



Estimation of coastal tsunami height and arrival time at Kalpakkam

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After the devastation of the Indian Ocean tsunami of 2004, there is an increased emphasis on tsunami wave modeling for disaster management studies. In this work, a new approach of estimation of coastal tsunami height is proposed and tested for the locations around Kalpakkam. The proposed methodology uses uniformly spaced coarse meshes throughout the domain to calculate the nearshore deep sea wave height and then correlates it with the corresponding coastal tsunami height of a beach. Thus, the proposed method is simple and computationally economical. The method is successfully tested for three stations (Vizag, Chennai, Nagapattinam) around Kalpakkam for which reliable data sets of historical events are available. Next, a sensitivity analysis study is carried out to estimate the impact of a number of fault parameters on coastal tsunami amplitude and wave arrival time at Kalpakkam. Results show that though all the important fault parameters like slip, rake angle, dip angle, focal depth influence the coastal tsunami height, the slip value has the largest impact. It is also noted that while the tsunami waves arrive more rapidly at this coast with an increase of slip, dip angle and rake angle, they slow down with the increasing focal depth value.

[**Keywords:** Coastal tsunami height, Dip angle, Focal depth, Rake angle, Slip, Tsunami arrival time]

Introduction

Tsunamis are extreme oceanic events generally triggered by severe underwater earthquakes occurring at plate boundaries. The Indian Ocean tsunami of 26th December 2004 was initiated by a similar reason and it caused huge damage along the coastlines of several countries¹⁻². Similarly, the Japanese tsunami (7th April 2011) made devastation along the coastline of Japan. Moreover, the incident of 2011 initiated the accident of Fukushima nuclear reactor³. These events highlight the damage potential of a tsunami emphasizing the importance of tsunami wave modeling and early warning systems (specifically for a place where radioactive materials are being handled) to quantify the probable risk in case of future events. As the coastal part of Kalpakkam houses several nuclear facilities, it is very important to estimate the maximum possible tsunami height at the coast to ensure safety. In this context, it is important to mention that the tsunami wave height at deep sea increases significantly at a coast⁴. The estimation of the amplified coastal tsunami height provides an indication of the damage potential of a tsunami and so simulation and prediction of such waves are crucial for risk quantification.

During the initiation of a tsunami, the disturbance in the sea floor raises the water level at the source

location causing further waves which carry the energy. As the height of the initial wave is governed by a set of fault parameters of the source location, the tsunami height at a coast in turn depends on these variables. Thus, the quantification of risk of a selected region demands an analysis of variation in coastal tsunami height and arrival time as a function of important fault parameters. For this purpose, numerical simulation of tsunami waves is a popular approach for which sophisticated codes like FUNWAVE, COMCOT, etc.⁵⁻⁷ are commonly used. It is well-known that the height of a tsunami wave increases when it enters a shallow water region. This demands an increasingly finer meshing near a coast while coarse meshes are sufficient for deep-sea regions. The use of fine meshes increases the computational cost and hence researchers prefer to use scaling laws⁸ to reduce the difficulty.

In this study, a new scaling law which correlates the coastal tsunami height with the corresponding near shore deep sea wave height is proposed and tested for the beaches around Kalpakkam. The proposed law uses uniformly spaced coarse meshes throughout the domain. Coarse meshes are sufficient for the estimation of wave height at nearshore deep sea regions and thus the method becomes

computationally economical as it bypasses the requirements of fine meshing near a coast. It must be noted that tsunami is a rare phenomenon for the coastal parts of Tamil Nadu and reliable recorded data are available only of two historical events (31st December 1881 and 26th December 2004). There was an incident on 26th June 1941 but the measured data were not properly documented. Moreover, Okal⁹ pointed out that the increase in water level during this event might be insignificant. It is also important to mention that there are three stations (Vizag, Chennai, Nagapattinam) around Kalpakkam for which proper observational data are available for both the events (1881 and 2004). Therefore, the new scaling law is tested considering the said events for the locations mentioned above. It is found that the proposed law estimates the tsunami amplitudes at the beaches under consideration satisfactorily. So, the procedure is adopted in the study of risk assessment where the dependence of coastal tsunami height and tsunami arrival time on fault parameters is analyzed. Here, it can be noted that a sensitivity analysis of tsunami is a common approach for the quantification of risks. In this work, the study is carried out for the coastal part of Kalpakkam which houses a number of nuclear facilities and scientific establishments. The 2004 event is considered as the reference case and a detailed sensitivity analysis is performed by varying the important fault parameters.

