Role of bathymetry in tsunami devastation along the East Coast of India

The powerful earthquake measuring about *Mw* 9.3 in magnitude of 26 December 2004, nucleated in the northwestern coast of Sumatra, caused the most devastating tsunami ever recorded in the southeastern region of India. Most of the southern part of India, Sri Lanka and Indonesia faced the brunt of the natural phenomenon. The tsunami caused innumerable loss to property and human life. The oblique subduction of the Indo-Australian plate under the Burmese plate in northern Sumatra and in the Andaman–Nicobar region predominantly in the thrust motion[1] generated the massive tsunami in this region, which traversed in all directions to bring about unexpected misery and calamity. To ascertain the manifestation in the tsunami wave height amplitude due to shoaling, the topography of the seafloor is an important parameter for controlling the wave pattern of the tides. Here we attempt to analyse the bathymetry data on the eastern coast of India to access the effect of bathymetry in terms its gradient and maximum gradient on the propagation and enhancing the tidal magnitude.

The area of investigation on the Eastern Continental Margin extends from 8 to 20°N and 80 to 85°E bordering the Bay of Bengal that forms the northeastern part of the Indian Ocean. The coastline on the eastern margin is approximately 3200 km. The depth and width of the shelf, the steepness and width of the slope and the existence of a continental rise (Bengal fan) are all features that give each margin its characteristic physiographic signature. These signatures are the consequence of the breaking apart of the eastern coast from the Antarctic landmass[2]. On the eastern margin the width of shelf is not uniform, in the northern region it is wider and in the southern region it almost abuts the coastline, thereby creating gradients in the bathymetry. The region between India and Sri Lanka is shallow. The topography of the seafloor in the abyssal plane off the east coast of India is fairly 'monotonous'. In the north the bathymetry shows gentle slope and steepness in slope as we go towards south.

Based on the analysis of the tidal gauge measurement which were being operated by the Survey of India on the eastern coast, National Institute of Oceanography[3] Goa has indicated that maximum amplitude of the tidal wave was recorded at Paradeep (>3 m), Chennai and Visakhapatnam (2 m). In the western region covering Cochin, and Marmu Goa, low tides were observed following the appearance of the tsunami. The tidal gauge instrument at Nagapattinam which bore the maximum damage, became unoperational.

A tsunami run-up survey was conducted by NGRI scientists immediately after the event to study tsunami damages, inundation areas and to obtain estimates of tsunami heights from perishable evidences like watermarks on houses and ocean debris transported inland. According to these figures the highest mark was found around Nagapattinam (5 m), Karaikal

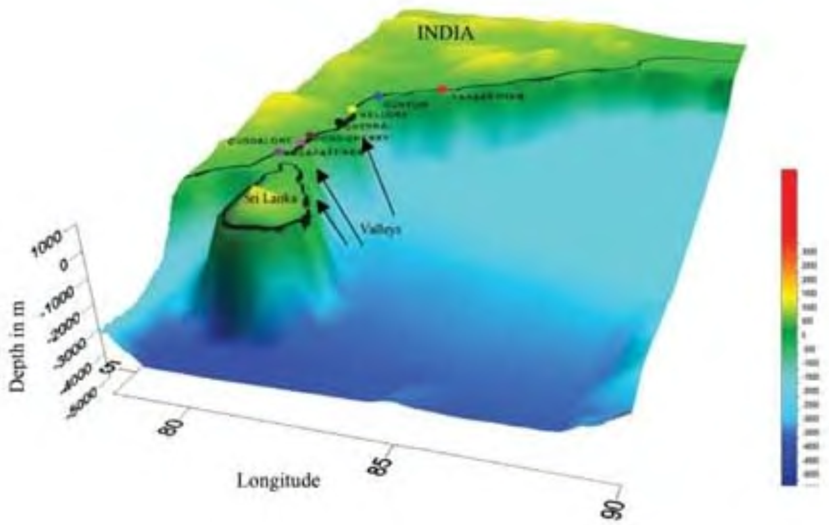

Figure 1. Bathymetry of the region in 3D with stations and coastline.

