MULTIPLE LAYER IDENTIFICATION AND TRANSPORTATION PATTERN ANALYSIS FOR ONSHORE TSUNAMI DEPOSIT AS THE EXTENDING TSUNAMI DATA – A CASE STUDY FROM THE THAI ANDAMAN COAST

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ABSTRACT

On 26th December 2004, a strong Indian Ocean earthquake of moment magnitude 9 generated a deadly tsunami that hit the west coast of southern Thailand and many coastal nations of the Indian Ocean. Two tsunami-affected areas on the Thai Andaman coast (Ao Kheuy beach and Khuk Khak beach) were investigated. Multiple sediment layers in the tsunami deposits are identified and are analyzed. The sediment transportation patterns are also determined. Tsunami deposits consist of graded sand layers overlying the pre-existing soil. The particle size profile of the tsunami sediment and the plot of grain-size standard deviation with depth are used to identify major layers in tsunami deposit. There are three major sediment layers in the tsunami deposit in the study areas. They reflect three depositional sequences created by three tsunami run-ups. The mean grain-size of tsunami deposit and the results of sediment trend analysis show that the tsunami deposit is generally fining upwards and landwards. Each major sediment layer is created by sediments settled from suspension in a set of run-up and backwash. The percentage by weight of sediment settled from suspension during the backwash is small when it is compared to the percentage by weight of sediment settled from suspension during the run-up. The 1st depositional sequence has higher quantity of coarse grain particles than the following depositional sequences. At a mild slope shore face, sediments are transported and deposited on land far from their origins. The number of major sediment layers in tsunami deposit can be used as the extending data for reconstructing individual tsunami run-up by using numerical and/or simple models.

Keywords: Tsunami deposit; depositional sequence; sediment layer identification; sediment transportation; extending tsunami data

INTRODUCTION

A sedimentary signature for onshore tsunami deposits has been defined (e.g. Nelson et al., 1996; Dawson and Shi, 2000; Whelan and Kelletat, 2003) but the particular hydrodynamic behavior of the long-period surge associated with tsunamigenic flooding is still under debate. In many tsunami studies, scientists have used data on tsunami run-up (e.g. number of tsunami run-ups, run-up height) to calibrate numerical models for undersea fault-generated and submarine landslide-generated tsunami (Dawson et al., 1991). Almost all cases, the number of tsunami run-ups have been based on eyewitness reports of the tsunami flood. This paper presents and describes methods to evaluate the number of tsunami run-ups and the tsunami sediment transportation pattern from the onshore tsunami deposit found after the December 26th, 2004 tsunami event (Indian Ocean tsunami) at Ao Kheuy beach and Khuk Khak beach, Phangnga province, Thailand.

STUDY AREAS

The study areas are Ao Kheuy beach and Khuk Khak beach located in Phangnga province, west coast of southern Thailand (Fig. 1). The reference coordinates are (432009E, 1029826N) for Ao Kheuy beach and (416269E, 961298N) for Khuk Khak beach. The geomorphic feature of study areas is described as open coastal zone. The pre-existing soils are coastal deposit and agricultural soil.

