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FLOOD ELEVATION, INUNDATION DISTANCE AND FLOW COMPETENCE OF THE 2004 SUMATRA-ANDAMAN TSUNAMI, AS RECORDED BY TSUNAMI DEPOSITS IN THIRTEEN SHORE-NORMAL PROFILES FROM THE TAMIL NADU COASTLINE, INDIA

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ABSTRACT

Thirteen shore-normal profiles in South-East India have been surveyed for tsunami deposit evidence of run-up height, flow depth, inundation distance, flow competence, and flow direction from the December 26 Sumatra-Andaman tsunami. Mud lines on buildings were surveyed into timed tide level (swash zone) to establish maximum still-water height, which ranged from 2.3 to 4.4 m mean tide level (MTL). Hanging debris and structural damage were used to establish maximum surge heights of 3.9 to 6 m MTL. Differences between maximum surge height and ground surface yielded flow depths of 1.2 to 3.2 m. Landward flow directions, as recorded by vegetation flop-overs, sand ripples, and debris shields averaged 250°N yielding an oblique wave attack of 30-40° in central study area. Maximum inundation distances of gravel, i.e., shore-normal distance from mid-swash zone, ranged from 30 to 60 m. Maximum sand transport ranged from 90 to 400 m in distance from the shoreline. Sand sheet deposits ranged from 1 to 30 cm in thickness, and included internal stratification, rare pebble and shell clasts. Maximum tsunami flood inundation, based on transported flotsam, ranged from 140 to 800 m in shore-normal distance. Flotsam transport exceeded sand transport by between 15 and 50% of maximum inundation distance in nine profiles. These preliminary reconnaissance observations characterize the recent tsunami inundation from low-to-moderate forcing, i.e, maximum still water 2-4 m MTL, in the low-relief settings of the South-East India coastal plain.

KEYWORDS: Tsunami, 2004 Sumatra-Andaman Rupture, Inundation Profiles, Deposits, Tamil Nadu

INTRODUCTION

Tsunami inundation profiles were surveyed at selected localities along the South-East (SE) Indian coast (Figure 1) as part of a reconnaissance survey of tsunami run-up following the December 26 Sumatra M_w 9.3 rupture. This great subduction zone earthquake from the Sumatra-Andaman margin (Stein and Okal, 2005) was widely felt on the SE Indian coast at about 0630 Indian Standard Time (IST) on December 26 (Chadha et al., 2005). It was followed two hours later by tsunami waves that struck the coast and inundated beaches, lagoons, and low-lying beach plains. Eyewitness accounts indicate that three tsunami waves struck the SE India coast, with the second wave being the largest.

The shore-normal inundation profiles presented in this paper compliment three other survey components including, proximal-site run-up, digital photo documentation, and social impacts (Yeh et al., 2005). This reconnaissance survey was completed during the week of January 7th-11th in coordination with the National Geophysical Research Institute and the National Institute of Ocean Technology of India. The field area for this reconnaissance survey is located in the northern portion of Tamil Nadu. It extends from Pulicat to Vedaranniyam, a coastal distance of about 350 km (Figure 1).

This paper includes ephemeral data on flow direction, high-water level, flow competence, and inundation distance from nine study localities. The nine localities were selected on the basis of (1) representative spatial distribution in SE India, and (2) coastal access during the aftermath of the disaster. The ephemeral data was collected within two weeks of the event to minimize data loss from wind, rain, and clean-up activities. Additional work is planned to extend the results of this reconnaissance survey with satellite images and detailed field mapping.

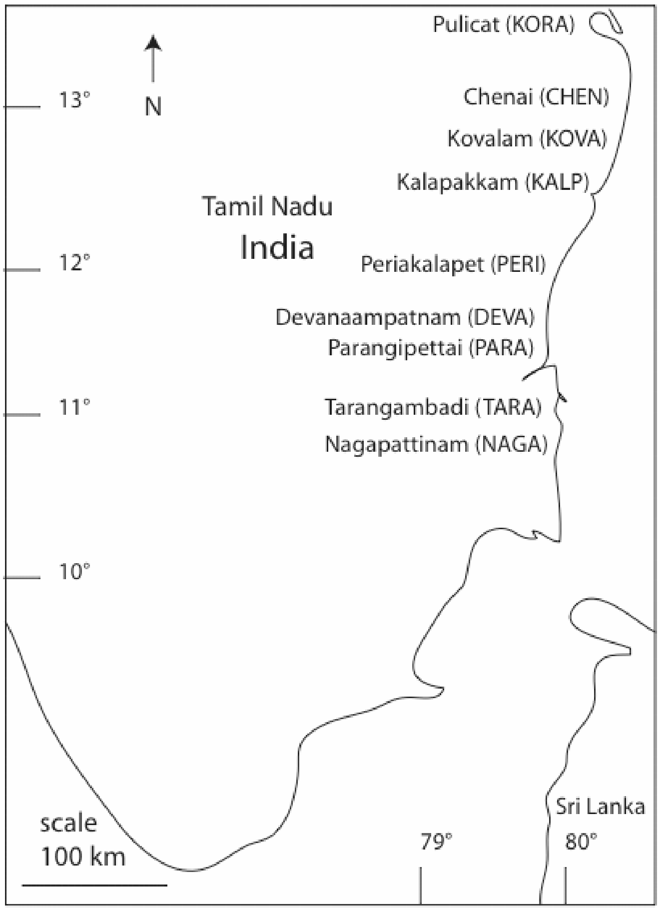


Fig. 1 Map of field area in Tamil Nadu, India, including nine profile localities and profile names in parentheses (see Table 1 for location details)

METHODS

Shore-normal profiles within the nine survey localities were positioned on the basis of representative high-water marks and line-of-sight traverses to beach swash zones (Table 1). Multiple profiles were collected at three localities – Korakuppau, Chennai, and Devanaanpattina, to establish potential alongshore variability. Additional measurements of proximal tsunami run-up, i.e., 50-100 m distance from the beach, were made at spot sites alongshore. Those proximal site data, which are reported separately (Yeh et al., 2005), include details on structural damage, foundation scour, and fatalities.