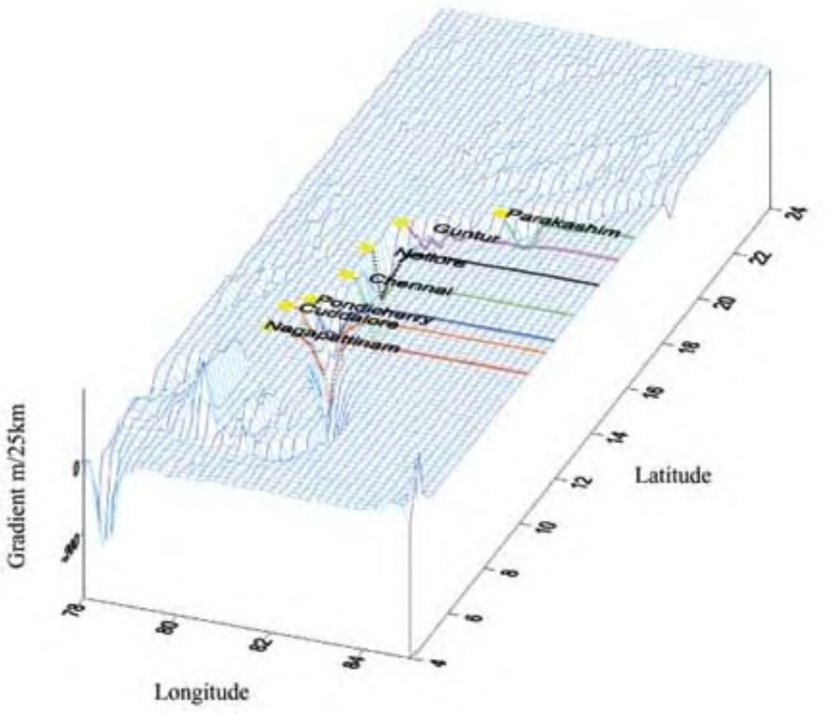

Figure 2. Gradients plotted against stations in a 3D wire frame map.

