of high-tide water. A full year observation on water levels in these areas is required to understand the impact of land subsidence/uplift in A&N.

The run-up levels along the Tamil Nadu coast, showed almost similar trend as noted for A&N. The worst affected area of Nagapattinam showed longer penetration of sea water (750 m) up to an elevation of 3.9 m due to the gentle slope of coastal land combined with the effect of tsunami wave diffraction caused by the northern tip of Sri Lanka (Figure 5). Presence of creeks like Vedaranyam canal in Nagapattinam facilitated sea water inundation up to 2.2 km inland. The Chennai areas showed less landward penetration of sea water (45 to 200 m) due to prevalence of wider elevated beaches, which have acted as barriers. The slope value of 1 in 227 for Nagapattinam compared to 1 in 39 at Chennai showing gentleness in Nagapattinam, further supports this interpretation (Table 2). Presence of offshore shoals along the Ennore coast (4–7 km from coast) subdued the effect of tsunami waves, saving the village of Kalanji where the sea water had penetrated only up to 45 m (Table 1). Nearshore bathymetry in the Ennore shoal region has been described elsewhere[3].

The run-up distances of sea water during tsunamis are as a result of the combination of several factors described earlier. Even though the inundation of sea water is greater where the beach/land-slope is gentle (Table 2), the run-up distances can also vary among the gentle land-slope areas wherever they are traversed by streets and houses of different density. Penetration of sea water to a relatively short distance in Nagapattinam having a higher coastal land-slope value in contrast to Car Nicobar (Table 2), is mainly due to higher density of houses and streets in Nagapattinam and also non-occurrence of land subsidence unlike in the Car Nicobar.

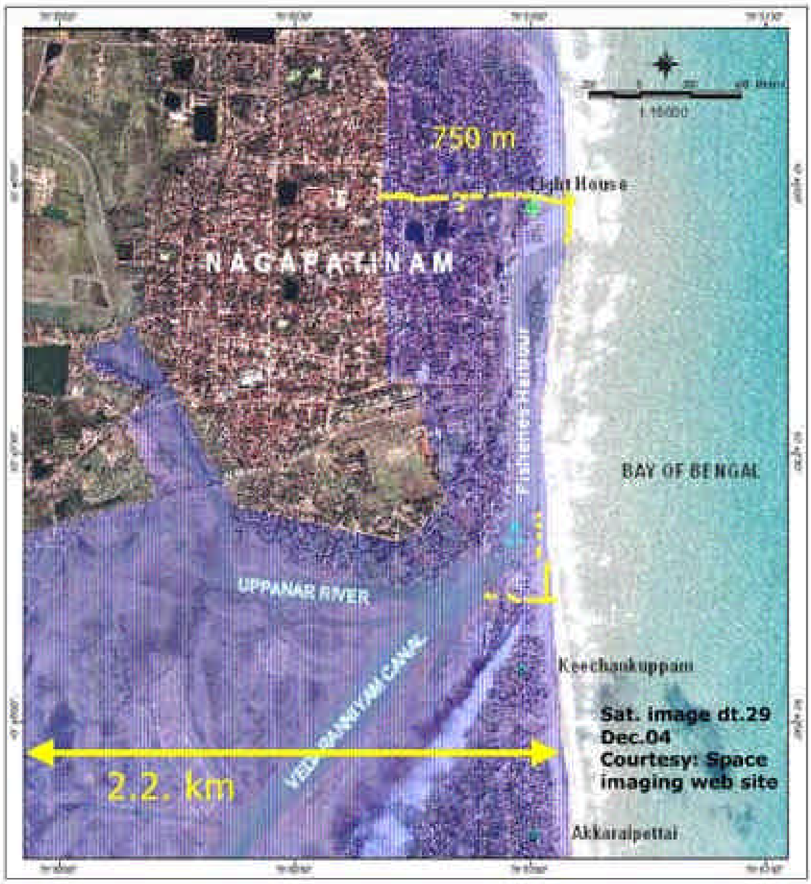

Figure 6. Satellite image of Nagapattinam showing inundation of sea water in settlement areas during tsunami.