In this paper we focus on indicators of flow inundation based on high-water deposits in the 13 shore-normal profiles. These indicators include (a) mud lines on standing structures, i.e., maximum still-water elevation, (b) heavy debris in branches or physical damage to standing structures, i.e., maximum surge elevation, and (c) flotsam debris on tree branches, roofs, and ground slopes, i.e., maximum splash elevations and/or maximum inundation distances (UNESCO, 1998).

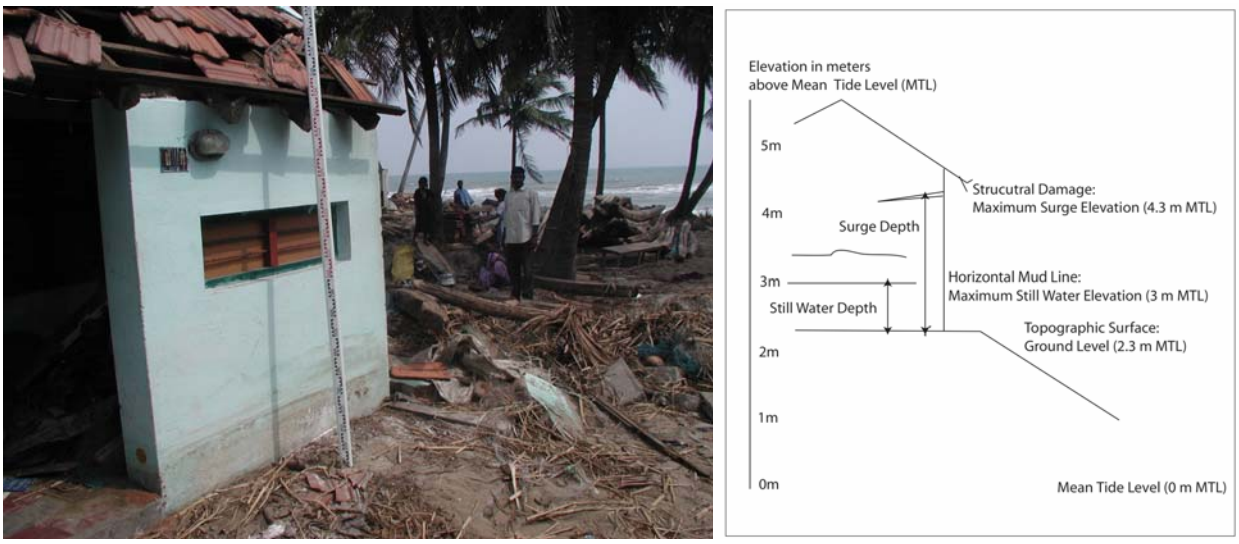
Maximum still-water elevations, i.e., mud lines, were preferentially taken from interior walls, which should minimize effects from turbulent flow around structures. Mud lines from exterior walls were used where horizontal mud lines at similar elevations could be correlated between buildings. Typically, the highest horizontal mud line was used to represent maximum still-water elevation (Figure 2). The vertical distance between the highest horizontal mud line and ground elevation, i.e., tripod footing surface, was measured to the nearest centimeter with a tape. This distance represents maximum still-water depth.

Table 1: Tsunami Inundation Profiles from Nine Localities in Tamil Nadu, SE India

Locality	Profile	Latitude
Pulicat, Korakuppau, Temple	KORA01	13.3836°
Korakuppau, Village	KORA02	13.3184°
Chennai South, Temple	CHEN01	13.0211°
Chennai South, Apartments	CHEN02	13.0173°
Kovalam	KOVA01	12.7914°
Kalpakkam	KALP01	12.5052°
Periakalapet*	PERI01	12.0285°
Devanaampatnam North	DEVA01	11.7495°
Devanaampatnam Central	DEVA02	11.7454°
Devanaampatnam South	DEVA03	11.7397°
Parangipettai Temple	PARO01	11.5129°
Tarangambadi Fort	TARA01	11.0271°
Nagapattinam North	NAGA01	10.7746°
Latitudes are in decimal degrees at the swash zone positions of the shore-normal inundation profiles (WGS84 datum).		

*Latitude given for the west end (landward end point) of the profile in the village center

Maximum surge elevations were measured from heavy debris caught in branches, and/or features reflecting apparent large-debris damage at elevations above mud lines. These features included displaced roof tiles, broken masonry, fresh gouges in plaster, and heavy woody debris left in broken or bent tree branches (Figure 2). Maximum splash elevations were established from light flotsam hanging in limbs of standing vegetation and/or draped on standing structures such as railings and roofs. In sites proximal to shorelines the light flotsam, i.e., paper and plastic bags, could have been lofted by tsunami wave-front winds.



(a) (b)

Fig. 2 (a) Photograph of proximal run-up site at profile DEVA01 (80 m position) showing mud line (maximum still-water elevation) at base of blue house, and surge damage to tile roof (maximum surge elevation) at roofline of blue house (the logs and beams that surround the house were left in place by receding tsunami water; photo view direction is towards the east with ocean shoreline in background); (b) Diagram of key tsunami flood heights taken from water, debris and/or damage marks on standing structures (the key features include calibrated MTL, topographic elevation, maximum still water elevation, maximum surge elevation, and corresponding differences of still-water depth and surge depth; measurements shown are averaged from several representative profiles in the study area)

Landward flow direction was measured from several different features. These features included vegetation flop-overs, debris streamers wrapped around trunks, and sand ripples and/or linear-scours (Allen, 1984). Flow feature bearings were taken with a Brunton compass. Flow bearings in the direction of flow are given in degrees (0-360) from true north (TN). Features that recorded seaward-directed return flow, including scours and driftwood lags, were observed in topographic depressions. Heavy mineral sorting was also observed in some tsunami sand sheets. The scour and mineral sorting evidence of tsunami bottom shear stress are discussed elsewhere (Yeh et al., 2005).

