Role of bathymetry in tsunami amplification – evidences from Andhra Pradesh coast

K. Nageswara Rao[1,*], P. Subraelu[1], A. S. Rajawat[2] and Ajai[2]

[1]Department of Geo-Engineering, Andhra University, Visakhapatnam 530 003, India
[2]Marine, Geo and Planetary Sciences Group, Space Applications Centre, Ahmedabad 380 015, India

Interpretation of satellite images representing both the pre- and post-tsunami of 26 December 2004 revealed three isolated locations along the Andhra Pradesh coast where the tsunami amplified despite its overall diminishing strength northward from Tamil Nadu. The digital elevation models generated from the depth contours traced from the National Hydrographic Charts indicated landward convexities in the 5 m depth contour juxtaposing the three locations. Apparently, the tsunami amplified locally as it entered these narrow canyon-like zones and threw up sediment onto casuarina plantations, aquaculture ponds, saltpans and other land-use features. The study highlights the possible role of nearshore bathymetry in tsunami amplification.

Keywords: Bathymetry, depth contour, landforms, tsumani amplification.

THE impact of the 2004 Indian Ocean tsunami on the coastal communities has been extensively researched, surveyed and documented. One of the common inferences made from various tsunami-affected coastal sectors was that the local landforms rendered some areas more vulnerable than others[1]. For instance, places like Nagapattinam and Cuddalore along the Tamil Nadu coast were among the worst affected by the tsunami because of their low-lying nature[2], as the linear valley-like swales behind the shore-parallel sand-dune ridges claimed several lives due to lateral flows from tidal inlets or breaches in dune ridges[3]. Several studies from various other parts such as along the coasts of Kerala[4], Andaman and Nicobar Islands[5], Sri Lanka[6], Thailand[7] and Myanmar[8] have highlighted the role of landforms in tsunami impact. The coastal bathymetry, i.e. the topography of the inner continental shelf region also played an important role in the tsunami intensity as observed from the Tamil Nadu coast[9], Andaman and Nicobar Islands[10], Sri Lanka[11] and Vietnam[12]. Field measurements at 19 stations along Tamil Nadu coast revealed that the tsunami reached variable distances ranging from 100 to 900 m and the increase in tsunami height even up to 7 m in the northern regions of Tamil Nadu coast is perhaps due to the offshore bathymetry in that region, wherein the 200 m depth contour was concave seaward, which possibly lead to the convergence of tsunami[9].

Despite an overall decrease in its intensity northward from Tamil Nadu along the east coast, the tsunami amplified at some isolated pockets in the Andhra Pradesh (AP) coast also. An attempt is made in this study to identify the coastal sectors that were significantly affected by the tsunami and to find out if there is any correlation between the offshore topography and the tsunami amplification at such locations along the AP coast.

IRS P6 LISS-3 satellite images of 23.5 m spatial resolution pertaining to the pre- and post-tsunami dates were compared for identifying the locations where the tsunami impact was significant in the entire 1030 km long AP coast. Although the pre-tsunami images used in this study pertain to different dates ranging from April to December 2004 and the post-tsunami images are from early 2005 to early 2006 depending on the availability of cloud-free data, the coastal changes considered in this study are caused by the 2004 tsunami as evident from the field observations and measurements made all along the AP coast within three months from the date of tsunami occurrence[13]. Furthermore, there was no possibility of such coastal changes having been caused by storm surges, as no such events occurred in the region during 2005. A comparison of the pre- and post-tsunami satellite images in GIS revealed significant changes in the coastal

Figure 1. Outline map of the peninsular part of India showing the locations of the three villages, namely Krishnapatnam, Gangapatnam and Chinnamailavanilanka (marked with solid triangles), along the eastern coast in Andhra Pradesh.

*For correspondence. (e-mail: nrkakani@yahoo.com)

features at three separate locations near Krishnapatnam, Gangapatnam and Chinnamailavanilanka villages from south to north along the AP coast (Figure 1).

Krishnapatnam is located about 2 km inland from the coast in the southernmost coastal district of Nellore in AP. To the east of the village along the coast, extensive casuarina plantations occupy the linear sand ridges that lie parallel to the shoreline. A comparison of the pre-tsunami (Figure 2 *a*) and the post-tsunami (Figure 2 *b*) satellite images indicated that along a 15 km long stretch of the shoreline the tsunami run-up led to sand accretion over variable widths of 33–470 m covering a total area of 135 ha. Field observations revealed that the thickness of the tsunami deposit is about 0.3–0.6 m and the tsunami height was about 1.52 m (~ 2.0–2.50 m amsl) and the maximum inundation distance is about 1 km inland from the shoreline. Casuarina trees in the area were buried by the tsunami sediments (Figure 2 *c*). Importantly, there were no casualties here.