Figure 7. Map showing Malacca in Car Nicobar and settlement areas close to coast.

The run-up level of 7 m in Car Nicobar and 3.9 m in Nagapattinam and the prevalence of these elevations at distances of 1.1 km and 750 m respectively, where moderate to large settlements occur close to the coast, indicate the need to consider elevation-based setback line in human settlement planning along the coastal areas of the country (Figures 6 and 7). Both the sites, along with others like Katchall island in the Nicobar group had huge loss of human life. For example, in Nagapattinam, there are dense households from the coast up to 1.5 km. The tsunami devastated the Nagapattinam area with a death toll of 6065 people and damaging as many as 40,000 houses (Source: TN Govt. website dated 14 February 2005). The loss of human life including missing was 1138 in Car Nicobar and 4655 in Katchall (Source: A&N Administration Notice dated 23 January 2005). It is well known that Nagapattinam is one of the low-lying coastal areas of the country and has experienced the fury of storm surges several times, as it is known to be one of the possible landfall points for cyclones. It is

Table 2. Coastal land-slope values of various locations in A&N and Tamil Nadu

Location	Distance of sea water penetration (in m)	Slope	Nature of coastal land
Chidiyatopu (South Andaman)	130	1 in 32	Short beach followed by steep elevated land
Hut Bay (Little Andaman)	1200	1 in 325	Low-lying coastal land with gentle slope for long distance
Malacca (Car Nicobar)	1000	1 in 167	Gentle coastal land up to 800 m and steep rise beyond
Campell Bay (Great Nicobar)	300	1 in 89	Elevated beach followed by gentle slope of coastal land
Nagapattinam (Tamil Nadu)	755	1 in 227	Coastal land with gentle slope interrupted by streets and houses
Chennai–Besant Nagar (Tamil Nadu)	200	1 in 39	Gentle beach for 100 m, followed by sand dunes of different elevations

clearly evident that even the HighTide Line to 200 m 'No development zone' and restricted human settlement between 200 and 500 m prescribed under CRZ III category of the Coastal Regulation Zone notification (1991) is insufficient. The present run-up levels and inundation distances can be used as guidelines to determine safe locations for resettlement of affected population for the present. However, for long-term human settlement planning, safe elevations along with distances from the coast or vulnerability lines for human settlement, especially in low-lying areas need to be determined taking into account other future probabilistics such as occurrence of epicentre of tsunamigenic earthquake close to A&N, direction of propagation of tsunami waves, anticipated sea level rise due to global warming, loss of beaches due to coastal erosion, etc. These vulnerability or setback lines need to be notified under the Town and Country Planning Acts or other pertinent Acts of the States, Centre/Union Territories, to give effect to adoption of location-specific elevation plus distance-based human settlement planning along the coastal areas of the country. Provision also needs to be made to protect the vacant area between the High Water Line and the setback line by declaring it as a 'No development zone' or as 'protected area'.

The observations of protection offered to human settlement by wide and elevated beaches and offshore shoals along the coastal stretches of Chennai clearly indicate the need to protect them from the threat of erosion.

1. Gica, E. and Teng, M. H., In Proceedings of 16th ASCE Engineering Mechanics Conference, University of Washington, Seattle, 2003, pp. 1–8.
2. Yalciner, A. C., Perincex, D., Ersoy, S., Presateya, S., Hidayat, R. and McAdoo, B., Report on 26 December 2004 Indian Ocean tsunami, Field survey during 21–31 January North of Sumatra by ITST, UNESCO IOC, 2005.
3. ICMAM, Integrated Coastal and Marine Area Management Plan for Chennai, The ICMAM Project Directorate, Department of Ocean Development, Chennai, 2002.

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