Assessing Tsunami Risk in Southwest Java, Indonesia: Paleo-Tsunami Deposits and Inundation Modeling

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Assessing Tsunami Risk in Southwest Java, Indonesia: Paleo-Tsunami Deposits and Inundation Modeling

Han Deng

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Assessing Tsunami Risk in Southwest Java, Indonesia: Paleo-Tsunami Deposits and Inundation Modeling

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Master of Science

Samples from 13 different sites along the south coast of West Java yield 7 candidate paleo-tsunami sands, which may represent 4 different paleo-tsunami events. Ages obtained from one deposit may document a tsunami and coastal subsidence from an earthquake in 1,053 AD. The tsunami deposit from this event is preserved in an uplifted marine terrace exposed at Panto Cape, Banten Province. We speculated that the terrace has been uplifted about 4.6 m to the present height of 2 m above sea level, since the 1053 AD event at a rate of 4.8 mm/a. This uplift is strong evidence that strain is accumulating at the Java Trench and enough has already accumulated to generate a megathrust earthquake event.

Numerical models using ComMIT of possible megathrust earthquake scenarios were constructed using the 2004 Sumatra earthquake, 30-m fault slip, and the 2011 Japan earthquake as proxies. These three scenarios yield earthquakes of Mw 9.3, 9.5 and 8.9, respectively. The worst case scenario is used to estimate the extent of tsunami inundation of the SW coast of Java, which totals 643 km². The total number of people who inhabit the inundation area is around 451,000. Some coastal configurations cause a no escape situation where the modeled tsunami arrives in less than 20 minutes, which is not enough time for those near the coast to escape far enough inland or to a sufficient elevation to avoid the tsunami. These areas include the coastlines of Sukabumi, Cianjur and west Garut Regencies and the Pameungpeuk area.

Keywords: Central Indonesia, southwest Java, Java Trench, numerical modeling, inundation maps, paleo-tsunami deposits, evacuation
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1.0 TECTONIC SETTING AND HISTORICAL PRECEDENT

Java Island, Indonesia is the most populated islands in the world and one of the most tectonically active coastal nations on Earth. The island consists mostly of products of an ocean-continent subduction zone (Hamilton, et al., 1979). An oceanic part of the Australian Plate subducts beneath a continental part of the Sunda Plate at the Java Trench. The trench represents the plate boundary and is around 200 km offshore of the south coast of Java (Fig. 1). Between the trench and the southern coast of Java is a forearc basin. The convergence rate between the two plates at the trench is 69 mm/a (Hanifa et al., 2014).

Historical records kept by Dutch colonists as early as the late 16\(^{th}\) century and later by Indonesian scientists document at least 90 destructive earthquakes and 10 tsunamis in the Java region (Latief et al, 2000; Harris and Major, 2016). Some of these events may be related to slip along the plate boundary interface of the Java Trench, like the few Mw 7.0-7.7 events in the instrumental record (Fig. 1). In contrast, the Sumatra Trench has generated 8 megathrust earthquakes (> Mw 8.5) in the past 200 years (Newcomb and McCann, 1984), including 2 earthquakes since 2003.

Available historical records provide no evidence of megathrust earthquakes along the entire 2,000 km length of the Java Trench during the past 431 years (Harris and Major, 2016). Assuming that the historical records in Java are as accurate as they are in the more sparsely colonized Sumatra, a Java megathrust event may be imminent. The largest megathrust events likely have long recurrence intervals due to the amount of time it takes to accumulate enough energy for such an event. Perhaps the available records are too short to have captured the last giant event. A similar situation existed in Sumatra (Monecke et al., 2008) with the 2004 Mw 9.2 megathrust event and the 2011 Mw 9.0 megathrust event in Japan (Sagiya et al., 2011), both of which had no
clear historical precedent.

2.0 MEGATHRUST EARTHQUAKE IN JAVA?

The lack of historical and instrumental evidence for a megathrust earthquake along the entire Java Trench has fueled debates about whether or not it has accumulated enough elastic strain to generate megathrust events or if it behaves mostly by creep (i.e. Newcomb and McCann, 1987; McCaffrey, 2007). The marked slip deficit along the entire Java Trench begs an explanation (Fig. 2).