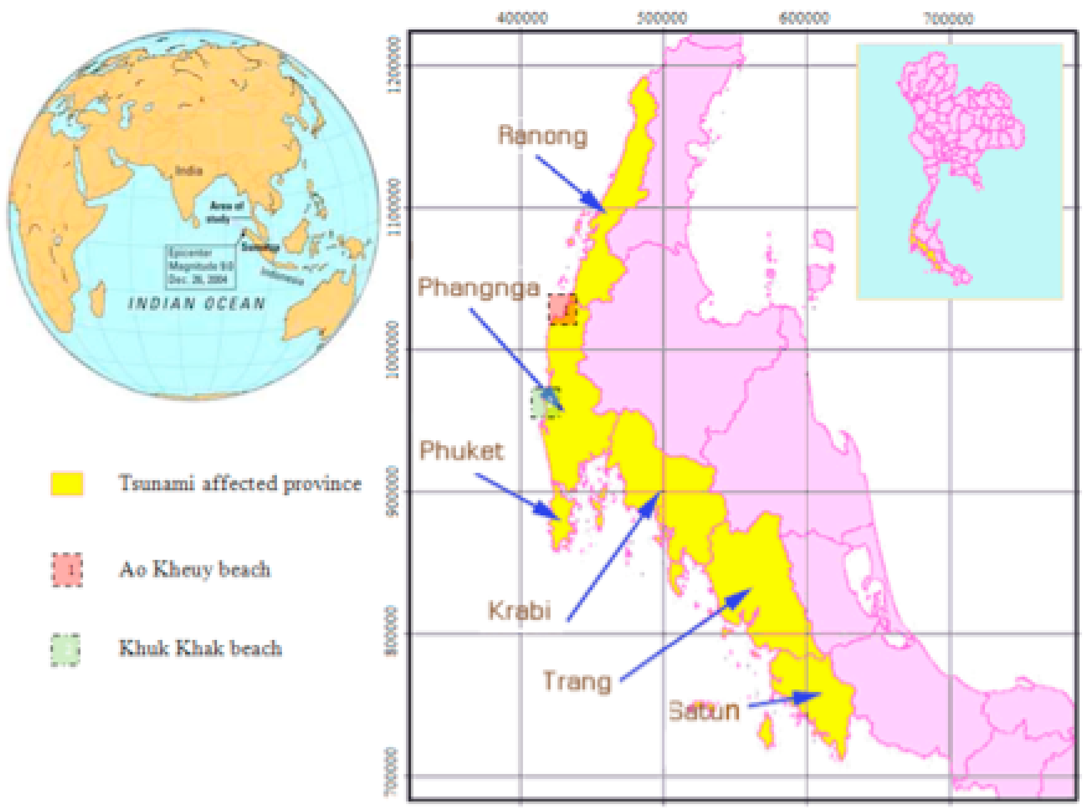


Figure 1. Study areas: 1) Ao Kheuy beach, 2) Khuk Khak beach.

METHODOLOGY

Initially, number of tsunami run-ups and run-up heights were obtained from eyewitness reports and local people's observations. Topographical profile investigations, tsunami deposit thickness measurements and sediment sample collections were made in study areas in August to October 2007. Tsunami deposit samples were collected at a distance between 50 to 300 m inland from coastline. Topographical profiles are established by the combination of the automatic level measurement and Thai topographical map. Collecting samples are analyzed for grain-size distribution by the wet-sieve method. Mean grain-size, standard deviation, skewness, and kurtosis are calculated on the basis of the percentile statistics of Folk and Ward (1957). The major sediment layers in the tsunami deposit are evaluated from the particle size profile for the tsunami sediment layer (grain-size distribution curve contiguous 1 cm-thick samples) and the plot of standard deviation with depth. The sediment transportation patterns are analyzed by a sediment trend analysis (STA) followed McLaren et al. (2007).

RESULTS

Topography of study areas

Ao Kheuy beach is an agricultural area with coconut and palm trees. The shore face slope is about 1:100 (Fig. 2). The backshore and upland zone consist of berm, dune and channel. The tsunami run-up inundation is about 250 m inland from the coastline. From local people's observations, there were 3 waves, which came inland, and the run-up height was about 4-6 meters.

Khuk Khak beach is an agricultural area with coconut trees. The shore face slope is about 1:600 (Fig. 3). The backshore and upland zone consist of berm, dune and road. The tsunami run-up inundation reached about 2 km inland from the coastline. From local people's observations, tsunami run-up height was about 8-10 meters.

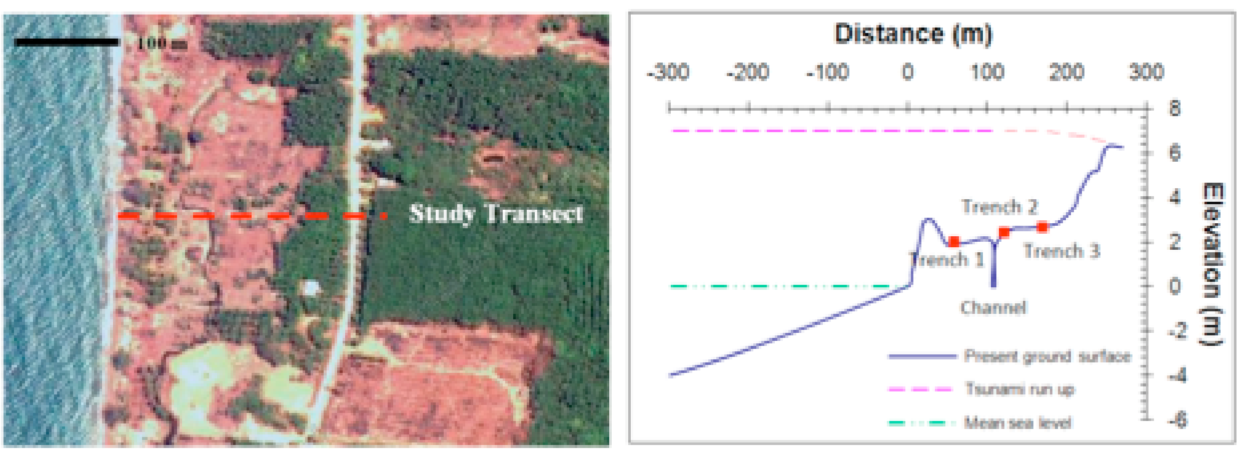
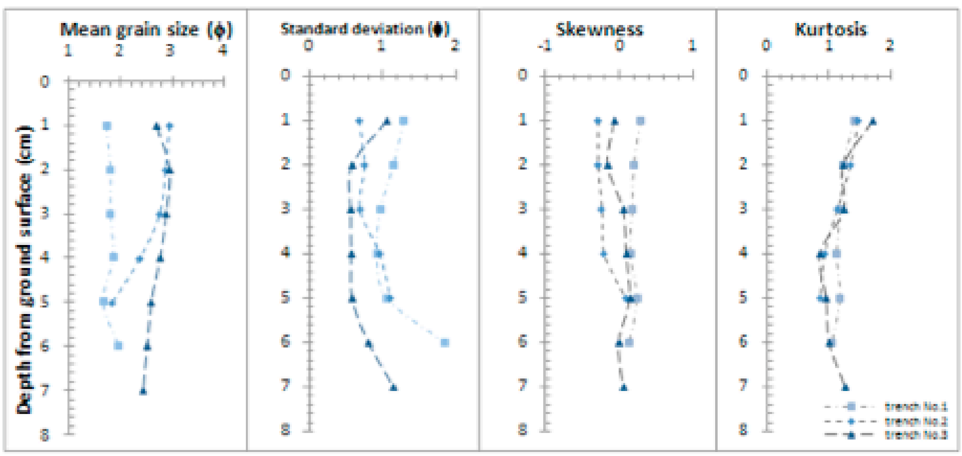
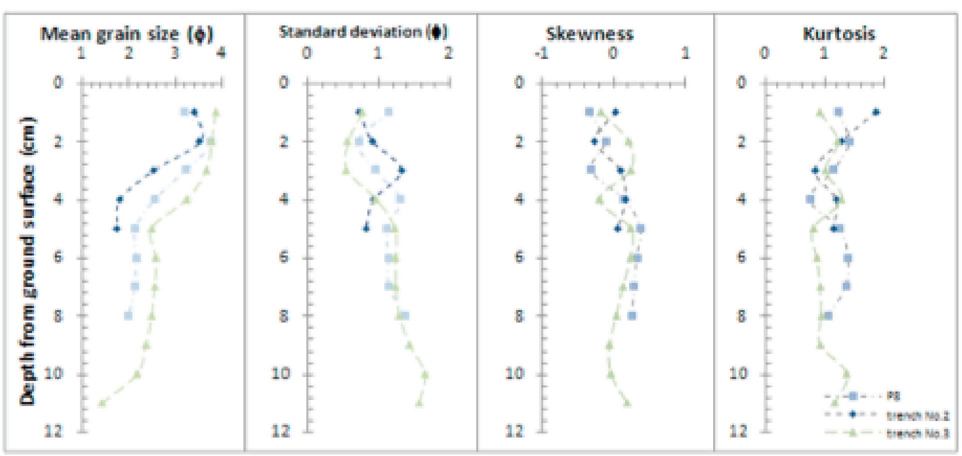