Elevations of high water deposits were established relative to local mean tidal level by use of profile topographic surveys. Topographic surveys were performed with a bubble-level transit mounted on a tripod and extendable stadia rod (Figure 3). Horizontal sighting distances were generally less than 100 m between level and stadia rod. Elevations were measured to the nearest centimeter. Total profile errors of ±0.1 m are assumed for the single-sighting, single-direction, leveling surveys. Profile end points were located by 12-channel GPS (±10 m error) using the WGS84 datum.

Fig. 3 Photograph of level and tripod setup on profile PERI01 (170 m position) for shooting level line from tsunami high-water deposits to beach swash zones

Intermediate distances were measured by pacing in the shorter profiles and by additional GPS positions in the longer profiles. Estimated sea level was established for each profile based on timed, mid-swash zone positions. Set-up was considered to be negligible during the survey period, i.e., prevailing minor breezes and small surf $H_{1/3} < 0.5\,\text{m}$ (Figure 4). Tide level corrections for this micro-tidal coast, i.e., tidal range ~ 1.0 m, were computed from predicted tide tables (Yeh et al., 2005). The mean tide level (MTL) datum is assumed to be within 0.25 m error.

Three levels of relative flow competence were established from maximum landward transport of gravel, sand, and flotsam debris. The gravel size material included large (> 2 cm diameter) shells, brick and mortar fragments, and road gravel. A possible lack of gravel source material precluded evidence of high flow competence in some settings.

Beach sand (typically 0.1 to 0.5 mm grain diameter) was present in all profile localities. The tsunami sand deposits were not differentiated between potential dune, beach, and/or near-shore sources. Flotsam included organic debris, plastic bags, and paper litter.

Maximum inundation positions were generally evident from semi-continuous debris lines that crossed streets, vacant lots, fields, and wetland surfaces. Large inundation distances in some locations were related to localized flow through dune-ridge gaps or tidal inlets. Field observations were used to discriminate between shore-normal flow from the open beach and lateral flow entering the inter-ridge valleys from dune-ridge gaps or tidal inlets. The discrimination between shore-normal inundation and lateral inundation was based on shore-parallel versus shore-perpendicular debris lines, respectively.

Fig. 4 Photograph of stadia rod near beach endpoint of profile NAGA01 (10 m position) with swash zone at the right (stadia rod was held at mid-swash, i.e. mean water level, to establish timed tide level during survey)

RESULTS

Tsunami inundation data are presented from thirteen shore-normal profiles located between 13.4 and 10.7 degree latitude along the Tamil Nadu coastline. The inundation observations are grouped under measurements of surge flow direction, run-up height, and zones of relative flow competence.

1. Flow Direction

Flow features were recorded in eight inundation profiles (Table 2). The flow features include vegetation flop-overs, orientated beams, debris streamers around tree trunks, and sand ripples (Figure 5).

Fig. 5 Photograph of sand ripples and vegetation flop-overs that serve as indicators of tsunami flow direction, i.e., to right of figure (bearing 245° TN), at position 300 m of profile PARO01 (photograph view direction is to the south)

The flow directions in proximal settings ranged from 220 to 290° TN. The mean bearing of measured flow direction from the proximal sites in the eight profiles is approximately 250° TN. These data suggest an oblique angle of tsunami wave attack, particularly in profiles between 11.5 and 12° latitude, where the shoreline trends north to north-east. The tsunami wave attack (~ 250° TN) is on the order of 30-40° from shore-normal (~ 270-290° TN) in the central study area.

Flow bearings changed in direction with increasing landward distance in several of lowest-relief profiles including DEVA01, DEVA03 and PARA01 (Table 2). In Profile DEVA03 the flow bearings changed from 290° at the 180 m position to 310° at the 340 m position, and to 340° at the 430 m position. The shift in flow direction from south-west (SW) to north-west (NW) with increasing landward distance in this profile reflects increasing lateral flow from a tidal inlet located just south of the profile. Northward flow continued north from DEVA03 to inundate the landward side of the DEVA01 dune ridge. A similar change in flow bearing occurred in profile PARA01. Flow bearings in PARA01 changed from 245° in the proximal barrier spit at the 300 m position, to 320° behind a shore-parallel dune ridge at the 600 m position (see the section on 'Profile Topography' below). Tsunami lateral flow at the distal end of PARA01 likely originated from a tidal lagoon located just south of the profile.

Table 2: End Point Coordinates and Flow Bearings for Tsunami Inundation Profiles

Profile	Orientation	Latitude	Longitude	Flow Bearing
KORA01	East-West	13°23.018'	80°20.007'	(80 m) 270°
KORA02	East-West	13°22.883'	80°20.015'	-
CHEN01	East-West	13°1.263'	80°16.722'	-
CHEN02	East-West	13°1.037'	80°16.692'	-
KOVA01	East-West	12°47.485'	80°15.132'	-
KALP01	SE-NW	12°30.312'	80°9.688'	(40 m) 280°
PERI01*	East-West	12°1.708'	79°51.95'	(40 m) 260°
DEVA01	East-West	11°44.97'	79°47.09'	(60 m) 220°
DEVA02	East-West	11°44.723'	79°47.323'	(40 m) 220°
DEVA03	East-West	11°44.383'	79°47.138'	(180 m) 290°
-	-	-	-	(340 m) 310°
-	-	-	-	(430 m) 340°
PARA01	East-West	11°30.772'	79°46.403'	(300 m) 245°
-	-	-	-	(600 m) 320°
-	-	-	-	(700 m) 290°
TARA01	East-West	11°1.625'	79°51.372'	-
NAGA01	East-West	10°46.425'	79°51.05'	(200 m) 230°
Orientation of profiles is generally shore-normal (east to west). Profile GPS end points are generally located at east end of profiles in swash zones. Flow bearings are from flop-overs, ripples, or debris streamers at profile distance (m), and are given (in degrees) in the direction of flow relative to true north (TN).				