More detailed investigations of the cause of the slip deficit used a network of continuously recording GPS stations over a two-year period (Hanifa et al., 2014). These measurements document up to 5.7 mm/a of uplift along the SW Java coast and 6.6 mm/a shortening across the island. It is estimated from this study that the subduction interface offshore SW Java is 70-82% coupled, and that the uplift is from inter-seismic strain accumulation. Whether these results are representative of the entire Java Trench is yet to be tested. However, for SW Java it is clear that elastic strain is accumulating at around the same rate as the convergence rate, 69 mm/a, at the trench (Hanifa, et al. 2014).

If the Java Trench does accumulate elastic strain with a 69 mm/a slip rate, then it is one of the most dangerous seismic gaps known with at least 30 meters of potential slip accumulating in the past 431 years, which may be an underestimate. The sudden release of this amount of slip along the entire 2,000 km length of the Java Trench could produce a megathrust earthquake of Mw 9.6 (McCaffrey, 2007), which would be the largest earthquake ever recorded. This event would produce a massive tsunami that would strike the most populated coastal region ever struck by a tsunami (Harris and Major, 2016).
3.0 OTHER CONTROLLING FACTORS OF TSUNAMI HAZARDS

Adding to the dilemma of tsunami disaster mitigation in Java is the common occurrence of slow-rupture earthquakes along the subduction interface such as the 1994 and 2006 events (Abercrombie, 2001, and Reymond, 2006). These events are referred to as ‘tsunami earthquakes’ because they have a long period, slow-rupture process, which translates into a large tsunami relative to the moment magnitude of the earthquake. In contrast to most earthquakes of Mw 7.5-7.9 with rupture velocities of 2.5 - 3.5 km/s, slow-rupture earthquakes have rupture velocities of ~ 1.0 km/s. At these slow velocities shaking intensities are nearly imperceptible even though displacements and tsunamis from these events are about two times greater than those from normal-rupture events (Bryant, 2008). Both the 1994 and 2006 earthquakes were not felt by many inhabitants of coastal areas closest to the epicenter (Fujii and Satake, 2006). It is possible that there were more tsunamis along the Java coast than recorded in historical records due simply to the slow rupturing process.

The bathymetry of coastlines also exerts a major control on tsunami behavior. Most of southern Java has a broad shelf (25-65 km wide) just offshore (Fig. 1). However, the area immediately offshore of SW Java is strikingly different and variable. In some places, there is no shelf at all. Other parts of the coast have large embayments. For example, in the western Banten Province, there is a broad shelf between mainland Java and the outer Tjinjil islands (Fig. 1). Seaward of the islands, there is a relatively steep continental margin. Whereas, between the Banten and West Java Provinces is the densely populated port of Pelabuhan Ratu (Fig. 3), which is located on the inland point of a narrow bay, adjacent to the steepest continental slope and submarine canyon on the Java coast (Fig. 1). Further to the east, there is no shelf. These bathymetric
patterns can greatly modify velocities and wave heights, making predictions of tsunami hazards difficult.

4.0 TSUNAMI RISK

The disaster potential of a megathrust earthquake along the Java Trench is heightened due to the fact that Indonesia is the fourth most populated country on Earth (Internet World Stats, 2017). The SW coastal region of Java, where we know strain is accumulating, is one of the most densely populated low-lying coastal areas in Indonesia. For these reasons, we have focused our investigation of tsunami hazards along the coast of SW Java (Fig. 3).

5.0 GUIDING QUESTIONS OF THE INVESTIGATION

We investigate three main questions:

1) Is there any geological evidence preserved for megathrust earthquakes along the western Java Trench and giant tsunamis in SW Java? To address this question we investigated coastal geomorphic features and deposits along the entire length of the SW Java coast for evidence of co-seismic deformation and giant tsunamis sourced from the Java Trench.