Figure 2. Satellite photo and profile of Ao Kheuy beach to show coastal characteristics and locations of onshore tsunami deposit sample collections.

Figure 3. Satellite photo and profile of Khuk Khak beach to show coastal characteristics and locations of onshore tsunami deposit sample collections.



a) Ao Kheuy beach



b) Khuk Khak beach

Figure 4. Vertical variations of mean grain-size, standard deviation, skewness and kurtosis for tsunami deposits at a) Ao Kheuy beach and b) Khak Khak beach.

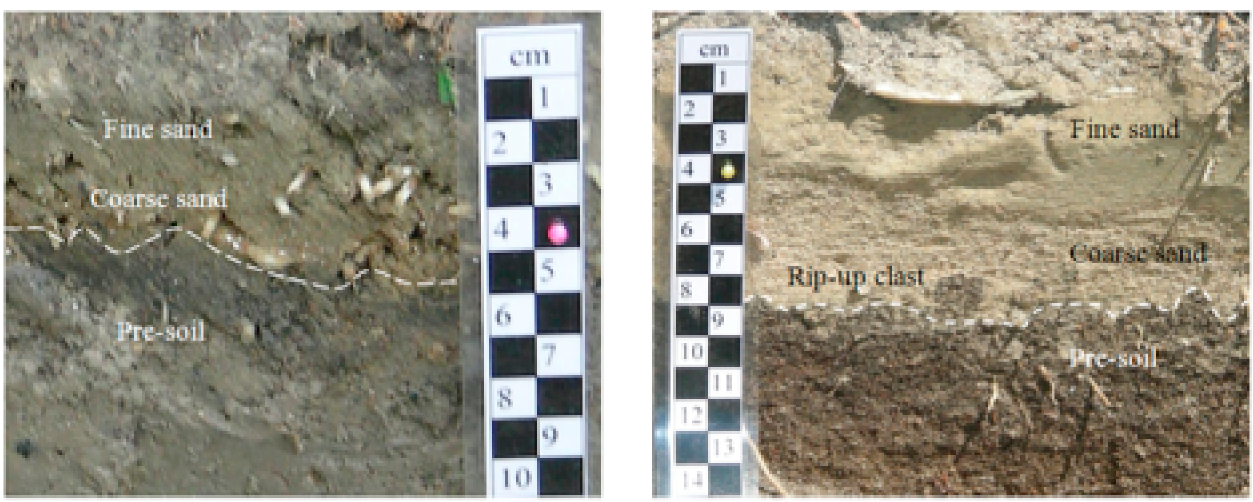
Grain-size analysis

The tsunami deposit grains present within each location largely occur within the size rage between gravel and clay with shell materials. The mean grain-size of the tsunami deposit varies between medium sand to very fine sand ($1<\phi_{mean}<4$). Entirely, tsunami deposit is characterized by a fining landward deposit (Fig. 4). There are variations in the composition of the particle size distributions as illustrated by the plot of standard deviation with depth that range from well sorted to poorly sorted sediments. The particle size distributions appear to have similar kurtosis values to the tsunami sediments presented by Singarasubramanian et al. (2006) which are lower than that described by Shi et al. (1995) and Dawson et al. (1996).