*GPS coordinates from the west end of the profile

2. Profile Topography

Topography was measured at key positions along each of the 13 profiles. These key positions include the swash zone, backshore, foredune ridge, representative high-water marks, maximum distances of gravel and sand transport, and maximum distance of flotsam transport. These positions are sufficient to represent breaks in slope of the subtle topography found in the low-relief coastal plain settings (Table 3). Maximum topographic relief as measured within the inundation zones of the 13 profiles ranged from 1.8 m in CHEN02 to 4.1 m in PARA01.

The heights of unstabilized foredunes, i.e., incipient foredunes, were measured at KORA01 (+2.7 m MTL), CHEN01 (+2.5 m MTL), KALAP01 (+2.4 m MTL), and NAGA (+3.4 m MTL) (Table 4). In the absence of incipient foredunes the first break in slope of the unstabilized backshore was measured at the foot of older, stabilized dunes. These most-landward positions of the active backshore ranged from 1.5 to

2.5 m MTL (Table 4). The unstabilized barrier sand spit at PARA01 had a crest elevation of +1.8 m at its western margin (400 m position).

Table 3: Topography of 13 Tsunami Inundation Profiles from Tamil Nadu

Profile	(Position) & Elevation (m)	(Position) & Elevation (m)	(Position) & Elevation (m)	(Position) & Elevation (m)	(Position) & Elevation (m)
KORA01	(0) +0.7	(25) +2.7	(80) +2.3	(90) +2.2	(160) +0.0
KORA02	(0) +0.7	(90) +2.5	(120) +0.5	(130) +1.0	(140) +1.5
CHEN01	(0) +0.0	(100) +2.5	(120) +2.1	(150) +2.0	-
CHEN02	(0) +0.1	(110) +1.9	-	-	-
KOVA01	(0) +0.4	(110) +1.5	(120) +2.0	(140) +3.0	(180) +4.6
KALP01	(0) +0.7	(30) +2.4	(160) +1.1	(190) +1.5	(360) +3.0
PERI01	(0) −0.19	(40) +3.7	(60) +3.9	(170) +5.7	-
DEVA01	(0) +0.5	(80) +1.8	(160) +3.3	(300) +1.0	-
DEVA02	(0) +0.4	(40) +2.0	(80) +3.5	-	-
DEVA03	(0) ~+0.5	(80) +1.5	(180) +1.5	(340) +0.5	(380) +0.5
-	(430) +0.7	-	-	-	-
PARA01	(0) +0.6	(400) +1.8	(480) +2.9	(600) +4.1	(700) +2.4
-	(840) +2.3	-	-	-	-
TARA01	(0) +0.0	(30) +3.5	(150) +3.0	(160) +2.0	(400) +2.0
NAGA01	(0) +0.4	(200) +3.4	(330) +2.4	(430) +2.3	(570) +2.0
-	(680) +2.3	-	-	-	-

Profile elevations are (in meters) relative to MTL at paced distances (positions in meters) between GPS end points.
Zero positions are taken at mid-swash, during timed tide level.
Tidal corrections for swash elevations are based on predicted tide tables, as detailed for this survey by Yeh et al. (2005).

Table 4: Summary of Upper Shoreface (Beach) Topography from Inundation Profiles

Profile	Foredune/ Backshore Elevation (m)	Beach Rise (m)	Beach Run (m)	Beach Gradient rise/run	Stabilized Dune Ridge Elevation (m)	Back-Beach Plain Elevation (m)
KORA01	+2.7	2.0	25	0.080	+2.7	+2.2
KORA02	+2.5	2.5	90	0.020	-	-
CHEN01	+2.5	2.5	100	0.025	+2.1	+2.0
CHEN02	+1.9	1.8	110	0.016	-	-
KOVA01	+1.5	1.1	110	0.010	+4.6	+4.6
KALP01	+2.4	1.7	30	0.056	+3.0	-
PERI01	+3.7*	3.9	40	0.097	+3.7	+5.7
DEVA01	+1.8	1.3	80	0.016	+3.3	+1.0
DEVA02	+2.0	1.6	40	0.040	+3.5	-
DEVA03	+1.5	1.0	80	0.012	-	+0.5
PARA01	+1.8	1.2	400	0.003	+4.1	+2.3
TARA01	+3.5*	3.5	30	0.117	+3.5	+2.0
NAGA01	+3.4	3.0	200	0.015	+2.3	+2.3

Foredune or backshore elevations are (in meters) relative to MTL.
Beach rise is computed from foredune or backshore elevation minus swash elevation.
Beach run is the distance from the swash to the foredune or backshore.
Stabilized dune ridge and back-beach plain elevations are (in meters) relative to MTL.

*Backshore height taken from stabilized dune ridge

The unstabilized backshores and incipient foredunes represent the uppermost shoreface. Together with the swash zone these environments form the active, i.e., undeveloped, beaches. The gradients of the active beaches range from 0.003 to 0.117 (Table 4). Offshore gradients were not measured during this reconnaissance survey. Two other profile characteristics that are of potential importance to tsunami inundation are elevations of stabilized dune ridges and the back-beach plains. Stabilized dune ridges, and/or developed dune ridges that abut the beach backshores, range in elevation from less than 2 m to 4.6 m MTL in 11 measured profiles. Back-beach plains extend landward of the stabilized dune ridges in some localities. The back-beach plain elevations range from 0.5 to 4.6 m MTL in eight profiles.