2) How tsunami hazards caused by a megathrust earthquake on the Java Trench effect the coastline? Because no earthquake or tsunami risk assessments are published for the SW Java coastal region we use numerical modeling constrained by data collected from our paleo-tsunami deposit surveys to construct likely earthquake and tsunami scenarios for the region. These models provide a worst-case estimate of the maximum tsunami inundation expected in coastal communities along the SW Java coast.
3) Who is most at risk of tsunami hazards along the SW coast of Java? To address this question we consider the distribution of population and the access to evacuation sites at higher elevations than wave heights predicted by the models in each section of the west coast of Java.

6.0 PALEO-TSUNAMI RECORDS

6.1 Difficulty of Finding Tsunami Deposits

If the western Java trench accumulates strain as shown by recent continuously recording GPS studies (Hanifa et al., 2014), it would have produced tsunamis that likely left some trace of catastrophic changes in depositional environments. For example, in places near shore where only mud is being deposited sheets of sand with marine organisms should be found that record inundation. If these sand deposits are subsequently buried by mud and undisturbed by erosion or bioturbation, they would likely be preserved in the geological record. Previous studies of tsunami deposit preservation in the tropics show that swales between sand ridges are the most likely sites to preserve tsunami sands because they are sites of ongoing low-energy deposition (Moenecke et al., 2008).

Swale and ridge topography is found along the SW Java coast in Banten Province and Pelabuhan Ratu, and is an important system to preserve tsunami deposits. Using differential GPS measurements along lines perpendicular to the coast we constructed topographic profiles of the coastal plain showing the ridge and swale patterns (Fig. 4, 6). These profiles show up to 4 ridges and 3 swales on the Pelabuhan Ratu profiles and up to 10 ridges and swales on the Banten profiles (Fig. 5, 7). Ridge and swale topography are common along coastlines that experience multiple megathrust earthquake events (Monecke et al., 2015).
We trenched and augered 15 sites throughout these swale regions (Fig. 4, 6). Five candidate paleo-tsunami sand layers were found in the Pelabuhan Ratu bay area and two in Banten. At each sampling site, the ground had been heavily disturbed by cultivation of rice or other types of agricultural activity. It is very difficult to find any sites where tsunamis would likely be preserved that were not disturbed by cultivation, fish farming or construction. Other processes rapidly rework tsunami deposits shortly after they are deposited, such as rapid erosion during heavy monsoonal storms and bioturbation by invertebrates (Paris et al., 2014). Augering also poses difficulties due to unevenness in the distribution of tsunami deposits and problems with deformation and contamination during the augering process. One of the most diagnostic features of tsunami deposits is marine material such as diatoms, forams or shell and coral fragments. However, in tropical areas with high water tables, especially in areas cultivated for rice, many of these materials dissolve (Atwater, 2007).

6.2 Tsunami Deposit Exploration in Pelabuhan Ratu

We explored for candidate paleo-tsunami deposits at 8 (A – H) locations in Pelabuhan Ratu (Fig. 4). Auger cores were initially taken in the swale closest to the coast, which only yielded sand with shells like the present beach. In the second and third swales inland, we found mostly organic-rich mud with some inter-beded medium to fine sand layers. However, none of the sands had any identifiable marine materials. At 5 of the sites, we found candidate tsunami sand layers that we correlate as events A and B (Fig. 8), which will be described in the following paragraphs.
Location A is 400 m inland and located on a rice field of a river fluvial terrace. The top layer was disturbed by cultivation with many roots.

Location B is 160 m inland. Other characteristics are the same as the location A’s description.

Location C is 400 m inland. It is bioturbated between 0 - 0.55 m (Fig. 9a). The 2.4-2.76 m sand is a candidate tsunami sand. The grain size is around 600 µm, coarse sand. The sand layer is much thicker than other layers in column C. However, location C is about 5 m away from a stream. Sand layers repeat in the C column implying that they may have been deposited by the migration of the stream.

Location D is located in the second swale, 400 m from the shore. Between 0.6 - 1.85 m is a highly weathered clay with fine sand mixed in. Vertical fluted structures throughout the cores signify intense bioturbation. The 3.2-4 m sand is likely too thick for a tsunami deposit unless it accumulated in a channel. The 3.2-4 m sand and 4.5-5 m sand are correlated to event B and event A (Fig. 8), respectively, due to the abundant occurrence of shells. The sand grain size in the 4.5-5 m layer is 8 mm (Fig. 9c). Between the two layers, no core was recovered.

