Serie Correlación Geológica - 36 (1-2): 27 - 38
Tucumán, 2020 - ISSN 1514-4186 - ISSN on-line 1666-9479

Variation in Tsunami Wave-Heights Due to Coastal Topography and Impact of Rock Boulders on Inundation: A Case Study of 2004 Indian Ocean Tsunami Along the Pondicherry Coast

Mounica JAKKULA[1] and Kirti SRIVASTAVA[1]

Resumen: *VARIACIÓN EN LAS ALTURAS DE LAS OLAS DEL TSUNAMI DEBIDO A LA TOPOGRAFÍA COSTERA Y EL IMPACTO DE LOS CANTOS RODADOS EN LA INUNDACIÓN: UN ESTUDIO DE CASO DEL TSUNAMI DEL OCÉANO ÍNDICO DE 2004 A LO LARGO DE LA COSTA DE PONDICHERRY.* El 26 de diciembre de 2004 la ciudad de Pondicherry, ubicada en la costa sureste de la India, se vio afectada por un tsunami. Regiones aledañas a lo largo de la costa no experimentaron inundaciones ni daños, situación que es valorada en el presente trabajo. Se estudiaron tres regiones a lo largo de la costa de Pondicherry a saber: (1) Playa de Auroville, (2) Calle costera, y (3) Playa Paraiso mediante el método de combinación de datos SRTM, CMAP y GEBCO, a través de información topográfica y batimétrica de alta resolución. La altura de las olas del tsunami y la extensión de la inundación se calculan utilizando el modelo TUNAMI N2 en la región de estudio. Se observa que las estructuras en la Calle costera de Pondicherry estaban intactas y casi no se produjeron inundaciones en esta región debido a los cantos rodados situados a lo largo de la costa durante el tsunami del Océano Índico de 2004. También se estudiaron las playas de Auroville (que tiene una pendiente pronunciada), y Paradise (que es relativamente plana) en relación a las alturas de las olas y el alcance de las inundaciones. Se considera que el malecón de la misma altura que los cantos rodados de las playas previas dan pauta de las fuerzas de oleaje. Los resultados revelan que las alturas de las olas del tsunami y la inundación en la playa de Auroville es mucho menor que en la playa Paradise, mientras que no hubo inundaciones a lo largo de la Calle Costera, destacándose que el uso de cantos rodados a lo largo de áreas costeras pobladas puede minimizar los daño debido a tsunamis

Abstract: Pondicherry located on the southeast coast of India was largely affected by the 26 Dec 2004 tsunami. However, a few regions along the Pondicherry coast did not experience any inundation/damage. In this study, we have considered three regions along the Pondicherry coast, namely (1) Auroville Beach (2) Beach Road, and (3) Paradise Beach. Combining SRTM, CMAP, and GEBCO data a high resolution topographic and bathymetric data is acquired for the study region. Tsunami wave heights and inundation extent is calculated using the TUNAMI N2 model in the study region. It is observed that the structures on the Beach Road of Pondicherry were untouched and almost no inundation occurred in this region due to the rock boulders situated along the coast during the 2004 Indian Ocean Tsunami. The Auroville Beach, having a steep slope, and the Paradise Beach, which is relatively flat is also studied for the tsunami wave-heights and inundation due to the variation in their topography. A sea wall of the same height as the boulders is considered to estimate the inundation along the Beach Road. Also, the surge forces are calculated along the sea wall. Results reveal that the tsunami wave heights and inundation at Auroville beach are much less than the Paradise beach, whereas there was no inundation along the Beach Road. Usage of rock boulders along populated coastal areas can minimize the damage due to tsunami.

Palabras clave: PTsunami de 2004, Costa de Pondicherry, India.

Key words: 2004 Tsunami, Pondicherry Coast, India.

[1] CSIR- National Geophysical Research Institute (CSIR-NGRI), Hyderabad, 500007, India. Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India. Email id: mounica.jakkula.iitk@gmail.com, kirti@ngri.res.in

Introduction

Tsunamis have been causing significant damage to the life and economy of vulnerable coastal regions. Many warning mechanisms like the DART (Data Assessing and Reporting of Tsunami) system have been established to evacuate people in time. But, as seen from the earlier tsunamis, the damage to the coastal structures is also very important. Tsunami loads on structures have become a significant topic of research in recent years.

Extensive research has been conducted on tsunami loads on significant structures like bridges and dams. One such work by Azadbakht and Yim (2015) calculates tsunami loads on bridges using simulations separately with initial impact and full inundation. Another effective approach to evaluate design equations for hydrodynamic loading conditions is quantifying the failure analysis of several buildings. Chock *et al.* (2012) adopted this approach in his Tohoku Tsunami-induced building damage analysis. Tsunami-induced hydrodynamic forces on infrastructure located in the vicinity of the shoreline were carried out by Nistor *et al.* (2009) for different inundation depths. In yet another experimental investigation Nouri *et al.* (2010) estimated the tsunami impact on free-standing structures of different shapes. The bores similar to the ones generated in the recent observed in the recent tsunami were generated by Palermo *et al.* (2012) using the dam-break process to generate turbulent hydraulic bores and studied the tsunami-induced forces and changes in bore depth and bore velocity by experimenting with different structures.

The calculation of tsunami loads is usually not done to small-scale structures. Also, the damage to the land, due to water salinity is pretty significant, hence the need for a reduction in inundation. Researchers are working to reduce the inundation through the study of the impact of hydrodynamic forces on classical coastal protection works (breakwaters, seawalls, reefs, etc.). An experimental study of tsunami waves acting on prevention structures along the coast such as seawalls and breakwaters is carried out by Mizutani and Imamura, (2001). Kunkel *et al.*, (2006) research on reduced tsunami impact due to coral reefs explains how a small change along the coast can reduce the drastic damage to the coast.

