2004 Indian Ocean tsunami inflow and outflow at Phuket, Thailand

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Abstract

At Bangtao Beach, Phuket, the 2004 Indian Ocean tsunami produced a repeated sequence in which rapid inflow of turbulent water was followed by ponding and then by gradual outflow. Photographs and eyewitness accounts show an initial withdrawal followed by a series of inflows. The tsunami left behind a sand sheet as much as 25 cm thick that contains parallel, inclined, landward and seaward lamina in addition to the normal grading commonly reported from tsunami deposits. The sheet contains evidence for two times of vigorous inflow. Each of these is marked by mud rip-ups, medium to coarse sand that grades upward to fine, landward-inclined laminae, and a sharp basal contact. The top of the sand sheet, when observed in the first days after the tsunami, abounded in current dune and ripple bedforms of mostly landward orientation. The tsunami’s first positive wave left no onshore sedimentary record in this pitting area. The second wave deposited sand that is much less extensive and slightly finer than that of the third wave. The deposit of both these waves contains multiple fining-upward sequences possibly due to multiple surges in one wave train. The depth-averaged flow velocity estimated from thickness and grain size are in the range 7–21 m/s, whereas, a near bottom threshold velocity calculated from bedforms reveals the order of magnitude difference from 1.74 to 1.03 m/s.

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1. Introduction

Geological study of the sand sheets deposited onshore by tsunamis, as a result of the observation made in both sides of the Pacific after the 1960 Chilean tsunami has expanded in the two past decades (e.g. Konno et al., 1961; Wright and Mella, 1963; Atwater, 1987; Dawson et al., 1988; Bourgeois et al., 1988; Long et al., 1989; Minoura and Nakaya, 1991; Bryant et al., 1992; Hindson et al., 1996; Bondevik et al., 1997; Clague et al., 2000; Moore, 2000; Goff et al., 2000; Fujiwara et al., 2003; Pinegina et al., 2003; Goff et al., 2004; Tuttle et al., 2004; Nelson et al., 2004; Cisternas et al., 2005; Williams et al., 2005; Nanayama and Shigeno, 2006; Jaffe and Gelfenbaum, 2007). The effort has grown further with investigation of the 2004 tsunami, which produced onshore sand sheets not just near the tsunami’s source (Moore et al., 2004; Tuttle et al., 2004; Nelson et al., 2004; Cisternas et al., 2005; Williams et al., 2005; Nanayama and Shigeno, 2006; Jaffe and Gelfenbaum, 2007).
but also on shores more than 500 km distant—in India (Chadha et al., 2005; Nagendra et al., 2005; Singarasubramanian et al., 2006), Sri Lanka (Goff et al., 2006), Malaysia (Hawkes et al., 2007), and Thailand (Szczucinski et al., 2005, 2006; Choowong et al., 2007; Hawkes et al., 2007; Hori et al., 2007; Umitsu et al., 2007).

This paper focuses on erosion and deposition by the 2004 Indian Ocean tsunami on Thailand's Andaman Sea coast near Phuket, where the sequence of tsunami waves can be inferred, in part, from tourist videos and eyewitness accounts (Choowong et al., 2007). The onshore sedimentary deposits in this area were investigated in the first weeks after the tsunami. By relating these
deposits to the photographs and eyewitness data, an attempt was made in this paper to reconstruct the hydraulic conditions of the tsunami flows that produced the observed sand sheet.

2. Eyewitnesses and hypothesis

Bangtao beach, a Phuket tourist destination, borders southern Le Phang Bay, north of Surin beach (Fig. 1A and B). Two days after the 2004 tsunami, field observation in the area was made, and eyewitnesses were interviewed.