INTERPRETATIONS

Identification for major sediment layers in the tsunami deposit

The tsunami deposit is a sand layer overlying pre-existing soil (rooted soil) with coarse particles near the base and fine particles toward the top (Fig. 5). In a few places, the tsunami deposit contains small rip-up clasts eroded from the pre-existing soil.



a) Ao Kheuy beach, Trench 2 *b) Khuk Khak beach, Test Pit 8*

Figure 5. Tsunami deposits overlying pre-existing soil; a) tsunami deposit overlying agricultural soil at Ao Kheuy beach, b) tsunami deposit overlying coastal deposit at Khuk Khak beach.

The tsunami sediment layer exhibits an erosional base and normal graded sand. The grain-size analysis as determined by the wet-sieve method for contiguous 1 cm-thick samples shows the sediment size profile as figure 6 and figure 7. In the study areas, fining-upwards sequence with variable thickness deposit is presented. Deposits have a bi-modal grain-size distribution at the lower

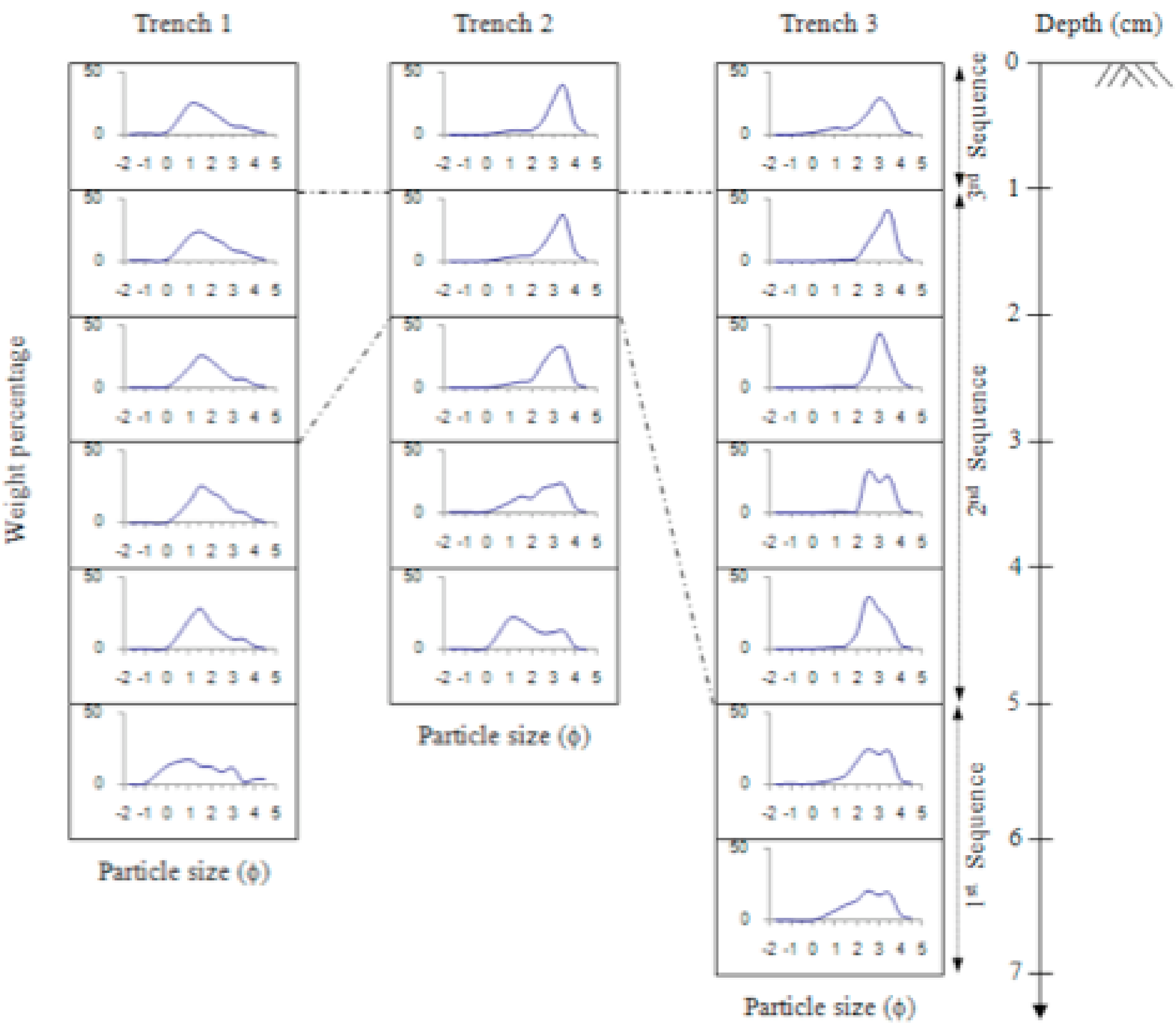


Figure 6. Particle sizes profile for the tsunami deposit at Ao Kheuy beach.