Study Area

The study area, Pondicherry, is situated on the east coast of India, between 79.87°E and 79.79°E longitudes and 12.05°N and 11.75°N latitudes. Figure 1 shows the location of the study area. Pondicherry's average elevation is close to the sea-level, and several sea inlets, referred to as "backwaters" are present. This coastal zone is largely low-lying with a gentle slope, thus making it highly vulnerable to inundation. Narayanan *et al.* (2015) using the depth profiles along the shore identified the Pondicherry Canyon and the bathymetry at Pondicherry is having a gentle slope of 0 to 25m (at 12 km from the shoreline). A maximum water depth of 300m is observed at 21km from the shore near the Pondicherry Canyon. The vulnerability assessment of the Pondicherry coast is carried out by Murali *et al.* (2013) and as it is a coastal city, a lot of studies on the Pondicherry coast from a tsunami point of view are carried out, Murthy (2016) and Anandabhaskaran *et al.*(2017).

Materials and Methods

In this paper, a study is done at three regions of Pondicherry Coast – Auroville Beach, Beach Road, and Paradise Beach. Due to variation in topography, the difference in run-up height and inundation extent are studied. Another study has been done on a certain region that experienced very little or no inundation during the 2004 Indian Ocean Tsunami. This

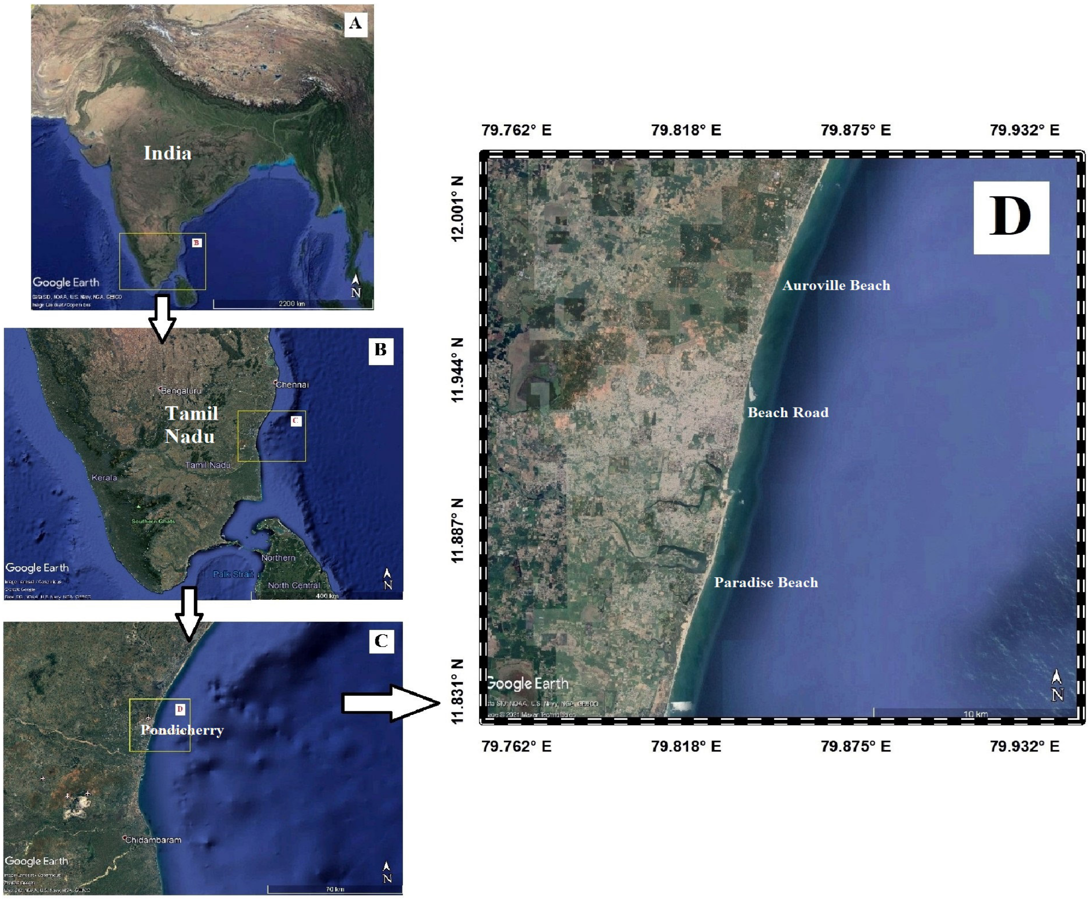

Figure 1. Location of the study area - Pondicherry. / **Figura 1.** *Ubicación del área de estudio - Pondicherry.*

region called the Beach Road shows accumulated rock boulders along its coast. During this tsunami, the boulders stopped the run-up waves from further going inland. So, it is assumed that the boulders act as a sea-wall to reduce the impact of tsunami waves. A sea-wall with a similar height as rock boulders is considered along the Beach Road and simulated for the 2004 Indian Ocean Tsunami scenario. Also, the forces of the tsunami waves are calculated on the sea wall. Thereby claiming that the boulders act as an excellent sea wall. The methodology flowchart is given in the figure 2.

Topographic and Bathymetric Data

The three study regions of the Pondicherry coast are (I) Beach Road, (II) Auroville Beach and (III) Paradise Beach. CMAP data for the Pondicherry coast is digitized (3 arc-seconds or 90 meters resolution) and field data of the height of boulders on the Beach Road is incorporated in it to get the bathymetric data. This is merged with the SRTM data (for the topography of study area, 90m DEM) and GEBCO data (450 m DEM) and is used to form the nested grids for the TUNAMI N2 code. Beach roads 1, 2 and 3 are the three locations considered to calculate the forces at those locations. Auroville Beach is located in the northern region; Beach road is in the central part while Paradise beach is situated in the southern part of the Pondicherry coast.