Eyewitness accounts make clear that the tsunami began with withdrawal of the sea (at 9:42 a.m.)—a false ebb that occurred quickly and exposed the seafloor for as much as 500 m offshore. A few minutes later, the 1st wave flooded just over the beach. Two to three minutes after that, without any intervening withdrawal, the 2nd tsunami inflow penetrated 200–300 m inland with water heights about 2 m from the ground. Another two minutes

Fig. 2. Bedforms produced by the 2004 tsunami wave train at Bangtao area (see locations of photos in Fig. 1C). (A) Landward-oriented symmetrical current dune. (B) Landward-oriented asymmetrical current dune. (C and D) Spatial distribution pattern of landward-oriented current dunes and ripples. (E) Landward-oriented ripple developed on landward-oriented current dune. (F) Seaward-oriented ripples superimposed landward-oriented current dune. White arrows indicate landward direction perpendicular to shoreline.
later, again without intervening withdrawal, the 3rd and strongest inflow velocity produced water levels up to 3 m height and extended as much as 1 km inland. Thereafter the water stood still for 10–15 min, then drained slowly. In photograph taken by eyewitnesses just a few minutes after this drainage, water stands about 50 cm above the ground. After this partial withdrawal, eyewitnesses observed 2 or 3 additional inflows before sea water returned to normal level. This final withdrawal exposed, on the formerly inundated land, large amounts of sandy sediment.

Hypothesis was made that tsunami deposits were derived from shoreface, beach and small channel deposits, particularly during the 3rd inflow. Supporting evidence, collected along five transect lines (Fig. 1C), includes internal sedimentary structures and surface bedforms that were observed.

3. Methodology

While making a regional survey of tsunami inundation distances and heights, a detailed study of surface sedimentary patterns in relation to internal structures was carried out. For this study, pits along 5 transect lines perpendicular to the coastline were dug. A leveling of the basal contact of the deposit and one of the deposit’s surface was measured by high accuracy survey camera. In total 46 pits spaced at 10 m intervals along each

<table>
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<tr>
<th>Bedform</th>
<th>Direction of leeside facing</th>
<th>Morphology</th>
<th>Dimension</th>
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<tr>
<td></td>
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<td>Wavelength (cm)</td>
<td>Height (cm)</td>
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<tr>
<td>Current dune (Fig. 2A)</td>
<td>Landward</td>
<td>Symmetrical slightly sinuous-crested</td>
<td>60–200</td>
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<tr>
<td>Current dune (Fig. 2B)</td>
<td>Landward</td>
<td>Asymmetrical straight-crested</td>
<td>60–120</td>
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<td>Current ripple (Fig. 2C)</td>
<td>Landward</td>
<td>Asymmetrical straight-crested</td>
<td>30–40</td>
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<tr>
<td>Current ripple (Fig. 2D)</td>
<td>Landward</td>
<td>Asymmetrical straight-crested</td>
<td>25–30</td>
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<tr>
<td>Current ripple (Fig. 2E)</td>
<td>Landward</td>
<td>Asymmetrical sinuous-crested</td>
<td>10–15</td>
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<tr>
<td>Current ripple (Fig. 2F)</td>
<td>Seaward</td>
<td>Asymmetrical sinuous-crested</td>
<td>8–12</td>
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Fig. 3. Map showing spatial distribution of different morphology of current dune and ripple bedforms with approximate direction of tsunami inflow and outflow estimated from orientation of surface morphology of bedforms.
Fig. 4. Bedforms and stratigraphic columns near the coast along a 30-m-long part of transect 1 (see pit locations in Fig. 1C). Stratigraphic columns of pits no. 1, 2 and 3 were drawn from peelings. Scale bar beneath pictures represent distance between pits.
transect were done. The transects themselves were 15 m apart. Supplemental pits at intervals of 5 m and 2 m allowed us to correlate stratigraphic units securely. Undisturbed samples of individual units were also collected. Detailed sketches of pit walls were made, and sediment peels were carried out later by spray cohesive to characterize internal sedimentary structures between layers and to aid in stratigraphic correlation. Bulk samples from each layer of tsunami deposits were collected for grain size analysis of the sand (grain diameter − 2 to 4 phi) by sieving. Grain size of samples collected from layer to layer of the 2004 deposit from all pits along transect 1 were analyzed by a settling tube. Mean diameter, skewness, standard deviation and kurtosis were calculated by the graphic method (Folk and Ward, 1957).