Location E is 615 m inland from the shoreline. The 4.3-5m clay (Fig. 9d) is correlated to event A owing to the depth, light color and shells, which are similar to the event A in location D. The fine grain size may indicate a more distal part of the tsunami since location E is 215 m more inland than location D. The absence of event B in column E may be due to the lack of swale conditions.

Location F is an abandoned sea cave 310 m inland. It filled with bat guano and sand. There is no shell material in the sand. The presence of the sand is difficult to explain by fluvial transport. Most of the sand layers are less than 5 cm thick. A layer of well-rounded gravel is found at 0.25 - 0.45 m depth. Nine lighter-colored sand
laminations, containing up to 50% quartz, are interlayered with 10 darker sand laminations in the trench profiles (Fig. 10). The alternating color most likely corresponds to differences in organic material from the bat guano.

Location G is 790 m from shore and is 12 m from an incised stream. Clay with coral fragments between 2 – 3.7 m depth is likely bioturbated tsunami deposits that correlate to event A or B.

Location H is 1 m thick layer of coarse, friable sand which is 370 m away from the coast.

6.3 Tsunami Deposit Exploration in Banten

We augered four cores and studied one wave cut outcrop in Banten Province, location I – M (Fig. 6, 11). Two candidate tsunami sands are found.

Location I is a wave-cut bank exposure of a coral terrace covered by 1 meter of coral debris mixed with coarse sand. The contact with the underlying coral is sharp and erosional (Fig. 12a). In the overlying debris, two layers are distinctly different in some places. The upper layer is darker due to the organic material from the overlying soil. It also is coarser in grain size and poorly sorted and contains whole shells. The lower layer mostly consists of moderately sorted broken coral fragments. No quartz are found in the debris. We regards the deposit on top of the coral terrace as event D. We sampled five of the coral fragments for radiocarbon age analysis. The samples from upper layer are collected at 5 – 60 cm below the ground; those from lower layer are collected at 75 – 95 cm below the ground (Fig. 12b). The coral fragments range in age between 663 and 1053 AD (Table 1). Because the fragments and their ages lack any systematic relationship with stratigraphic depth, it is likely they were all deposited during some high-energy event younger than 1053 AD. Differences between the upper and lower parts of the deposit may signify multiple waves associated with the
high-energy event. Whether the event was a tsunami or caused by storm waves is difficult to determine since the deposit is on the coast.

Location J is an auger site, 540 m inland from the coast. The upper part of the core shows yellow, weathered sand, but no other distinctions can be made between it and the sand down to 1 m depth, which is fine to medium grained and white. There is a well 10 m from the auger site that reaches a depth of 7 m. The well digger indicated that it showed white sand all the way to the bottom until reached some dark sand around 7 m depth. It is difficult to recognize a tsunami deposit in an environment like this without micro-sampling and detailed grain size analysis.

Location K is a trench excavated 890 m from shore in a swale that has been cultivated. From 0-2 m only light-colored sand was encountered with some charcoal. At 2 m depth, we discovered some thin layers of (0.5 cm) of cemented sand with shell fragments. These layers were also found in the banks of a nearby canal to the east (Fig. 13a). At a depth of 2.2 meters, we encountered some thin layers (1.5 cm) of angular gravel (Fig. 13b).

Location L is 920 m from shore and is essentially the same as Location K.

Location M is an auger site in a swale occupied by a rice field 1,010 m from the coast (Fig. 14). It is right on the extension of a swamp to the east (Fig. 6). We found shell fragments in medium-grained sand layers between 1.8 – 3.82 m depth (Fig. 14c), which is well correlated to the augered cores in the swamp to the west (personal communication with Eko Yulianto, Indonesian Institute of Sciences.). The sand layers with shell fragments, about 2 – 2.5 m below the water table, in the swamp cores, may be deposited from the same event as the Location M sand. The 1.8 – 3.82 m sand may have an age 10,588 BP, calculated by the sedimentation rate 0.17 mm/a in Lebak Regency (personal communication with Purna Sulastya Putra, Indonesian Institute of Sciences). Due to the sands consisting of marine materials, we consider candidates for
tsunami for a tsunami deposit and we label event C (Fig. 11).