Figure 3 shows the bathymetry and topography of the study region and the locates all the three beaches. It is observed that Paradise Beach (Figure 6) has a relatively flat coast compared to

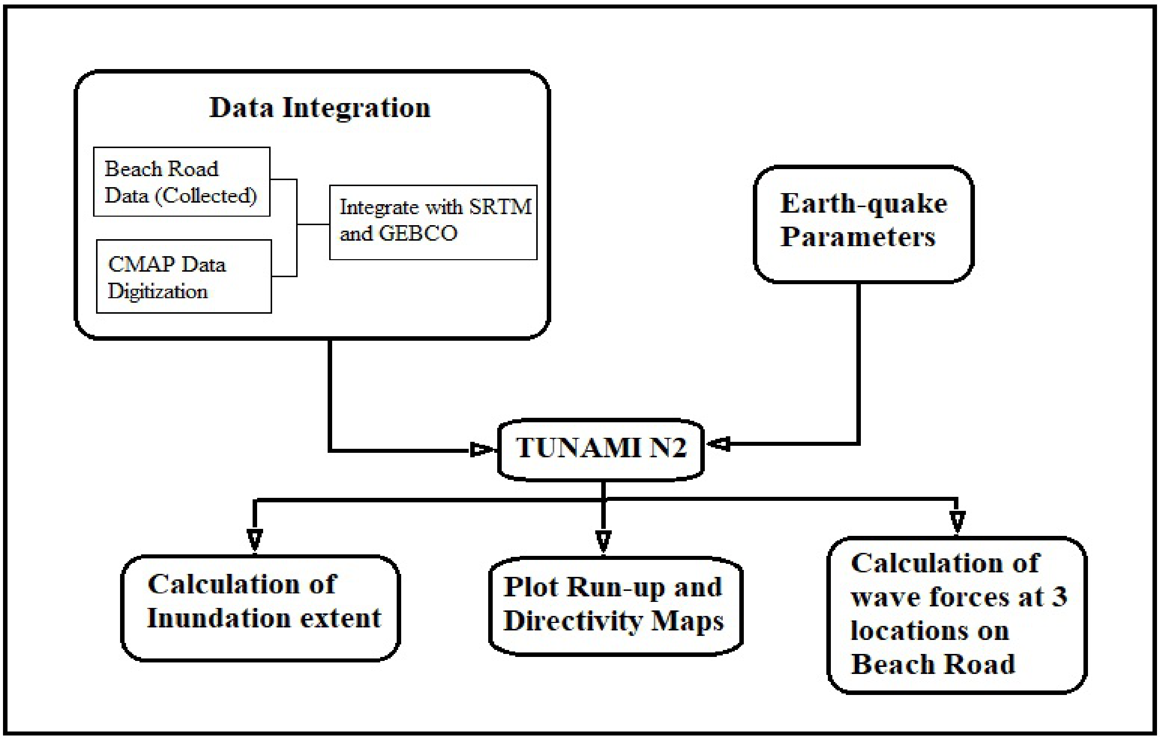

Figure 2. Methodology flowchart adopted for this study. / **Figura 2.** *Diagrama de flujo de la metodología adoptada para este estudio.*

the steep slope of Auroville Beach (Figure 4). This causes the run-up wave to go higher in the Paradise beach as compared to Auroville beach. The rock boulders along the Beach Road are shown in figure 5. For all three different beaches, the tsunami wave heights and the extent of inundation are computed.

Earthquake Source Parameters

The Andaman-Sumatra is currently one of the most seismically active regions in the world. The 26th December 2004 Sumatra earthquake of Mw 9.1 along the subduction zone between the Indian plate and Burmese plate triggered a tsunami causing large-scale devastation in the coastal cities across the Indian Ocean. In our study, we divided the entire Andaman-Sumatra subduction zone into five segments and computed the seafloor upliftment at t=0 seconds separately by considering a different set of fault parameters for all the segments and the fault parameters used in this study are given in table.1. Figure 7 shows the initial waves in the five segments.

TUNAMI N2

The objective of tsunami modeling research is to develop analytical and numerical models for faster and more reliable forecasts of tsunami source generation propagation and run-up/inundation through the ocean and striking coastal communities. Several codes to compute the tsunami propagation and inundation have been developed by various tsunami groups - MOST (Method of Splitting Tsunami), ANUGA (ANU- Australian National University, GA- Geoscience Australia), FUNWAVE (Fully Non-linear Wave Equations), etc. Several researchers discussed the theory of tsunami waves in the literature (Imamura, 1996; Imamura *et al.*, 2006; Yalciner *et al.*, 2005).

In this paper, TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis, Nº.2) code is used to simulate the past tsunamis and possible scenarios of tsunami genic earthquakes in the Indian Ocean to assess the hazard and impact on the coastal cities along the east and west coast of India. This code was developed by Fumihiko Imamura (1996)

Ioualalen et al, 2007	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5
Coordinates	95.10° E To 2.50 ° N	93.90 ° E To 4.33 ° N	93.41 ° E To 5.80 ° N	92.10 ° E To 9.10 ° N	92.0 °E To 10.5 °N
Length (km)	220	150	390	150	350
Width (km)	130	130	120	95	95
Depth (km)	25	25	25	25	25
Dip (degrees)	12	12	12	12	12
Strike (degrees)	300	340	338	356	10
Rake (degrees)	90	90	90	90	90
Slip (m)	15	15	06	06	06
Magnitude (Mw)	9.1				

Table 2. Source parameters of 2004 Sumatra earthquakes (after Ioualalen *et al.*, 2007). / **Tabla 2.** *Parámetros de fuente de los terremotos de Sumatra de 2004 (según Ioualalen* et al.*, 2007).*

and further modified by Yalciner et al. (2005) and uses a finite difference technique based on Staggered Leap-Frog scheme. This program is used to model tsunamis which are generated by the movement of the sea bottom due to earthquakes.