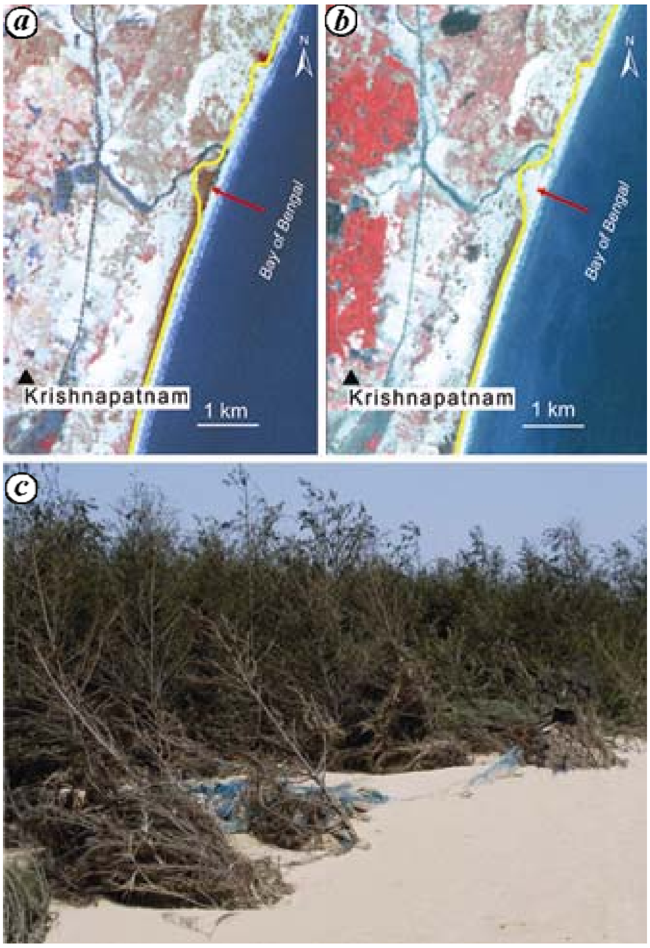

Figure 2. ***a***, Pre-tsunami satellite image (IRS P6 LISS 3 Path 102 Row 063) dated 17 April 2004. ***b***, Post-tsunami image (IRS P6 LISS 3 Path 102 Row 063) dated 25 January 2006 showing the coastal part near Krishnapatnam. Yellow-coloured line indicates the landward limit of the tsunami deposit. Note the maximum width of the tsunami deposit is at the location indicated by the red-coloured arrow where casuarina plantations which appear in brown colour in (***a***) are covered by the tsunami deposits which appear in white colour in (***b***). ***c***, Photograph of the area showing tsunami deposits overlapping the casuarina trees.

At about 29 km north of Krishnapatnam along the coast in the same district, the tsunami impact was much more significant near Gangapatnam, which is located at about 2.5 km inland from the shoreline and 6 km south of the Penner River estuary. The pre-tsunami IRS P6 LISS 3 image (Figure 3 *a*) showed that the coastline here is marked by a thin sandy beach, behind which lie a few patches of casuarina and other vegetation besides aquaculture ponds. However, in comparison, the post-tsunami image (Figure 3 *b*) shows large white sand patches over a linear stretch of 10 km, deposited by the tsunami over variable widths of 51–1000 m burying the vegetation and fish ponds in an area of 132 ha (Figure 3 *c*). The maximum inundation distance is about 1 km inland from the shoreline. Field studies revealed that the tsunami deposit is about 0.3 m thick. The water marks on the building at about 1.82 m above the ground (Figure 3 *d*) indicate that the overall tsunami elevation was about 3 m above the sea level at this location. The tsunami killed 11 persons here.

Further northward from this location, there was no visible evidence of the tsunami-induced deposition for