6.4 Discussion

Five candidate tsunami deposits in Pelabuhan Ratu and two tsunami deposits in Banten are found. We correlated candidate tsunami deposits in Pelabuhan Ratu events A and B. Deposits of event A, at depths that range from 2 – 5 m in the cores, are bluish grey mud or sand, and contain noticeable shells and coral fragments. Deposits of event B are thick sand sandwiched between mud or silt layers without marine materials by visual observation. In Banten, two candidate tsunami deposits are classified as event C and D. Event C deposit is a bluish gray, thick sand layer with shell fragment, which might be correlated to event A. The coral debris overlying uplifted coral is regarded as event D.

A large tsunami event usually deposits sediments on a large scale. Tsunami deposits are expected to be well-correlated between adjacent regions on the same coastline. However, these deposition events are difficult to compare together due to lacks of control points. Age data of different events in the two places and more auger data will greatly help construct the tsunami history of Java. Outside of current study area, western Bantan could be an ideal region to discover tsunami deposits ought to less human activities. It is of the importance of seeking for other uplift terraces along Java coastal line. On top of that, sedimentary analysis and microscope observation for foraminifera are essential for better identification of tsunami deposits.

7.0 GEOMORPHOLOGY OF LOCATION I IN PANTO CAPE, BANTEN

Along the coast at Banten an uplifted coral terrace is found. The coral has an eroded upper surface overlain by a 1 meter deposit of broken coral fragments and
coarse sand. The coral was likely deposited at a depth of 3-5 meters and is now around 1 meter above sea level. The mix of coarse coral sand and coral fragments overlying the coral may represent a tsunami deposit (Fig. 12). This coral terrace is minor, and cannot be traced along the coast beyond the local site. The localized nature of the terrace may be because the coral formed on an inactive part of a nearby river delta that juts out seaward from the coast.

7.1 Orthomosaic Map

An orthomosaic and DEM map was constructed of the marine terrace (Fig. 15) at locality I (Fig. 6) using a drone. The contour shows the cape is about 2 m high and slightly tilted to the southwest.

7.2 Uplift History

The uplifted coral and age data from the deposit that overlies the terrace provide an opportunity to reconstruct the uplift history of Panto Cape over the past thousand years. We start with the depth below current sea level at which the coral likely grew, the radiocarbon age of the overlying deposit, changes in sea level, and extrapolation of the uplift rate measured nearby by continuous GPS recording. Use these estimations to test whether it likely represents a major earthquake that occurred at around the time of the youngest coral ages.

We estimate from observations offshore SW Java that most coral grows at a depth of 1.5 – 4 m below sea level. However, regional sea level 1,000 years ago was 1 – 1.5 m higher than present (Horton et al., 2005). In this case, just changes in sea level over the past 1000 years can explain coral deposits at around sea level. However, if the present rate of coastal uplift of 3.7 – 5.7 mm/a (Hanifa, et al., 2014), due to interseismic locking of Java Trench, has persisted along the Banten coast for the past
1,000 years it is highly unlikely these corals would still be near sea level (Fig. 17). One reason the coral terraces are not uplifted as much as expected could be due to periodic, co-seismic coastal subsidence from major earthquakes along the Java Trench.

Panto Cape is 200 km from the Java Trench. Areas 200 km from the Sunda Trench during the 2004 Sumatra earthquake experienced 0-2 m of co-seismic subsidence (Sieh, et al., 2015). If we assume Panto Cape subsided at least 1 m during one co-seismic event since 1053, event D, the top of the coral reef would have dropped from a depth of 1.5-4.0 m to 2.5-5.0 m. If we use a mean depth of the coral of 3.75 m below sea level after one megathrust earthquake, the coral would have experienced at least 5 meters of uplift since 1053 at an average rate of 4.8 m/ka, placing it at an elevation of 2.25 m above sea level at 1053. However, sea level is now 1-1.5 m lower than it was at 1053, which would increase its elevation above current sea level to 3.25-3.75 m. Our measurements place the top of the coral at an elevation of 1 m above current sea level, which implies that there has likely been more than one co-seismic subsidence event along the Banten coast since the year 1053.