Initial condition:

The initial sea bottom deformation is necessary to obtain the initial surface wave. A complete set of closed-form analytical expressions to obtain the internal as well as surface deformation is given by Mansinha and Smylie method (Mansinha and Smylie, 1971). The information about the earthquake source parameters such as fault length, the width of the fault, focal depth, the angle between N & fault axis, dip angle, slip angle, and displacement is needed to compute the deformation at the source. Once the initial wave is generated one of the wavefronts would start moving toward the deep ocean and one moving toward the local shoreline.

Wave Propagation and Simulation:

Tsunamis waves are usually resolved using 2D hydrostatic models (Imamura *et al.*, 2006) and mathematically it is expressed as

$$\partial\eta/\partial t+\partial M/\partial x+\partial N/\partial y=0$$

$$\partial M/\partial t+\partial/\partial x\ (M^2/D)+\partial/\partial y\ (MN/D)+gD\ \partial\eta/\partial x+(gn^2)/D^{(7/3)}\ M\sqrt{(M^2+N^2)}=0$$

$$\partial N/\partial t+\partial/\partial x\ (MN/D)+\partial/\partial y\ (N^2/D)+gD\ \partial\eta/\partial x+(gn^2)/D^{(7/3)}\ N\sqrt{(M^2+N^2)}=0$$

In the above equation, M and N are expressed as

$$M=u(h+\eta)=uD \text{ and } N=\nu(h+\eta)=\nu D$$

where D is the total water depth given by $h+\eta$, t is time, h (x, y) is unperturbed depth, g is the gravitational acceleration, u and v are components of the horizontal velocities, M and N are the discharge fluxes in the x- and y- directions.

A finite-difference technique based on the Leap-Frog scheme is used to solve the tsunami wave propagation and a code is developed TUNAMI-N2 by Imamura *et al.* (2006). The formulation uses the central difference method with a second-order truncation error.

Boundary conditions:

The boundary conditions are free transmission (open boundary conditions) in the open sea and the perfect reflector on land are the two associated boundary conditions.

Results and Discussions

In the present study, the Sumatra tsunami is simulated to assess the inundation along the Pondicherry coast. The TUNAMI N2 code is used in quantifying the tsunami propagation,

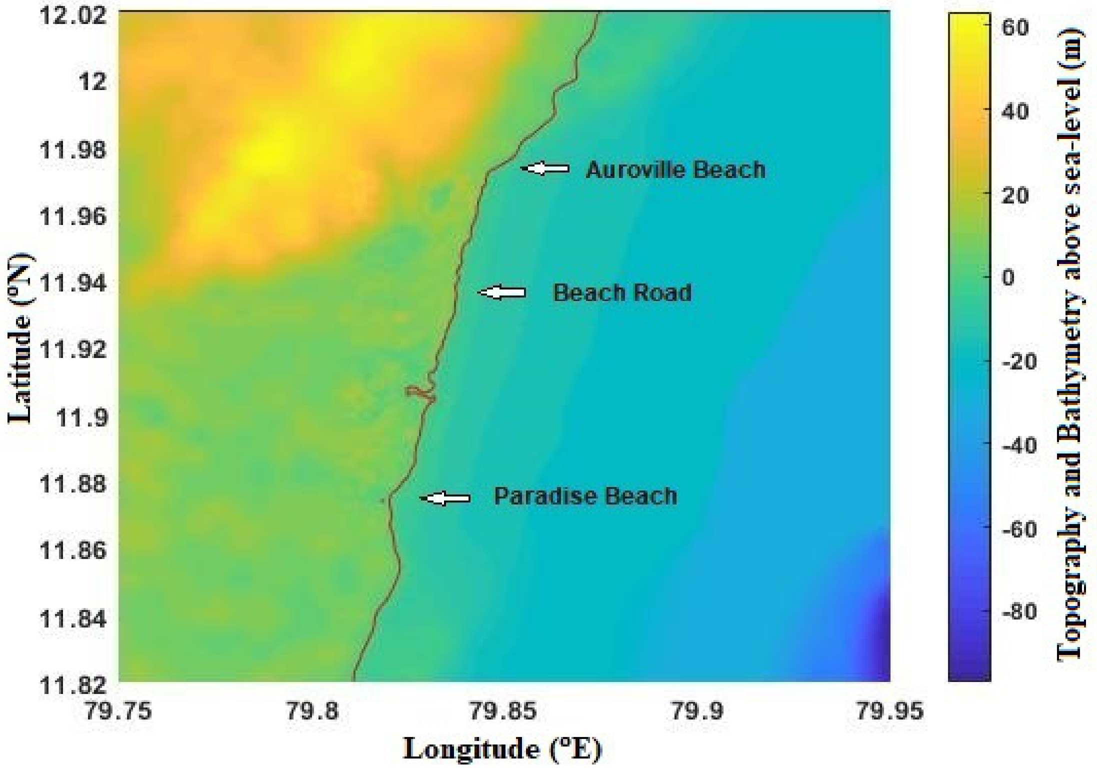

Figure 3. Topography and Bathymetry map of the study area showing the locations of the three beaches which are considered for the study. / **Figura 3.** *Mapa topográfico y batimétrico del área de estudio que muestra la ubicación de las tres playas consideradas para el estudio.*

arrival times, run-up, and inundation extents. Tsunami wave propagation at different time intervals is shown in figure 8. Tsunami directivity is computed and is shown in figure 9. Directivity map for the tsunami is computed by several researchers and run up and inundation extents along different coastal areas are computed (Swaroopa *et al.*, 2011).

The run-up above mean sea-level along the entire Pondicherry coast is shown in figure 10. The maximum runup and inundation extent at different locations is given in table 2. An increase in wave-heights is observed towards the southern region of the coast. Inundation is the highest around Paradise beach and very low or no inundation is observed along the Beach road.