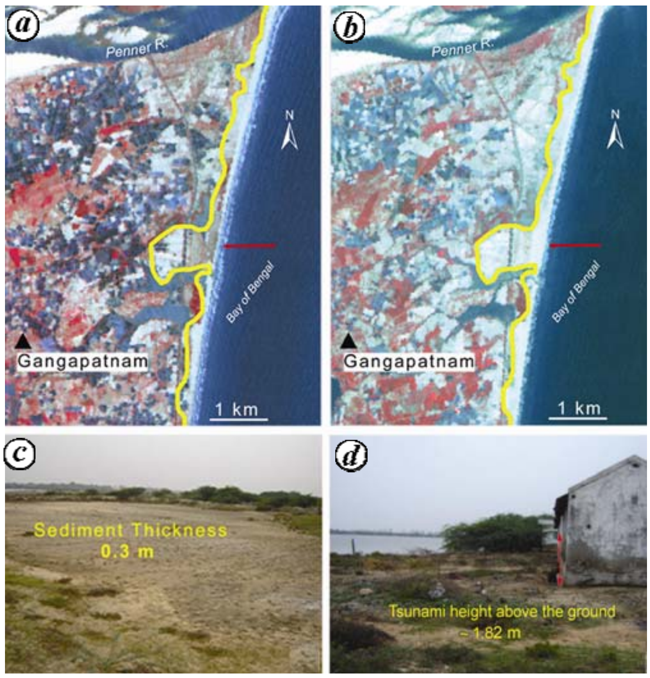

Figure 3. ***a***, Pre-tsunami satellite image (IRS P6 LISS 3 Path 102 Row 063) dated 17 April 2004. ***b***, Post-tsunami image (IRS P6 LISS 3 Path 102 Row 063) dated 25 January 2006 showing the coastal part near Gangapatnam. Yellow-coloured line indicates the landward limit of the tsunami deposit. Note the maximum width of the tsunami deposit is at the location indicated by the red-coloured arrow where vegetation which appears in brown colour in (***a***) is covered by the tsunami deposits which appear in white colour in (***b***). ***c***, ***d***, Field photographs showing the aquaculture ponds buried by tsunami sand deposits (***c***) and the tsunami run-up height of 1.82 m (~ 3.0 m above the sea level) in the area as indicated by the water marks on the walls (***d***).

several hundreds of kilometres. However, at Chinnamailavanilanka, which is located roughly 350 km north of Gangapatnam, close to the Vasishta distributary of the Godavari River, the tsunami deposited sand over a 7 km long and 82–292 m wide stretch covering an area of 108 ha, as revealed by a comparison of the pre-tsunami (Figure 4 *a*) and the post-tsunami (Figure 4 *b*) satellite images. Field observations revealed that the tsunami elevation here was about 2.5 m above the sea level (Figure 4 *c*) and the maximum inundation distance was 830 m inland from the shoreline[14]. Initially, the tsunami eroded about 40-cm thick sediment as evident from the exposed roots of the standing trees there (Figure 4 *d*), whereas further inland the tsunami deposited sand over the salt pans (Figure 4 *e*). The tsunami killed eight persons here.

Although the coastal topography and morphology at these locations might be responsible for significant tsunami run-up on land, it may not be the only factor responsible for tsunami impact. This is amply clear from the fact that there are no tsunami sediments deposited at many other low-lying segments of the AP coast, except at these three locations. Probably, the coastal bathymetry at these three locations is conducive for such amplification of the tsunami. An attempt is made here to study the nature of bathymetry off these three locations. The National Hydrographic Charts of the entire AP coast on 1 : 300,000 scale were used to extract the depth contours of 5, 10, 20, 30, 50, 100 and 200 m, which appear on the charts. Initially, all the charts were scanned and the resultant digital maps were geo-referenced in GIS. Then the contours and the shoreline were digitized as line features in GIS. A digital elevation model (DEM) of the bathymetry was generated for the AP coast using the depth contour data. Further, the offshore zones at Krishnapatnam, Gangapatnam and Chinnamailavanilanka, where the tsunami impact was prominent (as described above) were subset from DEM of the total AP coast. The post-tsunami satellite images pertaining to the three locations were then draped on the offshore DEMs of the respective locations.

At 50 times vertical exaggeration, the DEM showed canyon-like, convex landward bends in the 5 m depth contours at the three areas affected. For example, near Krishnapatnam sediment deposition occurred in the direction that coincides with the long axis of the canyon present in the offshore (Figure 5 *a*). Apparently, the tsunami amplified as it converged into the canyon and thereby pushed the sediments onto the coast opposite the canyon.

Figure 4. *a*, Pre-tsunami satellite image (IRS P6 LISS 3 Path 103 Row 061) dated 18 December 2004. ***b***, Post-tsunami image (IRS P6 LISS 3 Path 103 Row 061) dated 13 December 2005 showing the coastal part near Chinnamailavanilanka. Yellow-coloured line indicates the landward limit of the tsunami deposit. Note the increase in the width of the white-coloured strip along the shore in (***b***) when compared to that in (***a***), indicating the width of the tsunami deposit. ***c***–***e***, Photographs showing water marks on the wall inside the building indicating the tsunami run-up elevation which is about 2.5 m above the sea level (***c***); exposed tree roots due to the tsunami erosion (***d***), and salt pans buried by the tsunami sediments (***e***).