7.3 Uncertainties and limitations

In fact, the above, estimated values still need more calibrations and measurements to be more convincing. First, the GPS uplift rate is recent measurement may not represent the behavior of Java Trench during pass 1,000 years. Second, the absence of species control for coral growth depth may lead to a higher uplift rate for a deeper growth depth. Third, the co-seismic subsidence distribution on the hanging wall along the Sumatra Trench in the 2004 Sumatra Earthquake is not perfectly homogenous. Also, the subduction behavior of Java Trench maybe unlike Sumatra Trench, which makes the subsidence amount different. Fourth, the reduced height of the terrace from tsunami(s) erosion is considered not significant to count. Finally,
more than one subsidence earthquakes after 1,053 AD would require greater uplift rate as well. Due to the absence of precise controls, we rely on reasonable estimates for these values to provide a big picture for the terrace history reconstruction.

8.0 NUMERICAL MODEL

We developed three tsunami scenarios to construct a series of numerical models for possible inundation situations that account for the candidate tsunami deposits we discovered in auger and trench studies in Labek Regency, Banten. The purpose of the modeling was to provide a framework for developing tsunami inundation maps to guide tsunami disaster mitigation efforts in coastal communities in SW Java.

8.1 Community Model Interface for Tsunami (ComMIT)

The models were constructed using the Community Model Interface for Tsunami (ComMIT), which is an Internet-enabled interface around the National Oceanic and Atmospheric Administration’s (NOAA) Method Of Splitting Tsunamis (MOST) tsunami model (Titov et al., 2011). It uses initial conditions from a pre-computed propagation database of tsunami evolution from unit earthquakes. This database consists of 100 km * 50 km fault planes, called unit sources, along all ocean subduction zones of the world in several rows. Like MOST, ComMIT’s linearity of tsunami propagation in open oceans provides initial and boundary conditions for site-specific, high-resolution, non-linear inundation forecast models. The models comprise three grids containing progressively higher resolution bathymetry, topography, tsunami dynamics and inundation of dry land.

The bathymetry used in ComMIT is drawn from ETOPO1, which is a one arc-minute gridded global relief model produced by the NOAA National Geophysical Data
Center, and has been interpolated from 60 arc seconds to 3 arc seconds (ComMIT Manual 1.7.6). Onshore topography is from the CGIAR SRTM 90 m version 4 digital elevation model, that is produced by the CGIAR Consortium for Spatial Information. It is a 3 arc second database.

This program is an ideal modeling tool for areas with poor bathymetric and topographic control, like Indonesia. A ‘community’ model is a non-commercial model freely available with source code and documentation. ComMIT was originally developed for Indian Ocean countries and is designed for ease of use with the easy-to-interpret graphical interface. It allows nations without the resources to build their own code to develop tsunami modeling capability for predictive studies and tsunami hazards risk assessment. We use the comMIT resource so that our models can be incorporated into the current modeling efforts conducted by the Indonesian Geophysical Survey (BMKG). ComMIT runs on portable hardware and can be installed on various operating systems, like Linux, Mac, and Windows.

8.2 Numerical Domain

The computational domain we modeled extends from longitude 102.3 W to 109.5 W and latitude 4.7 S to 9.9 S. The longitude and latitude spacing of each computing grid is 120 arcs, 25 arcs, and 3 arcs, respectively. Model parameters are set as default where the minimum amplitude of input offshore waves is 0.0050 m, the minimum depth of offshore is basically 1.0 m, dry land depth of inundation is 0.1 m, and the friction coefficient (square of Manning’s roughness coefficient) is 0.0006. Every unit source presents the footwall of the deformed subduction zone which has equal area and rake, but differs in the strike, dip, and depth. Slip amount is manually adjustable, by which the program generates a total magnitude value automatically.
8.3 Model Scenarios

Three different scenario tsunamis were constructed based on comparisons with slip amounts and distributions of 1) the nearby 2004 Sumatra megathrust event, 2) a theoretical megathrust event on the western Java Trench and 3) the 2011 Japan megathrust earthquake.