part, with the finer peak increasing in percentage by weight towards the top as the percentage weight of the coarser peak decreases. However, the fining-upwards sequence contains multiple depositional sequences. The depositional sequence boundaries are identified by the increasing of percentage by weight of the coarse particles from the bottom to the top of deposit. It is not easy and not clear to identify the sediment sequences only with grain-size distribution curves as discussed by Smith et al. (2007). Additionally, the plot of standard deviation with depth and grain-size distribution curves for contiguous 1 cm-thick samples are presented to identify major sediment layers in tsunami deposit (Fig. 8). The break points in plot of standard deviation with depth mark a break in turbulence associated with a transition to a lower or higher Reynolds number run-up (Hindson and Andrade, 1999). From figure 8, the break point in plot of standard deviation with depth locates at the depth of

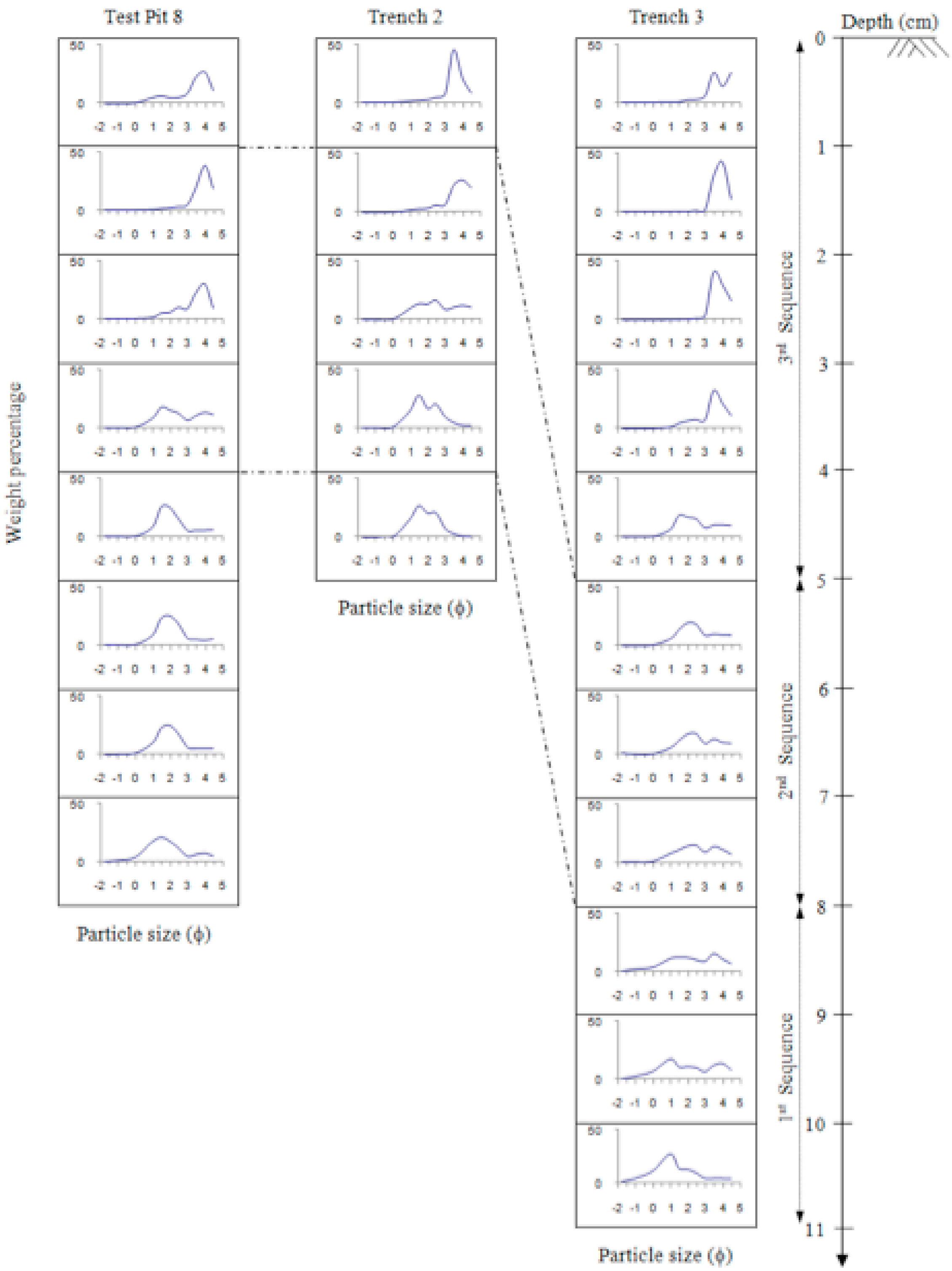
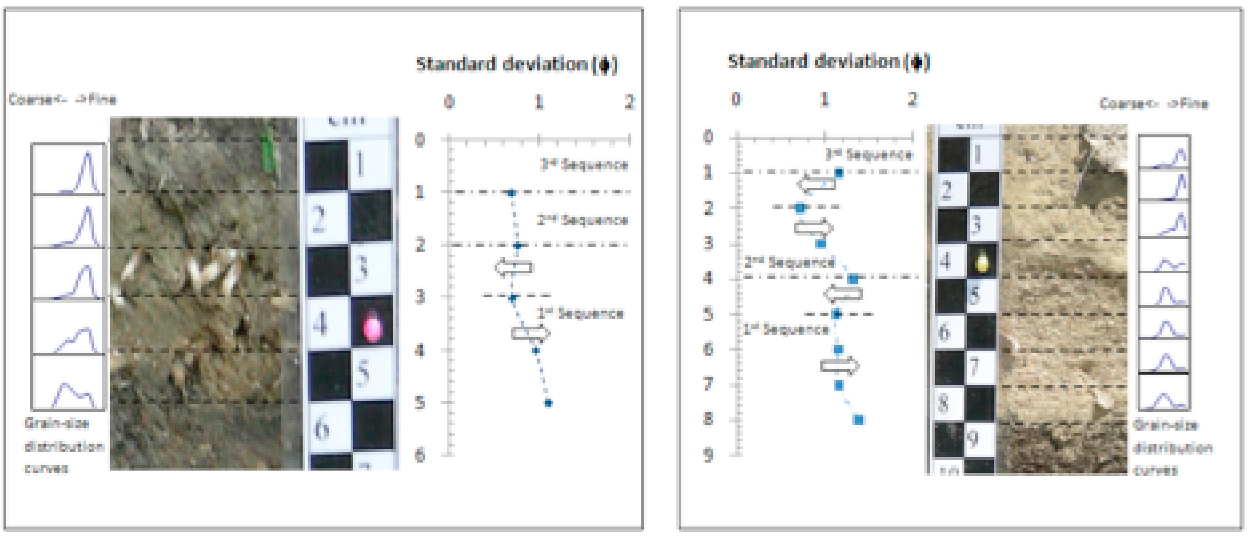