3. Flood Elevation

Maximum still-water elevations, as based on the highest, horizontal mud line deposits, ranged from 2.3 to 4.4 m MTL in nine profiles (Table 5). The highest maximum still-water elevations (4.4 and 4.3 m MTL) were recorded in the southernmost two profiles TARA and NAGA01 (Figure 6). Measured elevations of maximum still-water varied only slightly (0.1-0.7 m) within long profiles (KALP01 and NGA01) where mud lines were measured at multiple positions.

Table 5: Deposit Indicators of Tsunami High Water and Flow Competence

Profile	(Maximum Still-Water Position) & Elevation (m)	(Maximum Surge Position) & Elevation (m)	(Maximum Splash Position) & Elevation (m)	Maximum Gravel Distance (m)	Maximum Sand Distance (m)	Maximum Flotsam Distance (m)
KORA01	(80) +2.7	(25) +3.8	(90) +3.2	-	90	160
KORA02	(90) +3.5	(90) +4.5	-	-	-	140
-	-	(130) +1.3	-	-	-	-
CHEN01	(120) +2.9	-	-	-	-	150
CHEN02	(110) +3.0	-	-	40	90	140
KOVA01	(120) +3.4	(120) +4.2	-	-	120	180
-	-	(140) +5.6	-	-	-	-
KALP01	(160) +3.1	-	-	-	190	360
-	(190) +3.0	-	-	-	-	-
-	(360) +3.0	-	-	-	-	-
PERI01	(40) +3.7	(40) +6.0	-	60	130	170
-	-	(60) +5.9	-	-	-	-
DEVA01	(80) +2.3	(80) +4.3	-	60	110	160
-	-	-	-	-	-	300*
DEVA02	-	(40) +4.0	-	40	-	-
-	-	(80) +4.7	-	-	-	-
DEVA03	-	-	-	-	180	340
-	-	-	-	-	-	430*
PARA01	-	-	(600) +4.1	-	400	600
-	-	-	-	-	-	840*
TARA01	(30) +4.4	(30) +4.9	-	30	150	400
NAGA01	(430) +4.3	(430) +5.5	-	-	430	800
-	(570) +3.9	-	-	-	-	-
-	(680) +3.5	-	-	-	-	-

Still-water elevations, i.e., mud lines on structures, are taken at profile positions (m), and are measured relative to MTL.
Maximum surge elevations are taken from abrasion features on structures or heavy debris in trees, located at or near positions of still-water measurement.
Maximum splash elevations are taken from flotsam or light debris that was perched on structures (KOVA01) or hanging in bushes (KORA01, PARA01).

*Maximum inundation from lateral flow (shore-oblique) in inter-ridge valleys, at distal ends of two profiles (DEVA03, PARA01)

Maximum surge elevations were taken from sustained water levels that caused physical damage to buildings (Figure 6), and/or that left heavy debris in broken, twisted or bent tree branches. The measured elevations of maximum surge ranged from 3.8 to 6.0 m MTL in eight profiles (Table 5). Surge and splash levels varied significantly from maximum still-water elevations within some of the same profiles. In the KOVA01 profile the elevations of measured surge (+4.2 m MTL) and splash (5.6 m MTL) are substantially greater than the maximum still-water elevation (3.4 m MTL).

Fig. 6 Photograph of mud line at black arrow, and of flow-damaged awning at 1.2 m above the mud line, at the warehouse position 430 m in profile NAGA01 (the maximum still-water elevation, i.e. mud line, is 4.3 m MTL; the maximum surge, i.e. flow damaged awning, elevation is 5.5 m MTL; the surge elevation is confirmed by heavy debris at 5-6 m MTL in adjacent tree branches (see Figure 8); photo view direction is towards the east, with shoreline beyond view in the far background)

4. Flow Competence and Maximum Inundation Distance

Three zones of flow competence were established from the maximum transport distances of gravel, sand, and flotsam in the 13 profiles. Gravel transport ranged from 30 to 60 m distance from the swash zone in five profiles (Table 5). The gravel size clasts were largely derived from tsunami-damaged brick walls, foundations, and roofing tiles in the five profiles (Figure 7). Gravel size material was either absent or not observed in the remaining profile sites. Maximum sand transport ranged from 90 to 430 m distance from the swash zone in 11 profiles. The beach widths without vegetation in most profiles reached 30-50 m from the swash. Two exceptions included profiles PARO01 and NAGA01, which include broad sand spits, each about 300 m in width. With the exception of profiles PARO01 and NAGA01 the average sand transport distance was 130 m from the swash, or somewhat less than 100 m distance beyond the beach backshore. Tsunami sand deposits ranged from coarse upper (700-1000 microns) to very-fine upper (88-125 microns) in grain size, based on comparisons with grain-size cards. Tsunami sand deposit thickness was informally observed in a few localities (KALP01, DEVA03, NAGA01). Sand sheet thickness ranged from several tens of centimeters near beach backshores to 1 cm at the distal end of sand transport.

Sand sheets appeared to be fine in mean grain-size with increasing transport distance at the distal ends of sand sheets. However, careful examinations of proximal sand sheet layers showed little or no evidence of fining-upward sequences. Internal sedimentary structures in the sand sheets included planar-striated bedding and entrained pebbles and shell clasts.