Materials and Methods

The present work deals with the assessment of coastal tsunami height and arrival time for Kalpakkam region. This requires a detailed simulation of a number of tsunami events. For this purpose, a popular numerical model, Delft3D, is used in the present study. It is a known fact that when waves approach a coast, the amplitude increases. To reduce the computational cost of tracking such amplification, scaling laws^{8,10} are commonly used. In this work, an empirical equation is proposed which correlates the coastal tsunami height of a beach to the nearshore deep sea wave height. In this approach, uniformly spaced coarse grids are used to span the entire domain for the purpose of simulations. Then, the tsunami height at a coast is estimated using the following empirical relation.

$$H = Kh|\cos(\alpha)| \quad \dots (1)$$

Here, the term H represents the coastal tsunami height, K is a beach-specific empirical amplification

factor, h is the wave height at nearshore deep sea and α is the angular deviation of the beach under consideration from the main direction of propagation of tsunami waves.

The concept of angular deviation is pictorially indicated in Figure 1. Here, three imaginary points A, B and C represent a source, a point on the main direction of tsunami propagation and the observational beach in respective orders. Then, α indicates the angle between the lines AC and AB. Another important factor of Equation (1) is the term ‘wave height at near shore deep sea’ represented by h . This refers to the wave height at a place (located near a shore) where the effect of bottom friction starts to increase the wave height. In this work, the h value is estimated by numerical simulation of an event. Here, it is to be emphasized that in conventional way of numerical simulation of tsunami waves, the requirement of increasingly finer meshing is essential to capture the amplification of wave height near a coast. In this proposed approach, Equation (1) links h with H value so that the requirement of fine meshing can be bypassed. It is easy to note that the equation demands a site-specific estimation of the empirical constant K . Here, this is performed by comparing with the literature value of the coastal tsunami height of 2004 event. Then, the estimated value is used in subsequent calculations. For the purpose of simulation, a numerical model namely Delft3D is configured for the domain which extends between (77° E – 98.50° E) and (1.00° S – 21.40° N). Delft3D

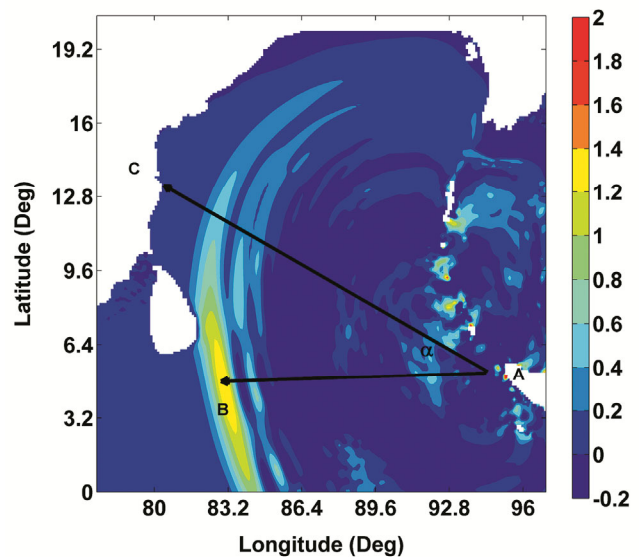


Fig. 1 — Pictorial representation of the angular deviation of a beach [$H = Kh|\cos(\alpha)|$]. The wave height scale is in metre

is a state-of- art free software that uses Okada model¹¹ to estimate the initial deformation in the ocean surface due to an earthquake. An important fact about the software is that, it has user-friendly free GUIs for pre and post-processing. In this study, first of all, the new scaling methodology is tested with two sets of uniform grids (0.1 degree and 0.05 degree). Both the studies provide reasonably accurate simulated results indicating applicability of the proposed approach in our region of interest. Next, considering the event of 2004 as the reference case, a detailed sensitivity analysis is performed for Kalpakkam region. This event is chosen as the reference case because this is a huge event of the recent past and so accurate data sets are available for all the locations. Here, it is necessary to mention that all the calculations of the sensitivity analysis stage are performed with uniform meshes of 0.05 degree and using the new scaling law. For simulations, the same extent of domain and same bathymetric data (GEBCO, resolution of 30 arc-seconds) are considered throughout the work.