The wave heights along the Auroville Beach (2.5m approx.) are smaller than the Paradise Beach (3.5m approx.). The Auroville beach which is along the northern part of the coast has a very steep slope towards the sea (Figure 4). This clearly explains the decrease in wave heights and inundation near the beaches compared to the Paradise beach (Figure 6).

Another study is made for understanding the effectiveness of having rock boulders along the coast for reducing the tsunami impact on the coast. The Beach road (Figure 5) is the most populated region along the entire Pondicherry coast. It consists of various buildings and structures and they are located very close to the coastal line, making them the most vulnerable region in case of a tsunami. The rock boulders lined along with the coast act as a sea wall. As explained earlier, we calculate forces assuming a sea wall instead of the boulders along the Beach road. Tsunami waves running up the shoreline exert surge force on a structure in its path and the surge force per unit width is given by Dames & Moore (1980) as

$$F/w=4.5\varrho g h^{2}$$

where ϱ is the density of water, g is the acceleration due to gravity, and h is the wave height.

Force per unit width is plotted with respect to time (Figure 11). It is observed that

Locations	Depth(m)	Wave heights(m)	Inundation (m)
Auroville Beach	-0.38	2.52	90
Beach Road 1	-0.36	3.19	negligible
Beach Road 2	-1.79	3.07	negligible
Beach Road 3	-1.31	2.97	negligible
Paradise Beach	-1.84	3.45	650

Table 3. Water depths at different locations with maximum tsunami wave heights and inundation. / **Tabla 3.** *Profundidades del agua en diferentes lugares con alturas máximas de olas de tsunami en estos lugares a lo largo de la costa de Pondicherry.*

the force per unit width of the order 10^5N/m. The maximum impact is observed around four hours after the earthquake. Construction of a seawall is an involved and expensive affair. Thus an array of rock boulders as shown in figure 5 can be used instead of a seawall. Also, boulders allow slight movement within the structure even though they are complexly packed and change their arrangement when experiencing marginally higher force. Whereas, a seawall might get destroyed and would require refurbishment.

Conclusions

The assessment of tsunami hazard along the coast of Pondicherry is the focus of this study. In the event of a tsunami, the difference in topography and bathymetry of the two beaches (Auroville and Paradise) results in different wave heights and inundation. The steep slope along a beach causes the wave to lose its height and energy, resulting in lesser wave-heights and inundation extent. This is observed at Auroville Beach which has a steeper slope as compared to

Figure 4. Auroville Beach showing a steep slope. / **Figura 4.** *Auroville Beach mostrando una pendiente pronunciada.*

Figure 5. Beach Road showing rock boulders all along the coast which acted as a sea wall. / **Figura 5.** *Beach Road mostrando cantos rodados a lo largo de la costa que actuaba como un malecón.*

Figure 6. Paradise Beach showing a flat coast. / **Figura 6.** *Paradise Beach mostrando una costa plana.*

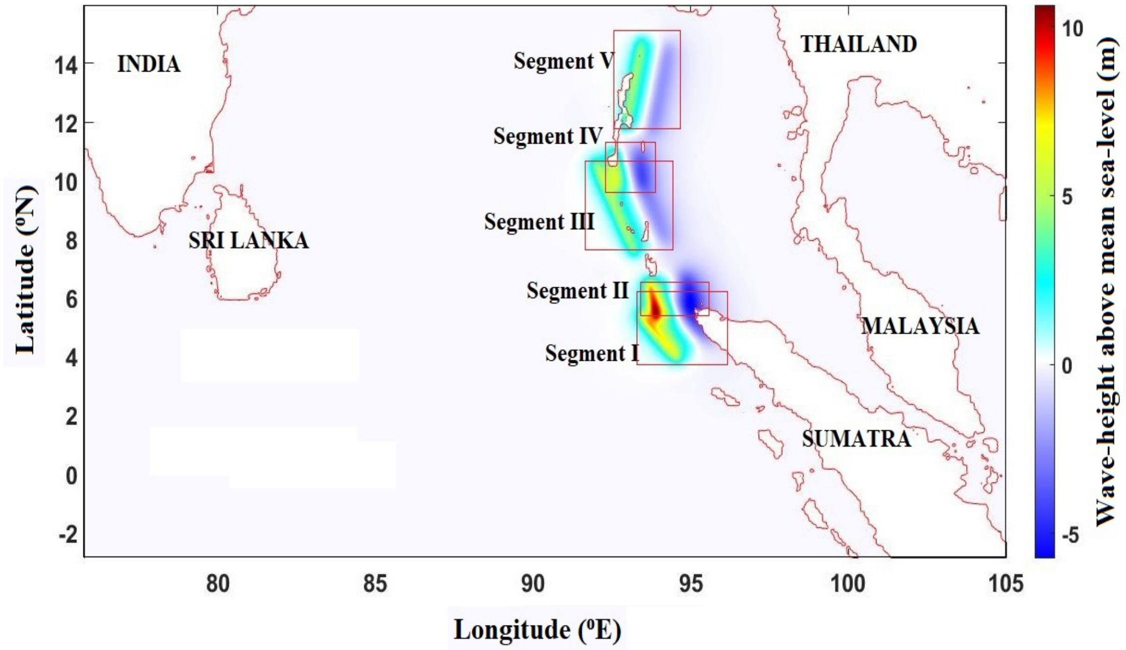

Figure 7. Wave-heights (Initial upliftment) at t=0 after the earth-quake. / **Figura 7.** *Alturas de las olas (levantamiento inicial) en t = 0 después del terremoto.*

Paradise beach and has lesser wave-height and inundation.