8.31 Scenario Tsunami 1: 2004 Sumatra megathrust earthquake

We use this scenario because it is well-documented and occurs on the same subduction interface as the Java Trench. Some conditions that differ between the Sumatra and Java segments of the Sunda Subduction Zone are that a thicker package of sediment is being subducted, the convergence rate is lower and the convergence direction is oblique in Sumatra. We use the slip distribution constructed for NOAA’s 2004 Sumatra tsunami model (Titov et al. 2016). The highest slip is 21 meters at the hypocenter, which is located on the southern part of the seismic gap (Fig. 18). We use a rupture zone length of 1000 km based on possible segment boundaries at Enggano Island on the west and subducted seamounts of the Roo Rise to the east. The computed magnitude of the scenario tsunami is Mw 9.3. The unit source parameters are shown in Table 2. The modeling results are presented in Table 4. The maximum tsunami flow depth and amplitude are at a river mouth at 7.5112 S, 107.4592 E.

8.32 Scenario Tsunami 2: Theoretical slip amount and pattern based on potential slip

Using the GPS convergence rate of 69 mm/a between Christmas Island (Australian Plate) and Java Island (Hanifa et al., 2014) as a proxy for a strain accumulation rate along the Java Trench near SW Java, we estimate that around 30 m of potential slip has accumulated since the time historical records have been kept (430 years). Due to the fact that the actual slip distribution is not knowable for the Java...
Trench, we use a hypocenter-independent model and assign the maximum slip of 30 m along the entire 1,000 km length of the fault plane so as to not bias tsunami run-up heights at one part of the fault zone.

8.33 Scenario Tsunami 3: Slip amount and distribution of 2011 Japan Earthquake on Java Trench

Many similarities exist between the Japan and Java Trenches. For example, both are relatively starved of incoming sediment on the down-going plate. In addition, the subducting plate is old and carries seamounts into the subduction zone. The main difference is that Java has a well-developed accretionary prism and forearc basin unlike the Japan Trench.

Japan’s 2011 earthquake is the world’s best recorded megathrust earthquake. Data from a high-density array of sensors are available including ocean bottom seismometers. Lacking any constraints from previous megathrust events along the Java Trench we use the well-constrained fault plane parameters from the 2011 Japan megathrust earthquake as a proxy for what may happen during a Java Trench megathrust event. The distribution of unit sources is given in Figure 18 and fault plane parameters in Table 3.

The rupture length is 500-km and depth 15.4 - 46.58 km. These parameters produce an earthquake of Mw 8.9. In the model for the Java Trench we place the epicenter due south of Pelabuhan Ratu Bay. We also use the Japan model (Titov et al., 2016) for the amount and distribution of slip on the Java Trench earthquake, with 21 meters slip at the hypocenter (Fig. 18). We consider this position of the epicenter a worst cases scenario for high-populated Pelabuhan Ratu. The results of the Java Trench model indicate that a coast with a shallower and broader continental shelf, like Pandeglang Regency (Fig. 1, 3), has higher maximum wave amplitudes and flow depth.
on shore than the deep canyon coastline adjacent to Pelabuhan Ratu. A shallow continental shelf condition is more critical than the distance from the seismic source. For example, the Sukabumi Regency coast is impacted less than Pandeglang Regency. The modeling results are in Table 5.

8.4 Reconstructing a Paleo-Earthquake Based on Field Deposits

Various earthquake magnitudes and slip amounts are tested in the numerical modeling to estimate the minimum size of an earthquake necessary to produce a tsunami large enough to reach the sites where candidate paleo-tsunami deposits are found, such as location M (Fig. 6). The model we use for experimentation is scenario 2 above, with a rupture length of 1,000 km and equal distribution of slip at the depth of the hypocenter for the entire fault plane. After gradually increasing slip by 1 m increments, the results that best fit the observations require an earthquake of Mw 9.4 with 22 m slip. The model tsunami arrived at the swamp of location M in 31 minutes after the rupture with 2.8 m flow depth and 11.5 m wave amplitude (Fig. 28).