Results and Discussion

This work deals with the assessment of coastal tsunami height and tsunami arrival time at Kalpakkam region. For this, a detailed study is conducted to estimate the variation of these two variables as a function of important fault parameters using a hybrid approach of relating a nearshore deep sea wave height with the corresponding coastal tsunami height. This approach requires an estimation of an empirical constant *K*, details of which are provided in the ‘Methodology’ section. Before applying the method for sensitivity analysis, it is required to validate the new scaling law for the computational domain considered in the study. This involves a proper

simulation of a few historical tsunamis (a) 31st December 1881 (causing earthquake 7.9 Richter) and (b) 26th December 2004 (causing earthquake 9.1 to 9.3 Richter) along the region. At first, the tsunami of 2004 is simulated (using uniform meshes of 0.1 degree resolution) for which the important fault parameters are obtained from the existing literature¹². The simulation provides the nearshore deep sea wave height *h* for three stations *viz.* Vizag, Chennai and Nagapattinam. Next, by comparing with the literature values of the observed tsunami heights at these coasts¹³⁻¹⁴, the values of *K* are evaluated for the said stations (Table 1). It can be noted that the simulated arrival time of the first waves matches well with the literature values¹³. Next, using the estimated values of *K*, the coastal tsunami heights are calculated for the 1881 event (Table 2). For this event, the fault parameters and observations mentioned in the published literature¹⁵ are adopted. For the simulation of this part, uniform grids of same resolution and the same bathymetric data set are used. It is easy to note a reasonable agreement between the simulated and the observed coastal tsunami heights. Moreover, the tsunami arrival time at different beaches also matches well with the literature values¹⁵. Following this, an analysis is carried out to understand the applicability of the proposed scaling law when the calculations are performed with different sizes of coarse meshes. For this part of the study, the same calculations are repeated with uniform meshes of 0.05 degree resolution. The estimated *K* values and the subsequent calculations (for 0.05 degree resolution) are shown in Tables 3 and 4. Here also, an agreement between the simulated and the literature values can be noted. An interesting observation of this part of the study is that the value of *h* changes with the reduction of mesh size

Table 1 — Estimation of K and comparison of arrival time (grids of 0.1 degree)

| Year | Location | h (m) | cos(α) | H-obs (m) | K | T-obs (min) | T-est (min) |
|------|--------------|-------|--------|-----------|-------|-------------|-------------|
| 2004 | Vizag | 0.70 | 0.11 | 1.00 | 12.99 | 156 | 159 |
| | Chennai | 1.08 | 0.39 | 2.00 | 4.75 | 156 | 170 |
| | Nagapattinam | 1.19 | 0.51 | 5.00 | 8.24 | 151 | 166 |

H-obs = Observed coastal tsunami height, T-obs = Observed arrival time of the first wave, and T-est = Estimated arrival time of the first wave

Table 2 — Estimation of tsunami of 1881 (grid 0.1 degree)

| Year | Location | h (m) | cos(α) | K | H-obs (m) | H-est (m) | T-obs (min) | T-est (min) |
|------|--------------|-------|--------|-------|-----------|-----------|-------------|-------------|
| 1881 | Vizag | 0.05 | 0.34 | 12.99 | 0.15 | 0.22 | 174 | 161 |
| | Chennai | 0.08 | 0.70 | 4.75 | 0.25 | 0.27 | 144 | 145 |
| | Nagapattinam | 0.09 | 0.82 | 8.24 | 0.80 | 0.61 | 145 | 151 |

H-obs = Observed coastal tsunami height, H-est = Estimated coastal tsunami height, T-obs = Observed arrival time of the first wave, and T-est = Estimated arrival time of the first wave

Table 3 — Estimation of K and comparison of arrival time (grids of 0.05 degree)

| Year | Location | h (m) | $ \cos(\alpha) $ | H-obs (m) | K | T-obs (min) | T-est (min) |
|------|--------------|---------|------------------|-----------|-------|-------------|-------------|
| 2004 | Vizag | 0.85 | 0.11 | 1.00 | 10.70 | 156 | 157 |
| | Chennai | 1.25 | 0.39 | 2.00 | 4.10 | 156 | 165 |
| | Nagapattinam | 1.55 | 0.51 | 5.00 | 6.33 | 151 | 162 |