The computed forces per unit width for the sea-wall are of the order 10^5N/m. These forces can be valuable input in designing a sea-wall. A similar study can be done for other populated locations to build sea-walls. Also, it can be concluded that these forces did not do

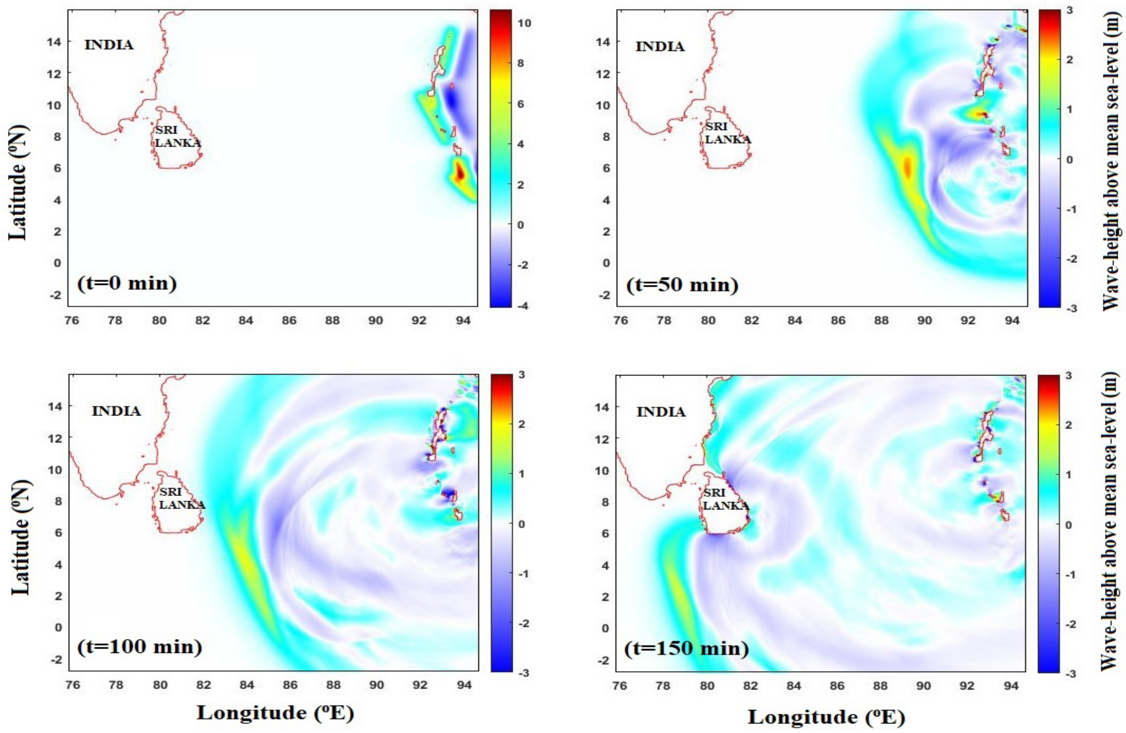

Figure 8. Tsunami wave propagation along the Indian Ocean. / **Figura 8.** *Propagación de ondas de tsunami a lo largo del Océano Índico.*

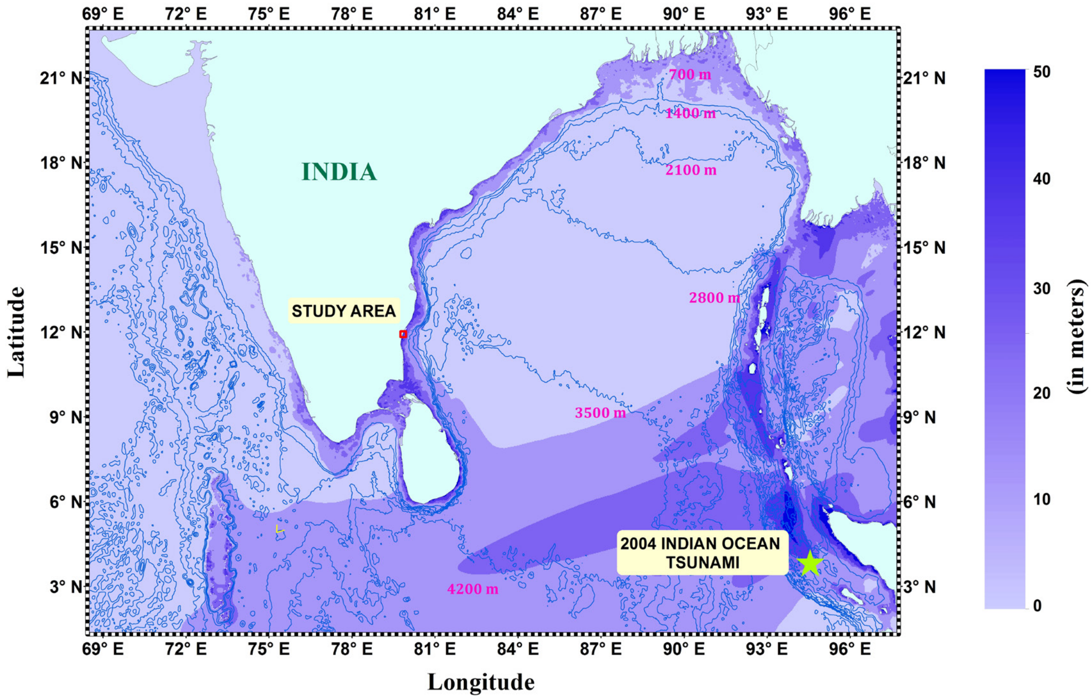

Figure 9. Tsunami directivity map for the 2004 Sumatra tsunami showing the maximum wave heights. / **Figura 9.** *Mapa de directividad del tsunami para el tsunami de Sumatra de 2004 que muestra las alturas máximas de las olas.*

any damage to the rock boulders.