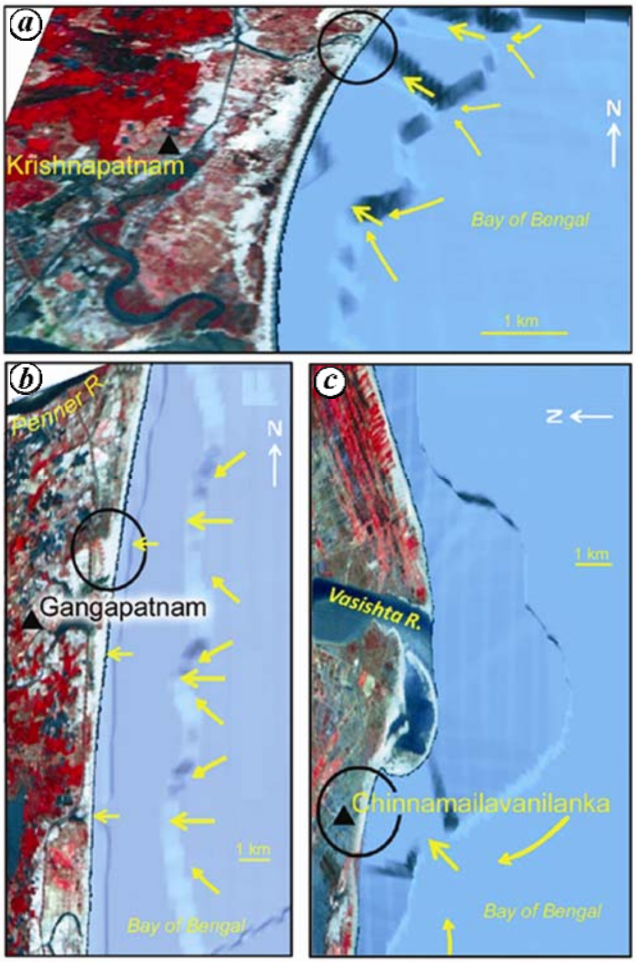

Figure 5. Bathymetry digital elevation model draped by the satellite images showing the convex landward canyon-like features around 5 m depth contour off (***a***) Krishnapatnam, (***b***) Gangapatnam and (***c***) Chinnamailavanilanka, where the tsunami impact was maximum along the AP coast. The vertical exaggeration of the offshore DEM is 50 times. Yellow-coloured arrows indicate the possible convergence of the tsunami into the canyon-like entrants. The maximum tsunami run-up areas are enclosed in black-coloured circles.

The similar landward convexities in the 5 m depth contour at Gangapatnam (Figure 5 *b*) and Chinnamailavanilanka (Figure 5 *c*) are perhaps responsible for tsunami amplification and funnelling through the narrow zones to push the sediment up onto the coastal land akin to what was observed earlier from the Tamil Nadu coast[9] where the seaward concavity (i.e. the landward convexity) in the 200 m depth contour was considered responsible for amplification of the tsunami to as much as 7 m leading to widespread inundation and loss of life. While more or less similar canyon-like features may be present along other coastal parts, it may be a combination of factors such as the nature of coastal and offshore topography, besides the angular direction of the coast with respect to the direction of tsunami approach that could determine the degree of tsunami amplification.

The present study based on the identification of the maximum tsunami-affected locations along the AP coast and the juxtaposition of the satellite images vis-á-vis, the DEMs of the underwater topography off the respective locations has indicated the possible role of coastal bathymetry in tsunami impact on the coastal lands. Therefore, detailed mapping of the nearshore bathymetry would also be an important input to the tsunami warning system being set up in India for accurate assessment of the vulnerability of different coastal segments to tsunamis.

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Characterization of colloids in the late Quaternary sediment sequences of Mahi River basin, Gujarat, India

R. Murali[1], C. N. Murthy[1,]* and L. S. Chamyal[2]

[1]Applied Chemistry Department, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara 390 001, India
[2]Department of Geology, Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara 390 002, India

Mobile colloidal particles are known to be ubiquitous in Quaternary fluvial sediments and subsurface environments which facilitate the transport of contaminants to the aquifer. Despite this harmful effect, very few efforts have been made to study the properties and transport of colloids in Quaternary sediments. In order to understand the properties of these colloids, samples were collected from the exposed late Quaternary sediment sequences dating back to 125 ka from the Mahi River basin. The isolated colloids from these sequences were characterized for their size distribution, electrical conductivity and concentration. The polydispersed colloidal particles occur in varying amounts at different depth intervals. The low electrical conductivity of colloids in the Rayka section could be related to the low concentration of colloids.

Keywords: Colloids, electrical conductivity, particle size, Quaternary sediments.

*For correspondence. (e-mail: chivukula_mn@yahoo.com)