H-obs = Observed coastal tsunami height, T-obs = Observed arrival time of the first wave, and T-est = Estimated arrival time of the first wave

Table 4 — Estimation of tsunami of 1881 (grid 0.05 degree)

| Year | Location | h (m) | $ \cos(\alpha) $ | K | H-obs (m) | H-est (m) | T-obs (min) | T-est (min) |
|------|--------------|---------|------------------|-------|-----------|-----------|-------------|-------------|
| 1881 | Vizag | 0.07 | 0.34 | 10.70 | 0.15 | 0.26 | 174 | 162 |
| | Chennai | 0.10 | 0.70 | 4.10 | 0.25 | 0.29 | 144 | 147 |
| | Nagapattinam | 0.14 | 0.82 | 6.33 | 0.80 | 0.73 | 145 | 150 |

H-obs = Observed coastal tsunami height, H-est = Estimated coastal tsunami height, T-obs = Observed arrival time of the first wave, and T-est = Estimated arrival time of the first wave

but the final result (coastal tsunami height) remains almost the same. As h is measured at a point where the bottom friction starts to play a role, the value of h is expected to increase with smaller grids. It is also noted that the constant K which connects H and h also changes with the variation of h , ensuring almost the same H value at a beach. This guarantees that the new scaling law will provide the same result irrespective of the mesh size. Here, it is important to note that if a particular bathymetric data set and uniform meshes are used for the determination of K , the same meshes and the same bathymetric condition must be maintained in subsequent calculations. Next, a discussion on the limitation of the proposed scaling law is provided. The new law co-relates the nearshore deep sea wave height with the coastal tsunami height through an empirical amplification factor K . As the value of K is not known, it is estimated using the observations of one event (2004) and is applied to the calculations of the other one (1881). Here, it is assumed that the nature of the coast under consideration remains unchanged between the occurrences of the events. If any change occurs (due to events like earthquakes, landslides or any construction on the beach), the method of estimation of K used in the paper becomes invalid. If K is measured experimentally, this limitation can be overcome.

The next part of the present paper deals with the sensitivity analysis of tsunami for the coastal part of Kalpakkam. As the proposed scaling method is working well for this region, the said approach is used in this part of study. Here, all the calculations are performed with uniformly spaced meshes of 0.05 degree resolution and the event of 2004 is chosen as the reference tsunami. Published literature¹⁶ mentioned that Kalpakkam region observed a coastal

Table 5 — Dependence of coastal tsunami height and arrival time on fault parameters

| Parameter | Parameter value | Coastal tsunami height (m) | Arrival time (min) |
|---------------------|-----------------|----------------------------|--------------------|
| Slip (m) | 10 | 6.07 | 167 |
| | 13 | 8.30 | 166 |
| | 17 | 10.39 | 165 |
| | 20 | 11.75 | 163 |
| rake angle (degree) | 60 | 3.40 | 167 |
| | 70 | 3.57 | 167 |
| | 80 | 3.73 | 166 |
| Dip angle (degree) | 90 | 4.10 | 165 |
| | 10 | 3.77 | 170 |
| | 12 | 4.10 | 165 |
| | 15 | 4.55 | 162 |
| Focal depth (km) | 20 | 4.88 | 161 |
| | 15 | 3.28 | 162 |
| | 25 | 4.10 | 165 |
| | 35 | 4.14 | 174 |

Arrival time = Estimated arrival time of the first wave

tsunami height of 4.1 m during the said event. It is well known that among all the fault parameters, the dip angle, rake angle, the slip length and the focal depth play very crucial role in determining the initial wave height (at the source location) and this in turn governs the coastal tsunami height and the wave arrival time at an observational beach. So a systematic variation of these parameters is carried out to study their impact. The results of this part are shown in Table 5. It can be noted that with the increase of all the fault parameters under consideration, the coastal tsunami height at Kalpakkam shore increases. However, among these variables, the slip length plays the most significant role. The variation of coastal tsunami height of Kalpakkam region as a function of slip is shown in Figure 2. Another important observation from this analysis is that the waves arrive at the coast a little bit rapidly with the increase in slip,