The rock boulders present along the Beach Road act as a sea wall and protect this region from inundation by dissipating the inco-

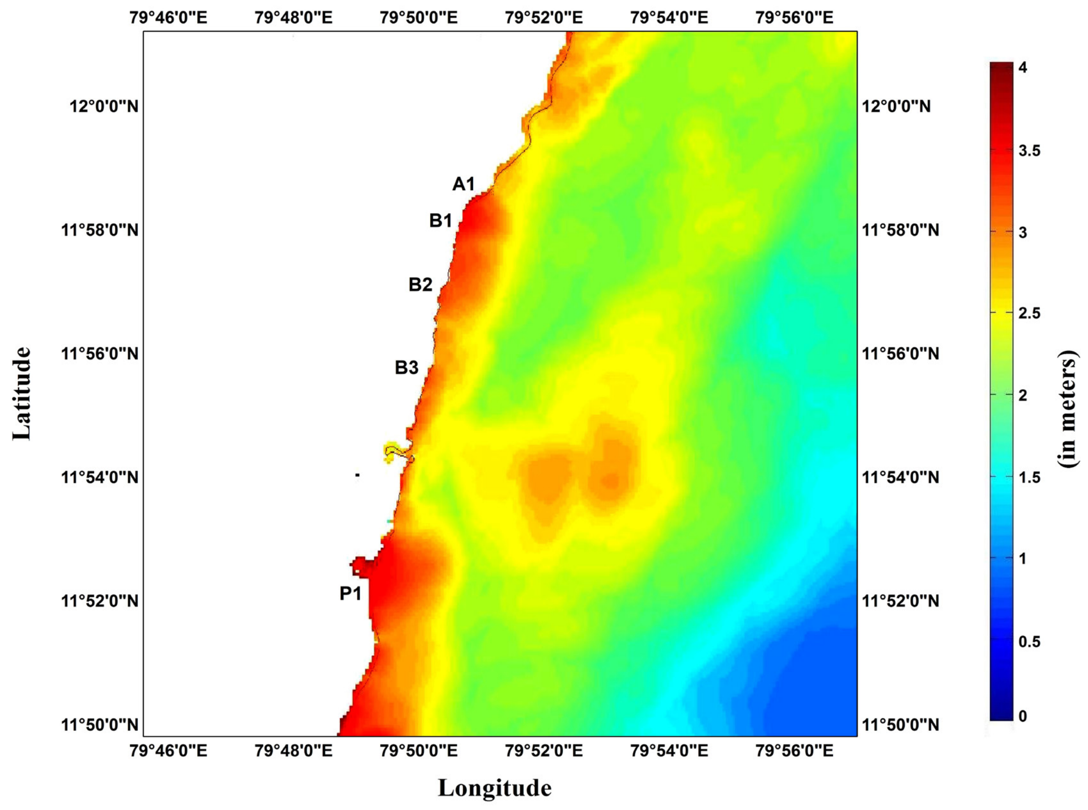

Figure 10. Run-ups along the coast of Pondicherry with the maximum run-up of about 4m near Paradise Beach. / **Figura 10.** *Carreras a lo largo de la costa de Pondicherry con una carrera máxima de unos 4 m cerca de Paradise Beach.*