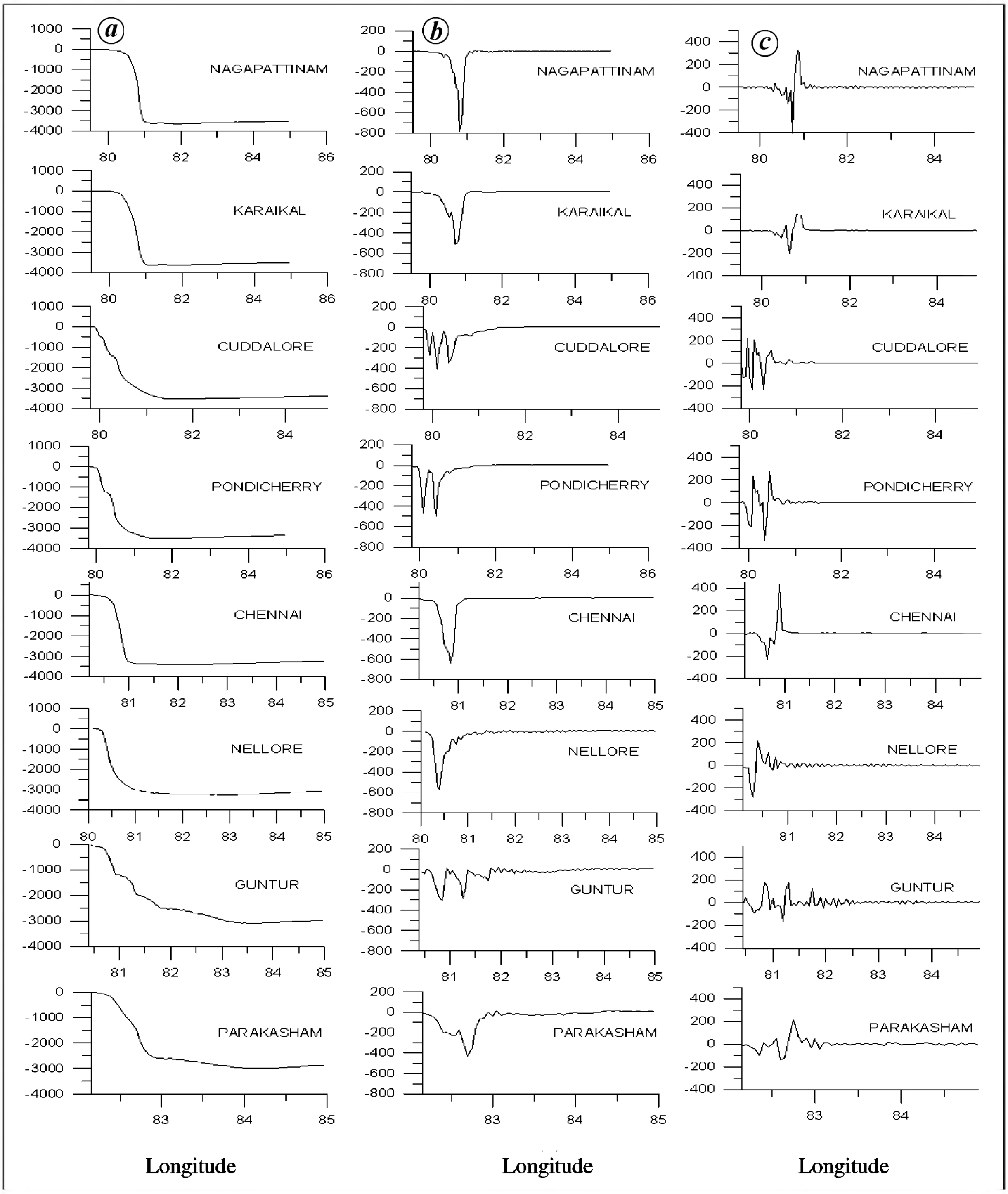

Figure 3. Graphs plotted with respect to bathymetry (***a***), gradient (***b***) and second derivative bathymetry (***c***) along the tracks for all the stations.

(4.4 m), Pondicherry (2.6 m) and Chennai (2.8 m)[4,5].

Kurien *et al.*[6] studied the inundation characteristics and geomorphologic impact of the Kerala coast in the western margin due to the tsunami and indicated that maximum inundation and damage was caused in the vicinity of Kayamkulam, which coincided with the high tide. However, the northern part of Kerala was not affected much owing to low tide in this region.

We have used a combination of GEBCO and Etopo2 bathymetry datasets for arriving at higher resolution seafloor relief and topography in the region of study. Utilizing these datasets we have prepared a 3D map to ascertain the pattern of bathymetry (Figure 1). Figure 1 shows a series of steep valleys adjacent to some coastal station in contrast to the normal bathymetry as expected in the passive continental margins. These valleys are clear in the vicinity of Nagapattinam and Chennai. Nagapattinam is sandwiched between the steep slope on the east and the shallow seafloor relief in the south adjoining Sri Lanka.

In Figure 2, we present the estimated gradients (first derivative) in the bathymetry in 3D view. Figure 2 clearly brings out the undulation in the bathymetry on a finer scale. Steep gradients are observed in the vicinity of Nagapattiman and Chennai. Over the other stations the gradients have a series of lows and highs indicating roughness in the seafloor relief. Moving towards north, the magnitude of the gradient reduces substantially.

To bring clarity to the pattern at each station, in Figure 3, we present profiles of bathymetry, estimated gradients and their second derivatives (to arrive at the maximum gradient) for the coastal stations under consideration. From the graphs we can infer that the bathymetry of Nagapattinam, Karaikal and Chennai are steep compared to the other stations. This aspect is also clearly visible in the gradient plots. The gradient in the vicinity of the stations Nagapattinam (800 m/25 km), Chennai (650 m/25 km), Nellore (580 m/25 km), Karaikal (500 m/25 km), for other stations the gradient shows a complex pattern. Even in the case of Karaikal, the gradient increases in steps. The second derivative of the bathymetry clearly shows maximum change of gradient at Nagapattinam and Chennai. For rest of the stations, the pattern of second derivative is complex.