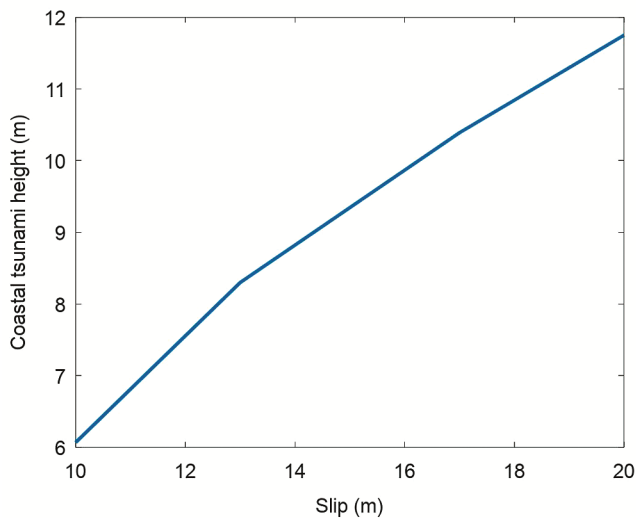


Fig. 2 — Variation in coastal tsunami height at Kalpakkam as a function of slip

dip and rake angle; they slow down with the increase in focal depth. It is worth mentioning here that the sensitivity analysis study basically constitutes a set of hypothetical events. The event of 2004 was one of the most destructive tsunamis of the recorded history. Published literature¹² stated that during this event, the slip value of different segments varied between 6 to 15 m. A hypothetical case considering a conservative slip value of 20 m in all segments (along with other parameters of the reference event) refers to a study of the worst possible case and the result indicates an ultra-conservative coastal tsunami height (11.75 m) at the shore of Kalpakkam region. This can be considered as the maximum possible coastal tsunami height at that location.

It is also essential to discuss the assumption of a conservative slip value of 20 m in all the segments. As per records, the earthquake with maximum magnitude (9.5 Richter) occurred in Chile on 22 May 1960. The earthquake that occurred on 26 December 2004 was of 9.1 to 9.3 Richter. Thus, the earthquake of 2004 was almost of the same magnitude as that of the highest recorded one. So, the assumption of 20 m slip in all segments represents a super conservative case. This may be representing an earthquake with a magnitude higher than the highest recorded one. Thus, the assumption of considering a slip value of 20 m in all the segments is good enough to estimate an upper-bound coastal tsunami height for Kalpakkam.

Conclusion

This work deals with the sensitivity analysis of tsunami height and arrival time at the coastal part of

Kalpakkam region. For the purpose of simulation of coastal tsunami height during an event, a simplified approach that uses simulation with coarse meshes along with an empirical relation is adopted. The method is tested for beaches around Kalpakkam (where observational data sets are available) considering the events of 2004 and 1881. The calculations are carried out with two different sets of uniformly spaced meshes (0.1 degree and 0.05 degree) and in both the cases, a reasonable agreement between the observed and the estimated values is noted. The results ensure that the new scaling law is applicable to any coarse meshes. Next, the variation in the coastal tsunami height and tsunami arrival time (at the shore of Kalpakkam) is assessed considering the event of 2004 as the reference case. For this, a series of simulations are performed with uniformly spaced meshes of 0.05 degree resolution. It is found that though the coastal tsunami height increases with the increase of all the parameters, the slip length has the most significant impact. On the other hand, the arrival of tsunami becomes slightly rapid with the increase of slip, dip and rake angle while the same becomes slower with the increase in the focal depth value. The tsunami of 2004 was a huge one due to a severe underwater earthquake. For the sensitivity analysis, a number of hypothetical cases are simulated considering the event of 2004 as the reference case. The particular case where a slip length of 20 m is considered in all the segments represents an ultra-conservative condition. So, the results of the sensitivity analysis indicate a maximum possible coastal tsunami height of about 11.75 m at Kalpakkam coast. This can be considered as the upper limit for this region.

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Conflict of Interest

There is no conflict of interest.

Ethical Statement

The work presented in this article is purely a numerical study. It is certified that the results reported

here are original and have not been published in any other journal.

Author Contributions

All the authors have contributed equally in developing the idea, performing the calculations and in the preparation of the manuscript.

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