4. Observations

4.1. Systematic classification of surface patterns

The post-tsunami sedimentary surface patterns observed at Bangtao include current dunes and ripples that

![Diagram of thickness of tsunami deposits from transects A to E.](image)

Fig. 5. Thickness of tsunami deposits from transects A to E (see locations of transects in Fig. 1C).
lack mud coating. Most of the current dunes and ripples exhibit landward-oriented morphology; their lee sides face landward (Fig. 2). The measurement of bedforms in terms of their wavelength, amplitude, bedform symmetry and asymmetry, lee and stoss angles, thickness of entire deposits from each pit and measured distance of inland distribution was carefully recorded (Table 1). The size of inflow current dune and ripple surface structures decreased landward (Fig. 2A to D). Surficial evidence for outflow was limited to small ripples superimposed on inflow dunes. These ripple marks have a seaward orientation (Fig. 2E and F). These sedimentary surface patterns may provide information about current dune-ripple transition velocity during inflow and imply minimal outflow deposition (Fig. 3).

4.2 Internal sedimentary structures and stratigraphic description

Internal sedimentary structures within sand sheets at Bangtao area consist of parallel lamination, landward and seaward inclined lamination, rip-up clasts of mud and sand, and graded bedding. The structures especially sharp contact help define two stratigraphic units (Units 1 and 2 in Fig. 4). Units 1 and 2 superimposed with clear sharp contact on former surface of buried soil. On all transects both units thin landward and terminate within 160 m of the shoreline (Fig. 5).

4.2.1. Unit 1

Unit 1 is present in a minority of the pits. Unit 1 was found along the 1st transect at pit numbers 1, 2, 3, 3+2 m (see correlation in Fig. 4) and on the 2nd transect at pit numbers 14 and 15 (see Fig. 1C for locations of pits). It contains normal-graded fine to medium sand with high percentage of medium sand. It also contains small rip-up mud clasts containing small amounts of shell fragments. Internal sedimentary structures consist mainly of parallel lamination, landward slightly inclined lamination truncated abruptly at the contact with overlying Unit 2. The sediments of this unit filled in micro-topographic depressions of buried soil underneath.

4.2.2. Unit 2

Unlike Unit 1, Unit 2 is present at all pits and transects. It contains generally normal-graded medium to coarse sand with shell fragments and cross-laminations that indicate a landward flow direction. Internal sedimentary structures consist of parallel lamination, inclined lamination (less than 3 degree dipping), trough cross-lamination and some rip-up mud and sand clasts.

4.3. Particle size analysis

Medium and coarse sand (with mean grain size between 0 and 2 phi) predominate in Units 1 and 2. Most of the grain-size analyses show a log-normal grain distribution with one main mode and poor sorting. All deposits contain shell fragments that were included for particle-size analysis. In mean grain diameter at the same place, Unit 2 is coarser than Unit 1. Mean grain diameter (phi) of Unit 1 from 1st transect (pit no. 1, 2, 3, 3+2 m) and 2nd transect (pit no. 14, 15), ranges from 0.32–1.18 with average of 0.836, whereas, Unit 2 from similar pits shows phi mean ranges from 0.02–1.83 with average of 0.672. Some of the tsunami-deposited sand differs from the area’s present-day beach sediments in Standard Deviation (SD) and Skewness (SK). SD and SK of post-tsunami beach sand range from 0.6 to 0.9, and −2 to 2, whereas, the 2004 deposit varies from 0.25 to 1.25, and −5 to 6, respectively.