It has been suggested[7] that the geomorphic characteristics of the shelf slope and rise on the continental margins are the imprints of the breaking history and the subsequent tectonic episodes. Broadening/narrowing of the shelf indicates the extent to which the margin was exposed to ice age[8]. The foot of the slope (maximum rate of change of gradient in the bathymetry) may primarily indicate the processes of rifting of the continent and may coincide with the continent–ocean boundary. In this context the breaking-up of the Indian plate becomes important for working out the configuration of geomorphic relief. The break-up of eastern Gondwanaland in the early Cretaceous (~118 Ma) was followed by seafloor spreading and evolution of the oceanic lithosphere underlying the present Bay of Bengal[9,10]. Subsequently, it drifted in north or northwest direction and collided with the Eurasian plate during the lower Eocene around 54 Ma to generate the world's highest mountain range[11]. This geodynamic cycle has resulted in providing the present geomorphic features on the eastern coast of India. The pattern of the shelf on the eastern continental margin is not uniform[5]; it narrows down near Nellore and Cuddalore and broadens in the north. The slope and gradient of the bathymetry are steep near these stations and in the vicinity of Chennai (Figures 1 and 2). These characteristics are clear in Figure 3; the second derivative graph indicates maximum gradient change is encountered at Chennai. Second derivative of the bathymetry gives an approximate estimate of where the maximum gradient occurs and may eventually become the primary place where the height of the wave starts building up rapidly.

In our study, the narrowing of the shelf in the southern part of India and steep gradient as well as maximum gradient occur in the vicinity of Nagapattinam, Cuddalore and Chennai, thereby providing proper conditions for enhancement of tidal wave and thus causing maximum damage to property and human life. Raval[12] suggested that the shape and bathymetry in the vicinity of Nagapattinam might have caused maximum damage at this site. Reefs, bays, entrances to rivers, all help modify the tsunami as it approaches the shore. The station at Cuddalore does not indicate significant change in bathymetry and its associated derivatives. Thus the bay shape of the coast and creek-like feature that encroach the land mass in the vicinity of Cuddalore, may have played a vital role in the devastation of this region. The station at Nagapattinam bore the maximum brunt as it is trapped in a peculiar configuration of steep gradient in the east and broad shallow waters in the south. The combined effect of these might have resulted in the highest casualties in this region.

In the present study, we have attempted to assess the role of bathymetry and its derivatives in modifying the propagation of the tsunami wave of 26 December 2004. We conclude that under-sea configuration has an important role in enhancing the wave height, as some coastal stations on the eastern margin of India have suffered maximum damages where the bathymetry parameters have shown an anomalous pattern. Further detailed studies in this direction in terms of modelling for the present scenario may help us understand the wave dynamics in a fuller sense.

1. Ammon *et al.*, *Science*, 2005, **308**, 1133–1139.
2. Norton, I. O. and Sclater, J. G., *J. Geophys. Res.*, 1979, **84**, 6803–6830.
3. Report, National Institute of Oceanography, Goa.
4. Chadha, R. K., Latha, G., Yeh, H., Peterson, C. and Katada, T., *Curr. Sci.*, 2005, **88**, 1297–1300.
5. United Nations Disaster Management Team Situation Report, India, 2004.
6. Kurien, N. P., Pillai, A. P., Rajith, K., Murali Krishnan, B. T. and Kalaisaran, P., *Curr. Sci.*, 2005, **90**, 240–249.
7. Symonds, P. A., Eldholm, O., Mascle, J. and Moore, G. F., *Continental Shelf Limits* (eds Cook, P. J. and Carleton, C. M.), Oxford University Press, USA, 2000, pp. 25–62.
8. Prescott, V., *Continental Shelf Limits* (eds Cook, P. J. and Carleton, C. M.), Oxford University Press, USA, 2000, pp. 64–83.
9. Curray, J. R., Emmel, F. J., Moore, D. G. and Russel, W. R., *The Ocean Basins and Margins. Vol. 6, The Indian Ocean* (eds Narian, A. E. and Stehli, F. G.), Plenum, New York, 1982, pp. 399–450.
10. Curray, J. R., *Geology*, 1991, **19**, 1097–1100.
11. Gopal Rao, D. *et al.*, *Mar. Geophys. Res.*, 1994, **16**, 225–236.
12. Raval, U., *J. Geol. Soc. India*, 2005, **65**, 647–649.

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