Maximum inundation distances were established in 12 profiles on the basis of the most-landward distribution of flotsam in debris lines or as anomalous articles, e.g., clothing, mats, fishing floats, etc. Maximum inundation in 12 shore-normal profiles ranged from 140 to 800 m from the swash zone

(Table 5). Based on local topography, flow direction indicators (see below), and the orientation of debris lines it was apparent that maximum landward inundation occurred by lateral flow in profiles KORA02, DEVA01, DEVA03, PARO01, and TARA01. Specifically, lateral flow filled interdune-ridge valleys that were landward of shore-parallel dune ridges in DEVA01, DEVA03 and PARO01. The interdune-ridge valleys at the landward ends of these profiles were connected to tidal inlet channels. Lateral flow also filled shallow valleys in KORA02 and TARA01, where breaches in shore-parallel dune-ridges allowed tsunami to inundate the back-ridge valleys.

Fig. 7 Photograph of high flow competence as shown by zone of gravel (brick) mobilization in profile PERI01 (60 m) (flow direction was towards the southwest, i.e. the lower left of photo; photo view direction is towards the north)

Fig. 8 Distal sand sheet deposits at 430 m position in profile (NAGA01) (computed still-water depth (2.0 m) and surge depth (3.2 m) are well established (Table 6) for this profile position (see Figure 7); inundation continued for another 370 m distance landward of this position without sand sheet deposition; Nagapattinam lighthouse is in photo background behind the collapsed structure; photo view direction is to the south)

DISCUSSION

1. Maximum Still-Water Elevation

The mean value of measured still-water elevation, i.e., tsunami flood elevation, from nine inundation profiles along the SE Coast of India is 3.3 m MTL (Table 6). The largest magnitude of still-water run-up, i.e., 4.0-4.5 m MTL, was only observed at two profiles, i.e., TARA01 and NAGA01, both profiles being located near the southern end of the field area. Although still-water elevation was low-to-moderate in this field area, there was substantial loss of life and property. Computed still-water depths, i.e., difference between still-water elevation and corresponding ground elevation, ranged from 0.4 to 2.0 m in the nine profiles.

Table 6: Summary of High Water Deposit Elevations and Estimated Flow Depths

Profile	Still-Water Elevation (m MTL)	Still-Water Depth (m)	Surge Elevation (m MTL)	Surge Depth (m)
KORA01	2.7	0.4	3.8	1.2
KORA02	3.5	1.0	4.5	2.0
CHEN01	2.9	0.8	-	-
CHEN02	3.0	1.1	-	-
KOVA01	3.4	1.3	4.2	2.2
KALP01	3.1	2.0	-	-
PERI01	3.7	-	6.0	2.3
DEVA01	2.3	0.5	4.3	2.5
DEVA02	-	-	4.7	1.2
TARA01	4.4	0.9	4.9	1.4
NAGA01	4.3	2.0	5.5	3.2
Still-water and surge elevations are from maximum, recorded still-water and surge deposits in proximal positions (see Table 5). Elevations are given in meters relative to estimated MTL. Depth is elevation difference in meters between high-water deposit and ground surface.				

2. Surge Elevation

Significant differences were observed between still-water elevations and surge elevations in the measured profiles. Specifically, proximal position comparisons of still-water and surge elevations can be made in six profiles, including KORA01, KORA02, KOVA01, DEVA01, TARA01 and NAGA01 (Table 6). The mean difference between maximum still-water elevation and maximum surge elevation for the six comparison positions is 1.1 m. The additional mean surge height, i.e., ~ 1 m above maximum still water, might have been critical to survival in some localities. The computed surge depths, i.e., difference between surge elevation and corresponding ground elevation, ranged from 1.2 to 3.2 m in eight profiles.

Most of the single story structures in the proximal settings of the surveyed profiles are only 2.5 m in height above ground surface. Surge water depths in excess of 2.0 m occurred in at least one half of the measured profiles that contained unambiguous, maximum surge water levels (Table 6). The largest, concentrated loss of life in the field area occurred in the NAGA01 locality, with a measured surge water depth of at least three meters at a distance of 430 m from the profile swash zone (Figure 6). This surge depth was greater than the height of single story residences in proximal positions. The surge depth also reached the second floor of multi-story buildings in proximal neighborhoods of Nagapattinam, located just south of the NAGA01 profile (Figure 9).

Surge water levels were amplified (1-2 m) in some profiles, i.e., KORA01, KOVA01, PERI01, DEVA01, and TARA01, where the flow was constricted between buildings, or ramped-up against the sides of buildings. The local controls on surge height, including high-gradient slopes and flow constriction around buildings should be considered as important variables in the analysis of tsunami hazard in moderate run-up localities.

Fig. 9 Measured still-water depth (2 m) and surge depth (3 m) on a remnant standing structure in a proximal position (150 m landward of backshore) in Nagapattinam (this site is located northwest of the Nagapatttinam lighthouse; rubble is from collapsed buildings adjacent to the standing structure; this neighborhood suffered substantial loss of life; photo view direction is to the south)

3. Flow Competence

Flow competence was semi-quantitatively evaluated by landward transport of gravel, sand, and flotsam materials. Gravel transport, i.e., brick fragments 2-10 cm diameter, is thought to reflect very high flow competence, with associated flow velocities of at least several meters per second (Hjulstrom, 1939; Allen, 1984). The mean value of maximum gravel transport was 45 m distance from the shoreline in 5 profiles (Table 7). The greatest structural damage was observed in the zone of highest flow competence, i.e., gravel transport. Failure modes of unreinforced masonry structures included both frontal wall collapse from external flow pressure and trailing wall collapse from internal pressures of water-filled structures.