Figure 7. Particle sizes profile for the tsunami deposit at Khuk Khak beach.

increasing of percentage by weight of the coarse particles in the grain-size distribution curve. Thus, that location must be a major sediment boundary. At the study areas, there is a pattern of three depositional sequences in tsunami deposits. There are minor break points in the standard deviation pattern in the 1st depositional sequence in the tsunami deposit at Ao Kheuy beach, and in the 1st and the 2nd depositional sequences in the tsunami deposit at Khuk Khak beach. It could be said that the major sediment layer associates with deposits from two flow characteristics, which might be run-up and backwash (or drawdown). From those depositional sequences, it seems likely that the study areas were reached by three waves, which generated three run-ups.



a) Ao Kheuy beach, Trench 2 b) Khuk Khak beach, Test Pit 8

Legend: ⇨ = Run-up; ⇦ = Backwash or drawdown
-·-·-· = Major layer boundary; - - - - - = Minor layer boundary

Figure 8. Example plots of standard deviation with depth and grain-size distribution curves for contiguous 1 cm-thick samples at a) Ao Kheuy bech and b) Khuk Khak beach, to show the identification of major sediment layers.

Tsunami sediment transportation analysis

Smith et al (2007) discussed that as each wave of the tsunami flowed onshore, the turbulent water contained a considerable volume of sediment of all sizes. As velocity decreased, turbulence was reduced and the sediment began to settle out. Fining-upwards sequences developed from each wave during the process, with coarser particles settling out first and finer ones later. The direction of run-up flow was almost perpendicular to the coastline, whereas backwash flow directions were controlled by topography (Umitsu et al., 2007). Backwash or drawdown carried sediments, which were not deposited back out to the sea or to the lower level area.

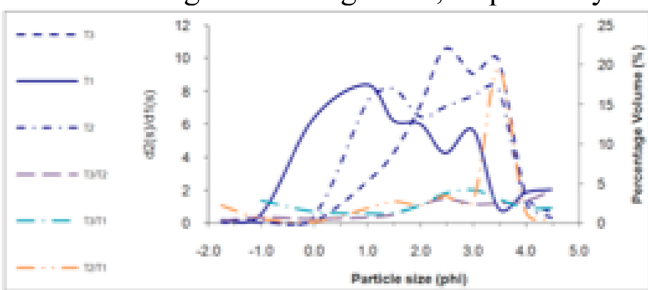
Tsunami sediment transportation pattern is interpreted follow McLaren et al. (2007) for discussion with the considerations articulated by Smith et al. (2007). When the transport direction is unequivocally known, $d_2(s)$ can be related to $d_1(s)$ by a function $X(s)$ as:

$$X(s) = d_2(s)/d_1(s)$$

In this paper, the representative grain-size distribution curve of each depositional sequence (major sediment layer in the tsunami deposit), which is a summary of grain-size distribution curve of contiguous 1 cm-thick in each depositional sequence, is taken sequentially in a known transport direction. For examples:

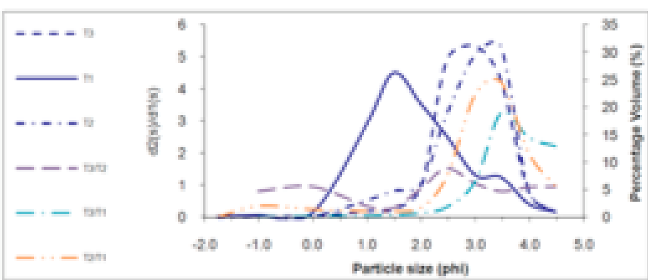
1) d_1 is the sediment distribution at Trench 1 and d_2 is the sediment distribution at Trench 2;
2) d_1 is the sediment distribution at Trench 2 and d_2 is the sediment distribution at Trench 3; and
3) d_1 is the sediment distribution at Trench 1 and d_2 is the sediment distribution at Trench 3

The resulting patterns of tsunami sediment transportation for Ao Kheuy beach and Khuk Khak beach are shown in figure 9 and figure 10, respectively.