5. Discussions

5.1. Sediment sources

A unimodal grain-size distribution can provide evidence that a tsunami deposit has a single marine source (e.g. Shi et al., 1995; Dawson et al., 1996). However, some tsunami deposits have bimodal grain distributions that imply combinations of marine and terrestrial sources (e.g. Minoura et al., 1996; Nanayama and Shigeno, 2006).

The grain compositions and grain size distributions from Bangtao suggest derivation in part from beaches. Some of the deposit may have been derived, in addition, from shoreface sediments, nearby channel sediments locating in the north of the area and former ground sediments, as shown by rip-up clasts of mud and sand.

5.2. Sedimentary record of inflow and outflow

Except where surface bedforms have been described (Sato et al., 1995; Nanayama et al., 2000), sedimentologic inferences about tsunami inflow and outflow have depended on internal structures. Structures previously used to infer repeated waves include mud interbeds (Konno et al., 1961; Atwater et al., 2005, p.18), fining-upward succession of normal-graded units (e.g. Benson et al., 1997; Gelfenbaum and Jaffe, 2003), multiple graded sand sheets and sharp erosional bases (e.g. Nanayama et al., 2000). Directional indicators include flame structures at the bases of tsunami beds (Minoura and Nakata, 1994), orientation of rip-up clasts (Jaffe and
Fig. 6. Diagram showing depth-averaged tsunami flow velocity calculated from mean grain size and tsunami-deposit thickness by method of Jaffe and Gelfenbaum (2007). (A) Flow velocity of Unit 1 deposited by the 2nd inflow ranges from approximately 20 m/s at 30 m inland to approximately 15 m/s at 80 m inland, whereas (B) Unit 2 deposits resulting from the 3rd inflow reveal the decrease flow velocity from approximately 20 m/s at 30 m inland to approximately less than 10 m/s at 160 m inland.
Gelfenbaum, 2007), and fallen plants knocked down by tsunami flows (Atwater et al., 2005, p.18). Deformed convolutions in underlying pre-tsunami deposits were also mentioned (Choowong et al., 2007).

At Bangtao, the combination of eyewitness accounts, post-tsunami photographs, and tsunami geology suggest the following sequence of events:

1. The first tsunami uprush wave did not cross beach ridge. Accordingly it did not register as a unit in the onshore tsunami-laid sand sheet (also see topographic profile in Fig. 7A).
2. Inflow during the second wave deposited Unit 1.
3. Stronger, more extensive inflow from the third wave with flow depth up to 3 m deposited the coarser, more extensive Unit 2. This inflow eroded the surface of Unit 1 and suspended a large amount of beach sediments, transported them inland, and produced current dunes and ripples.
4. Outflow had no lasting stratigraphic record at the sites we examined. Its effects were instead limited to the small seaward-oriented ripple marks superimposed on landward-oriented dune surfaces.

At Bangtao, rip-up mud clasts were preserved within inflow tsunami depositional layers similar to that previously reported by Jaffe and Gelfenbaum (2007). Such differences, where noted in 1995 tsunami deposits at Flores Island, Indonesia, were interpreted by Shi et al. (1995) as evidence of tsunami sedimentation rates are too high for tsunami sediment to become well sorted and also possible that such differences are a result of turbulent flow.

5.3. Tsunami flow velocity

Two approaches to estimate the velocity of the inflows responsible for Units 1 and 2 were carried out. The first uses a simplified depth-averaged tsunami flow speed (Jaffe and Gelfenbaum, 2007) developed for tsunami sedimentology. The second uses equations for the threshold of sediment motion (Komar and Miller, 1973) and applies them to the capping bedforms and internal grain size of Unit 2. The resulting estimates differ by an order of magnitude.