Table 7: Summary of Profile Flow Competence and Inundation Distance

Profile	Maximum Gravel Distance (m)	Maximum Sand Distance (m)	Shore Normal Inundation (m)	Lateral Inundation (m)
KORA01	-	90	160	-
KORA02	-	-	140	-
CHEN01	-	-	150	-
CHEN02	40	90	140	-
KOVA01	-	120	180	-
KALP01	-	190	360	-
PERI01	60	130	170	-
DEVA01	60	110	160	300
DEVA02	40	-	-	-
DEVA03	-	180	340	430
PARA01	-	400	600	840
TARA01	30	150	400	-
NAGA01	-	430	800	-

Distances of flow competence (gravel or sand transport) and inundation (shore-normal and lateral flow) are given in meters landward of the profile swash zone (zero position) (see Table 5).

Secondary shore-parallel flow was enhanced in some proximal high-gradient localities, such as profile DEVA01, where oblique surge attack (Table 2) set-up alongshore flow against a stabilized dune ridge (Figure 10).

Sand transport is thought to reflect high flow competence, with associated flow velocities of at least several decimeters per second (Allen, 1985). The mean value of maximum sand transport in four of the five profiles was 120 m distance, or nearly three times the distance of maximum gravel transport. The apparent mobilization of sand occurred at greater distances (400 m distance) in two profiles, i.e., PARO01 and NAGA01. In those two profiles broad sand spits (300 m in width) extended landward of the beach backshore position. The sand spits were mantled by eolian sand, which likely served as a local source of entrained sand in the distal tsunami deposits. The shorter distances of tsunami sand transport (100-200 m) over vegetated surfaces in the remaining profiles likely reflect the progressive loss of sand from the tsunami water column by particle settling and bottom entrapment during steady-state or decelerating flow. Therefore, the maximum distances of sand transport represent minimum distances of high-flow competence in some profiles (see further discussion below).

Fig. 10 Photograph of asymmetric damage and bimodal beam orientation indicating transient southwest oblique tsunami flow near profile DEVA01 (the catastrophic collapse of the trailing wall suggests that failure resulted from unbalanced internal pressures of the water-filled structure; photograph view direction is to the east; the structure is about 40 m landward from the swash zone, with shoreline visible in photo background).

Maximum inundation distance (shore-normal) exceeded maximum sand transport in 11 profiles by an average of 150 m (Table 8).

The sand transport distance as a percent of maximum inundation distance ranged from 80 percent (CHEN01) to 37 percent (TARA01). The average distance of sand transport relative to maximum inundation for the 11 profiles is 60 percent. The sand transport distance reached slightly more than one half of the maximum inundation distance in the 10 profiles. The difference between sand transport and maximum inundation distance generally increased with increasing length of the shore-normal profiles.

4. Low-Velocity Shallow-Water Traps

Low elevation valleys (0.5-2.0 m MTL) were inundated by lateral flow in several long profiles, including DEVA01, DEVA03, PARA01, and TARA01. The inundation distances in these profiles were of the order of one-half kilometer (Table 5). The low-lying valleys behind shore-parallel dune ridges were filled by lateral flow from tidal inlets (DEVA01, DEVA03 and PARA01) or from breaches in the dune ridge (TARA01). Filling of the back ridge valleys by lateral flow potentially cut off evacuation routes. A lack of surge damage, sand transport, and/or soil rip-ups in the distal profile positions (Table 5) suggest that filling of the low valleys occurred by low-velocity inundation. However, about 20% of the reported deaths, mostly children, in the Tarangambadi village occurred in the shallow landward valley of profile TARA01, i.e., profile positions 160-400 m. The measured maximum still-water depth in this part of the profile was 0.9-1.1 m. Low velocity flooding of ~ 1 m water depth proved to be fatal to some residents in the distal ends of profiles DEVA03, PARA01, TARA01 and NAGA01.

Table 8: Differences between Sand Transport and Shore-Normal Inundation Distance

Profile	Maximum Sand Transport (m)	Maximum Inundation (m)	Difference in Distance (m)	Sand Transport % of Inundation (%)
KORA01	90	160	70	56
CHEN01	120	150	30	80
CHEN02	90	140	50	64
KOVA01	120	180	60	67
KALP01	190	360	170	53
PERI01	130	170	40	76
DEVA01	110	160	50	69
DEVA03	180	340	160	53
PARA01	400	840	440	48
TARA01	150	400	250	37
NAGA01	430	800	370	54
Transport distances are measured in shore-normal flow direction (Table 5). Sand transport as a percent of maximum inundation is computed as (maximum sand transport distance/maximum inundation distance) × 100.				

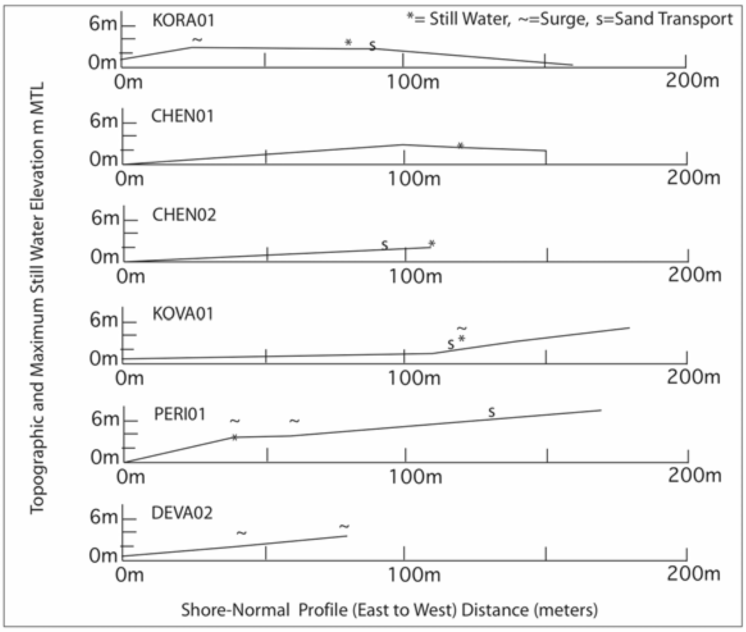
5. Substantial Impact of Low-to-Moderate Flood Elevation

Two factors apparently account for the substantial impact of the moderate tsunami run-up along the Tamil Nadu coast. First, the coastal topography is low due to a low-lying coastal plain and small dune ridges (0.5-4.6 m MTL; see Table 9 and Figure 11). Second, the micro-tidal range and low-storm surge run-up in the area have permitted development at relatively low elevations (+1.5-3 m MTL) in measured profiles localities. Most of the apparent damage and reported loss of life in the impacted communities occurred in proximal settings, i.e., 50-150 m from the shoreline, at ground elevations of less than 3 m MTL. However, lives were also lost in distal sites at TARA01 (~ 300 m profile position) and NAGA01 (~ 700 m profile position) where low-velocity inundation ranged from 0.9 to 1.3 m depth.