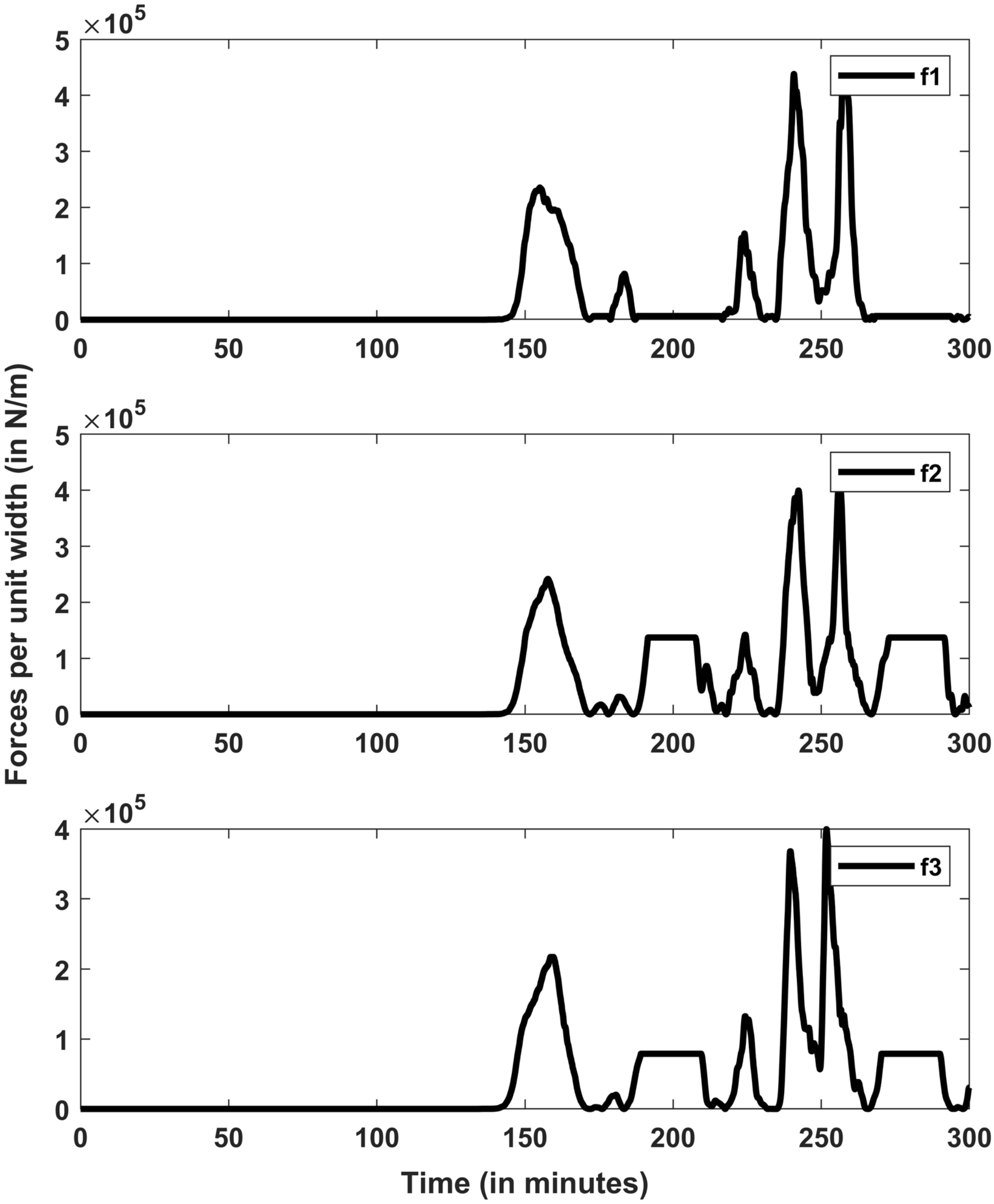

Figure 11. Tsunami Force per unit width with respect to time computed at three different locations along the beach road where the boulders acted as a sea wall. / **Figura 11.** *Fuerza del tsunami por unidad de ancho con respecto al tiempo calculado en tres lugares diferentes a lo largo del camino de la playa donde los cantos rodados actuaban como un malecón.*

ming energy of the wave. In the case of an actual sea wall, it can be easily destroyed by tsunami waves when compared to the rock boulders as the total impact energy is directly taken by the wall. Whereas, the irregular shapes of the boulders play a significant role in dissipating the flow energy of the wave gradually over a very short distance. The surface of the boulders deflects the wave locally in various directions and nullify the net force applied by the tsunami wave. Eventually, the surge wave breaks and loses its velocity. Hence, no inundation or a slight overflow is observed.

Acknowledgements

The authors are thankful to the Director, National Geophysical Research Institute, Hyderabad, for his kind permission to publish this work. The first author Mrs. Mounica wishes to thank UGC for her fellowship and AcSIR under which this study is performed at NGRI.

References

Anandabaskaran, V. and Vijayakumar, G. 2017. Studies on Morphological Changes of Puducherry Coast – A review, *International Journal of Engineering Research & Technology,* 6-8.

Azadbakht, M. and Yim, S.C. 2015. Simulation and estimation of tsunami loads on bridge superstructures, *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 141, 2.

Chock, G., Robertson, I., Carden, L. and Yu, G. 2012. Tohoku tsunami-induced building damage analysis including the contribution of earthquake resistant design to tsunami resilience of multi-story buildings, *Proceedings of the international symposium on engineering lessons learned from the 2011 Great East Japan Earthquake"*

Dames and Moore. 1980. Design and construction standards for residential construction in tsunami prone areas in Hawaii, *Federal Emergency Management Agency, Washington, D.C.*

Imamura, F. 1996. Review of tsunami simulation with a finite difference method, *Long-wave runup models*, pp. 25-42.

Imamura, F., Yalciner, A.C. and Ozyurt, G. 2006. Tsunami modelling manual, *UNESCO IOC international training course on Tsunami Numerical Modelling.*

Ioualalen, M., Asavanant, J. Kaewbanjak, N. Grilli, ST. Kirby, JT. and Watts, P. 2007. Modeling the 26 December 2004 Indian Ocean tsunami: Case study of impact in Thailand, *Journal of Geophysical Research: Oceans,* 112, C7.

Kunkel, C.M., Hallberg, R.W. and Oppenheimer, M. 2006. Coral reefs reduce tsunami impact in model simulations, *Geophysical Research Letters*, 33: L23612.

Mansinha, L. and Smylie, D.E. 1971. The displacement fields of inclined faults, *Bulletin of the Seismological Society of America*, 61, (5) 1433-1440.

Mizutani, S. and Imamura, F. 2001. Dynamic wave force of tsunamis acting on a structure, *In Proc. of the International Tsunami Symposium*.

Murali, R. Ankita, M. Amrita, S. and Vethamony, P. 2013. Coastal Vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process, *Natural Hazards and Earth System Sciences*, 13: 3291-3311.

Murthy, K.S.R. 2016. Baseline geophysical data for hazard management in coastal areas in relation to earthquakes and tsunamis, *International Journal of Ocean and Climate Systems.*

Narayanan, R.M. Sharmila, K.J. and Dharanirajan, K. 2015. Bathymetry and Sea Floor Characteristics of Cuddalore and Pondicherry Coast – India, *International Journal of Earth Sciences and Engineering*, 08: 02

Nistor, I. Palermo, D. Nouri, Y. Murty, T. and Saatcioglu, M. 2009. Tsunami-induced forces on structures, *Handbook of coastal and ocean engineering*, pp.261-286.

Nouri, Y. Nistor, I. Palermo, D. and Cornett, A. 2010. Experimental investigation of tsunami impact on free standing structures, *Coastal Engineering Journal*, 52 (01): 43-70.

Palermo, D. Nistor, I. Al-Faesly, T. and Cornett, A. 2012. Impact of tsunami forces on structures: the university of Ottawa experience, *In Proceedings of the fifth international tsunami symposium, Ispra, Italy.*

Swaroopa Rani, V. Kirti Srivastava and Dimri, V.P. 2011. Tsunami Propagation and Inundation Due to Tsunamigenic Earthquakes in the Sumatra-Andaman Subduction Zone: Impact at Visakhapatnam, *Marine Geodesy,* 34: 48-58.

Yalciner, A.C. Perincek, D. Ersoy, S. Presateya, G. Hidayat, R. and McAdoo, B. 2005. Report on December 26, 2004, Indian Ocean Tsunami, Field Survey on Jan 21-31 at North of Sumatra. *ITST of UNESCO IOC.*

Received : December 8, 2020
Accepted : February 3, 2021