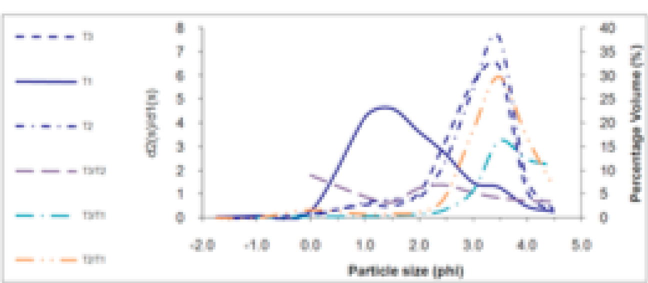
1st depositional sequence

d_1	d_2	Pattern
Trench 1 (T1)	Trench 2 (T2)	Net accretion
Trench 2 (T2)	Trench 3 (T3)	Total deposition 1
Trench 1 (T1)	Trench 3 (T3)	Net accretion



2nd depositional sequence

d_1	d_2	Pattern
Trench 1 (T1)	Trench 2 (T2)	Net accretion
Trench 2 (T2)	Trench 3 (T3)	Dynamic Equilibrium
Trench 1 (T1)	Trench 3 (T3)	Net accretion

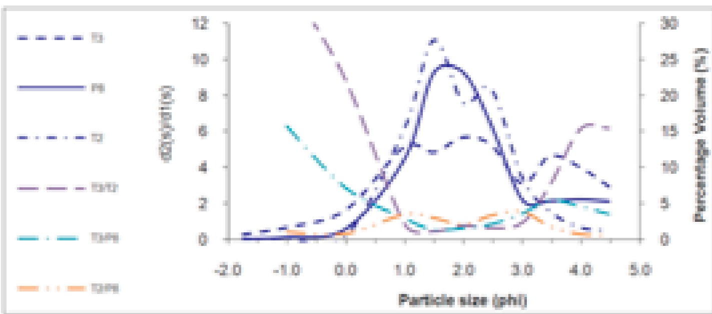


3rd depositional sequence

d_1	d_2	Pattern
Trench 1 (T1)	Trench 2 (T2)	Net accretion
Trench 2 (T2)	Trench 3 (T3)	Total deposition 2
Trench 1 (T1)	Trench 3 (T3)	Net accretion

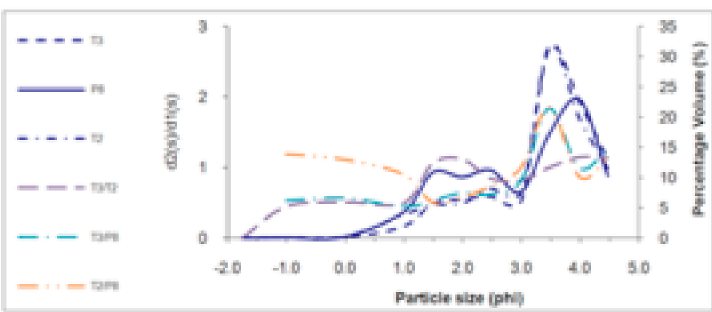
Figure 9. Sediment trend analysis results for onshore tsunami sediment transportation at Ao Kheuy beach.

The grain-size modes of each depositional sequence at Ao Kheuy beach do not significantly differ, however the deposit fines upward. The major transportation pattern of tsunami sediment during depositional process is net accretion and total deposition, which deposits are fining in the direction of transport, however, more grains are deposited than eroded. The deposit grain-size modes of each depositional sequence at Khuk Khak beach show that the deposit fines upward. The major transportation pattern is total deposition, which sediments must fine in the direction of transport. Once deposited, there is no further transport. Some sediment is usually found far from their sources. In the study areas, there is a net erosion pattern for the transportation pattern, but no erosion evidence on the surface of the lower sequence of sedimentation is observed, and, the net erosion pattern is less compared to other patterns.



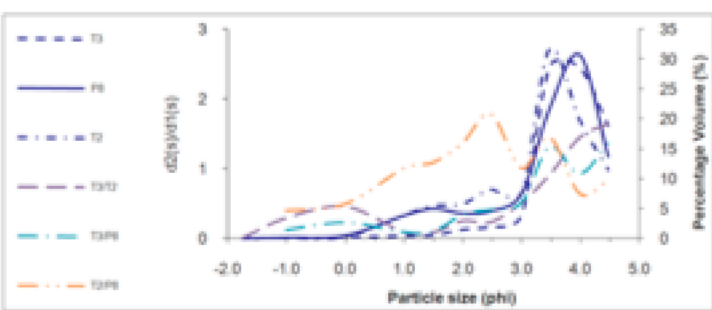
1^{st} depositional sequence

d_1	d_2	Pattern
Test Pit 8 (P8)	Trench 2 (T2)	Dynamic Equilibrium
Trench 2 (T2)	Trench 3 (T3)	Total deposition 1
Test Pit 8 (P8)	Trench 3 (T3)	Total deposition 1