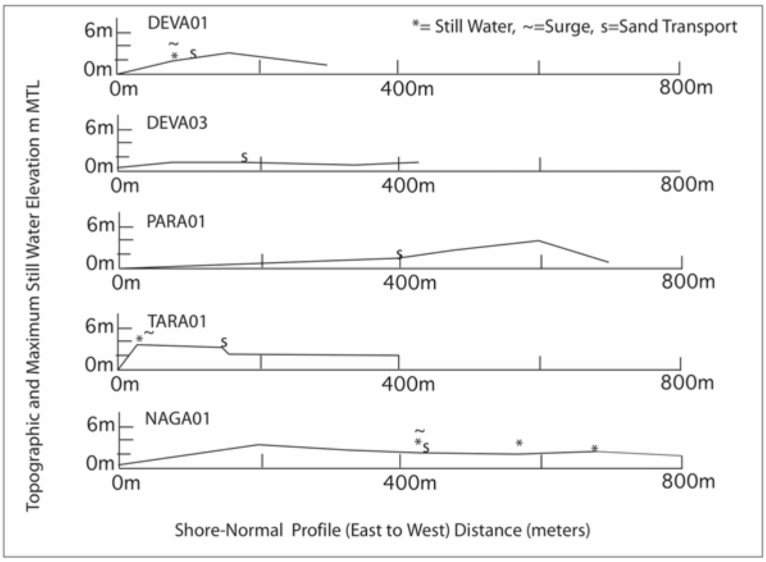
Table 9: Factors Leading to Significant Inundation under Low to Moderate Flood Heights

Locality Name	Inundation Distance (m)	Flood Elevation (m MTL)	Beach Gradient (%)	Back-Beach Plain Elevation (m MTL)
Korakuppau	160	+2.7	0.080	+2.2
Chennai	150	+2.9	0.025	+2.0
Kovalam	180	+3.4	0.010	+4.6
Kalpakkam	360	+3.1	0.056	+3.0
Periyakalapet	170	+3.7	0.097	+5.7
Devanaanpattina	430	+2.3	0.012	+0.7
Parangipettai	840	+2.9	0.003	+2.3
Tarangambadi	400	+4.4	0.117	+2.0
Nagapattinam	800	+4.3	0.015	+2.3
Inundation is the maximum inundation from shore-normal or lateral flow (Table 5). Flood elevations, i.e., maximum still-water elevation MTL are from proximal or near-proximal sites (Table 5). Beach gradients and back-beach plain elevations are summarized from Table 4.				

The measured range of tsunami flood elevation, i.e., maximum still water (2-4 m MTL), was very close to the coastal relief in SE India (Figure 11). Small differences in flood elevation and coastal topography resulted in large differences in tsunami inundation (140-840 m), and associated loss of life. Maximum still-water elevation is not correlated to local beach gradient (Table 9), so it is assumed to reflect regional forcing and effects from offshore topography. The small increase in maximum still-water elevation from the northern profiles (2-3 m MTL) to the southern profiles TARA01 and NAGA01 (4.3-4.4 m MTL) proved to be critical for life safety in the low-lying, coastal villages and cities in the Tamil Nadu region.



(a)



(b)

Fig. 11 (a) Shorter inundation profiles (less than 200 m distance), (b) Longer inundation profiles (greater than 300 m distance), showing topography (lines), maximum inundation distance (line terminations), and maximum still-water elevation (*), maximum surge elevation (~), and maximum distance of sand transport (*s*) (all distances are measured from the swash zone, i.e. zero distance, and elevation data are from Tables 3 and 5)

CONCLUSIONS

Tsunami inundation profiles from nine localities in the SE India coast established low-to-moderate flood elevations, i.e., 2-4 meters MTL from the December 26, 2004 Sumatra-Andaman rupture. Relative to same site ground elevations these maximum still-water elevations resulted in flow depths of 0.4 to 2 m. However, measured surge elevations added 1-2 m of high water elevation, thereby resulting in local flows of 1.2 to 3.2 m water depth. These flow depths exceeded the heights of some single story structures in proximal profile positions near the exposed beaches. Measured distances of gravel and/or sand mobilization demonstrated very-high flow velocities (meters per second) in the proximal profile positions (0-100 m landward distance). Most of the reported fatalities occurred in these exposed settings. However, significant loss of life also occurred in distal profile positions, i.e., 300-700 m distance from the beach, in low velocity flows of 0.9-1.2 m water depth. Measured inundation distances (140-840 m) varied as a function of regional flood elevation (2-4.5 m MTL) and coastal plain relief (0.5-5 m MTL). A small increase in regional flood elevation from 2-3 m MTL in the northern localities to 3-4 m MTL in the southernmost localities had a pronounced impact on mortality and structural damage. The close scaling of flood elevation (2-4 m MTL) relative to local topography (0.5-5 m MTL) proved to be critical to inundation hazard from the December 26, 2004 tsunami in the northern Tamil Nadu region of SE India.

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