The model of Jaffe and Gelfenbaum (2007) relates a tsunami’s flow velocity to its deposit’s mean grain size and thickness. The model is intended for areas having simple topography, a well-measured tsunami deposit geometry, predominance of normal-graded layers, presence of a wide zone from about 50 to 200 m inland with fairly constant grain size texture, and high-quality flow depth indicators. The 2004 tsunami deposits at Bangtao share these attributes with the 1998 Papua New Guinea

![Fig. 7. (A) Post-tsunami topographic profile along transect 1. Gray area in left indicate post-tsunami beach sand recovered until 2007. (B) Reconstructed schematic diagram showing vertical profiles of computed depth-averaged tsunami flow and the near-bottom threshold velocities (Ut) calculated from oscillatory-wave equations of Komar and Miller (1973). The depth-averaged flow velocity, from Fig. 6, is expressed as multiples of Ut. The intervening flow velocities are interpolated.](image-url)
tsunami deposits with which Jaffe and Gelfenbaum (2007) calibrated their model. Accordingly, field parameters of tsunami deposit thickness and laboratory measurements of grain size distribution of Unit 1 and Unit 2 were input into Jaffe and Gelfenbaum’s graphical model (Fig. 6). Particle density of 2.65 g/cm³ was assumed.

The results for the 2nd inflow, recorded by Unit 1, imply flow speeds of 19 m/s at 30 m inland and 15.5 m/s at 80 m inland. For the 3rd inflow, recorded by coarser-grained Unit 2, the model suggests 21 m/s at 30 m inland and 7 m/s at 160 m inland. The Jaffe and Gelfenbaum model assumes that all sediment rains out of suspension, but bedforms at Bangtao suggest that there was significant bedload transport. It is, however, important to note here that results of flow speed calculation, as a result of an untested model, show a 3.5 m/s difference across just 50 meters, then they are internally inconsistent with a model of Jaffe and Gelfenbaum that assumes steady uniform flow.

Near bottom threshold velocity for generating bedforms for this study was derived from empirical relationships for the transition from laminar to turbulent motion under unidirectional currents has been suggested (e.g. Miller et al., 1977; Allen and Homewood, 1984), equations suggested by Komar and Miller (1973) were applied to this work because they considered wavelength and mean diameter of sediment as factors for controlling near bottom threshold flow velocity:

$$\rho U_t^2/(\rho s - \rho)gD = 0.21(\lambda/0.8D)^{1/2}$$  \hspace{1cm} (1)

for sediment diameter <0.5 mm (medium sand and finer), and

$$\rho U_t^2/(\rho s - \rho)gD = 0.46(\lambda/0.8D)^{1/4}$$  \hspace{1cm} (2)

for sediment diameter >0.5 mm (coarse sand and coarser), where \( \rho = \) density of water (≈997.044 kg/m³), \( \rho s = \) density of sediment grain (≈2.65 g/cm³), \( g = \) acceleration of gravity (≈9.8 m/s²), \( D = \) mean grain diameter (m), \( \lambda = \) spacing of sediment ripples (m), \( U_t = \) near-bottom threshold velocity.

Results of calculation in a near bottom threshold velocity from mean grain diameter \( D \) and ripple spacing \( \lambda \) of bedforms imply a velocity of 1.74 m/s for the biggest current dune \( (D=0.65 \text{ mm}, \lambda=2.0 \text{ m}) \) and 1.03 m/s for typical ripples \( (D=0.325 \text{ mm}, \lambda=0.10 \text{ m}) \). However, depth-averaged flow and near bottom threshold velocities decreased inland. The depth-averaged flow and near-bottom threshold velocities from Bangtao, Phuket reveals the order of magnitude difference with relation to flow depth (Fig. 7). Landward decrease in flow velocity was also suggested by Fritz et al (2006) at Banda Aceh where tsunami flow velocity within the range of 2 to 5 m/s was estimated from two survivor videos recorded at 3 km from the open ocean.

5.4. Reconstruction of hydraulic conditions

The following reconstruction of hydraulic conditions of the December 26, 2004 tsunami at Bangtao is based on eyewitness’s accounts, photographs taken during the tsunami, internal sedimentary structures, surficial bedforms and the results of particle-size analysis.