2^{nd} depositional sequence

d_1	d_2	Pattern
Test Pit 8 (P8)	Trench 2 (T2)	Total deposition 2
Trench 2 (T2)	Trench 3 (T3)	Total deposition 2
Test Pit 8 (P8)	Trench 3 (T3)	Total deposition 2



3^{rd} depositional sequence

d_1	d_2	Pattern
Test Pit 8 (P8)	Trench 2 (T2)	Net erosion
Trench 2 (T2)	Trench 3 (T3)	Total deposition 1
Test Pit 8 (P8)	Trench 3 (T3)	Total deposition 1

Figure 10. Sediment trend analysis results for onshore tsunami sediment transportation at Khuk Khak beach.

DISCUSSION

The tsunami deposits observed at Ao Kheuy beach and Khuk Khak beach share many of the modern tsunami deposit characteristics in locations around the world. For example, Shi et al. (1995) noted the presence of an upward fining sequence in the sediment sheets at Flores. They recognized that the sediment sheet has an erosional contact with the underlying soil (pre-existing soil), and is composed of a wide range of sediment sizes. The particle size profile for the tsunami sediment layer is used to identify major sediment layers in the tsunami deposit, but it is not easy and not as clear as that discussed by Smith et al. (2004, 2006). The identification for major sediment layers gives higher accuracy when the particle size profile from the wet-sieve analysis method and the plot of standard deviation with depth are considered together. The identification for major sediment layers in tsunami deposit gives three depositional sequences, which reflect three tsunami run-ups at Ao Kheuy beach and Khuk Khak beach. The number of run-ups from the identification for major sediment layers in the tsunami deposit corresponds to eyewitness reports. Therefore, the identification method for major sediment layers in the tsunami deposit may be applied to interpret number of tsunami run-ups at tsunami-affected areas where lack of eyewitness reports.

It is recognized that tsunami flow onshore can be complex (e.g. Shi, 1995). Smith et al. (2007) argued that the pattern of fining-upwards sequences across an embayment might show that each sequence was the deposit of an individual wave. Onshore tsunami sediment transportation analysis shows that, deposits fine in the direction of transport. There is a net erosion pattern, which sediment coarsens along the transport path, more gains are eroded than deposited, but there is no evidence of erosion on the surface of the lower sediment sequence. Wang et al. (2006) concluded that in the area where the surface of the lower sediment is non-vegetated (e.g. clean sand deposit), the erosional surface is not apparent. Hindson and Andrade (1999) concluded that multiple wave sets can be detected in tsunami deposits, although it is difficult to distinguish between these and tsunami backwash. In this study, the results show that the sediments in each depositional sequence settled form two flow characteristics, which might be run-up and backwash (or drawdown). The 1st and the 2nd depositional sequences are easy to observe that depositional phenomenon from a particle size profile and a plot of standard deviation with depth (Fig. 8). The thickness of tsunami deposit suggests that the sediments settled from run-up are more significant than the sediment settled from backwash. Tsunamis do not transport significant quantities of material from the offshore zone, with the majority of the erosional activity occurring onshore, and typically involving the removal of sand from the beaches and coastal dunes (Hindson and Andrade, 1999). This conclusion is appropriate for Ao Kheuy beach. However, for Khuk Khak beach, which the slope of shore face is mild, the sediment transportation patterns suggest that the sediments of the 2nd depositional sequence are found far from their source. Therefore, at a mild slope shore face, some sediment is transported far from their sources.

Generally, tsunami is a set of waves, which creates a set of run-ups when it encounters land. Details of tsunami deposit thickness and grain-size from multiple layer identification and transportation pattern analysis for an onshore tsunami deposit can be put in the simple models for reconstructing tsunami run-up (e.g. Jaffe and Gelfenbuam, 2007; Soulsby et al., 2007). The results from reconstructing tsunami run-up with details of tsunami deposit thickness and grain-size from multiple layer identification can be evaluated the individual run-up characteristics.

CONCLUSIONS

The tsunami deposit found at Ao Kheuy beach and Khuk Khak beach is a sand layer overlying pre-existing soil with an erosional base. The sediments fine upward and landward. Apparently, tsunamis are, in general, both erosive and depositional in nature. At Ao Kheuy beach and Khuk Khak beach, Phang-nga province, Thailand, there are three major sediment layers in the tsunami deposit. It suggests that flooding (run-up) took place from three waves and tsunami deposits settled from run-up and backwash (or drawdown). Sediments created by run-up are more significant than sediments created by backwash. The sediment transportation patterns show that tsunami deposits fine landward, more grains being deposited than eroded. There is some evidence of erosion only at the base of the 1st sediment sequence. Sediments are transported far from their origin at a mild slope shore face. The numbers of major sediment layers in the tsunami deposit can be used to interpret the event apart from eyewitness reports (e.g. number of run-ups for ancient tsunamis which the eyewitness reports are not existent, thickness and particle size of sediments which are transported and deposited by individual run-up) for reconstructing individual tsunami run-up by using numerical and/or simple models.

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