The tsunami started at 9:42 a.m. local time with a leading withdrawal seen all along Thailand’s Andaman coast and recorded there on tide gauges (Choowong et al., 2007). Most or all of the erosion and deposition in the area of our pits at Bangtao occurred between 9:45 and 10:20 a.m. local time. This erosion and deposition occurred during two periods of inflow. The second of these was followed by outflow. Reconstruction of the 2004 Indian Ocean tsunami based on hydraulic interpretation was divided into 5 episodes as follows (Fig. 8).

5.4.1. Episode I: Leading withdrawal

Around 9:42 a.m. local time, seawater receded rapidly to the distance of about 500 m offshore far away from the coastline, approx. 4 m depth from mean sea level (MSL).

5.4.2. Episode II: Beach erosion and transportation by 1st inflow

A few minutes later, the first inflow reached a little higher level than MSL and barely reached the vegetation at the inland edge of the beach. Though the beach surface underwent erosion, the inflow thus did not carry the eroded sediment more than 30 m inland.

5.4.3. Episode III: Deposition of Unit 1 by 2nd inflow

A few minutes later, the second inflow ran onshore, where it reached the height of about 2 m above ground surface. It carried beach sediments at least 60–70 m inland, forming Unit 1.

5.4.4. Episode IV: Deposition and migration of Unit 2 by 3rd inflow

The third inflow, with a maximum onshore flow depth of about 3 m, buried Unit 1 with the thicker, more
Fig. 8. Reconstructed hydraulic conditions of the 2004 Indian Ocean tsunami at Bangtao, Phuket.
extensive Unit 2. The flow created landward-oriented dunes. A few minutes after, water stagnated at maximum height, then started draining off slowly.

5.4.5. Episode V: Disturbance of surface structure of Unit 2 by outflow

Outflow generated small seaward-oriented ripples on the dunes of Unit 2.

6. Conclusion

Surface and internal sedimentary structures of the 2004 tsunami deposits at Bangtao area provide an opportunity to understand flow conditions. Inflow landward-oriented current dunes and ripples were immediately recorded after the event and they exhibited typical internal sedimentary structures including parallel lamination, landward-and seaward-inclined laminations with normal-graded sand. Rip-up mud clasts were also recognized within layer of inflows.

Two event stratigraphical units of tsunami deposits in this area were interpreted. Unit 1 is distributed as far as 70 m inland with finer in grain size than Unit 2. Unit 2 is characterized by coarser sediment with well-preserved internal structures of current dune and ripple, and distributed as far as 160 m inland partly truncating Unit 1.

There is no indication of outflow deposits from surface sedimentary patterns, but the outflow can be expected to only disturb surface of inflow current dune bedforms and generated only small seaward-oriented small ripple marks superimposed on landward-oriented dune surfaces.

The estimation of depth-averaged flow velocity and near bottom threshold velocity was done based on grain size, thickness and surface structural patterns. The maximum depth-averaged flow velocity of tsunami wave train (that is the 3rd inflow) was about 21 m/s at 30 m inland to approximately 7 m/s at 160 m inland. Near bottom threshold velocity calculated from the biggest dune morphology shows a range of flow velocity of 1.74 to 1.03 m/s. At flow depth about 3 m, depth-averaged flow velocity was about 12 times greater than near bottom velocity and, in general, flow speed decreased landward as flow depth decreased.

According to field records, laboratory works together with eyewitnesses account, a proposal of hydraulic behavior of the 2004 tsunami event from Bangtao area can be made. The event started at 9:43 a.m., ending up at 10:20 a.m. local time, and is divided into 5 episodes: leading withdrawal, beach erosion and transportation by 1st inflow, deposition of Unit 1 by decelerated 2nd inflow, deposition and transport of Unit 2 by 3rd inflow and finally the disturbance of surface structure of Unit 2 by outflow.

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