9.0 EVACUATION ESTIMATION

9.1 General Evacuation Concept

After the tragedy of the 2004 Sumatra megathrust earthquake, Indonesia invested in a tsunami early warning system. The system was designed to detect an approaching tsunami wave and send information of its height in the open ocean via satellite to BMKG (Meteorological, Climatological and Geophysical Agency of Indonesia, Jakarta). BMKG processes these data and uses them to provide the first warning to local emergency management agencies. Theoretically, this process takes 5-7 min after the wave is detected.
A second warning is sent to confirm or cancel the first depending upon what other data are available. This warning can be released within 10-30 min. The third warning is issued after the coastal observation of a tsunami, and can be issued between 30-60 minutes. However, there have been 6 tsunamis since the buoys were deployed and no warning has reached the coastal communities affected by the tsunamis until after the tsunami arrived (Lauterjung et al., 2010). The major problem is that the Sunda and Java Trenches where most tsunamis are generated, are within 200 km of the coastline. This proximity leaves very little time for those in harm’s way to respond. Furthermore, transmitting the warnings requires a working power grid, which is likely to be compromised by the earthquake associated with the tsunami, as in the Sumatra 2004 and Japan 2011 events.

Therefore, we have developed a simple communication tool for helping coastal communities to recognize the signs that a tsunami may be approaching and how to respond. We call it the “20/20/20 principle.” The 20/20/20 principle communicates that if earthquake shakes for more than 20 seconds, people have 20 minutes to evacuate to places higher than 20 m before a tsunami arrives. Most of our models have tsunami arrival times of close to 20 minutes and achieve wave heights of 20 meters in many places.

9.2 Local Evacuation Based on Numerical Modeling

Before the 20/20/20 principle can be applied at the local level, tsunami inundation maps must be available that identify who is most at risk and where to evacuate. We use tsunami inundation output from worst case scenario numerical models with 30 m of slip (scenario 3).

For total evacuation time (Te), we use the time it takes for a positive tsunami wave to travel from its source to the coastal line (Tw), and the practical preparation time
(Tp). Thus, T_e is the time for coastal inhabitants to evacuate before being hit by a tsunami wave.

The wave travel time (Tw) estimates the time for the first wave of a tsunami from generating to inundating 1 m high on land. A 1-m height wave can actually prevent people from traveling or evacuating. The inundation models show that inhabitants who live further from the coast may have up to 5 minutes more to evacuate. Coastal geometry is taken into account where less time is available in areas with a broad, low coastal plain, and more time is available along hilly coastlines.

The practical preparation time (Tp) is dependent upon many factors, such as waiting for the shaking to stop, preparing to evacuate and the time to travel to a safe site. People will not be able to move during the earthquake due to intense shaking. Shaking from the 2004 Sumatra earthquake (Mw 9.3) and the 2011 Japan earthquake (Mw 9.0) lasted for 3 to 7 minutes depending on site characteristics. We use 5 minutes for the shaking evacuation delay.

After the shaking stops, we estimate that most people will roughly take 5 minutes to start the evacuation, which includes the time necessary to evacuate a damaged building, helping others, finding essential personal effects and so on. The shaking and start delays shorten the evacuation time at any place by at least 10 minutes. Depending on the travel time of the approaching tsunami this 10 minutes may make evacuation nearly impossible for inhabitants living on a large, flat coastal plain.

For the evacuation distance (De), we use the shortest, straight distance that people can travel with a speed (Vt) of a brisk walk, which is around 107 meters/minute or 4 mph (Wikipedia: en.wikipedia.org/wiki/Walking) within the total evacuation time (Te). We do not use a running speed due to delays likely caused by crowds, traffic jams, obstacles, slopes, and circuitous routes. We assume using motorized vehicles will slow the evacuation due to traffic. In highly populated areas (> 60 people per 0.01
km²), such as red areas in Pangandaran and Pelabuhan Ratu (Fig. 3), we half the brisk walk speed (53.5 m/min, 2 mph) to account for increased crowds and obstacles.

To summarize:

$$Te = Tw – Tp,$$
where $Tp = 10$ mins.

$$De = Te \times Vt,$$
where $Vt = 107$ m/min.

If $Te$ is negative, it is nearly impossible for the coastal community to reach a safe place when a tsunami generated. They are too close to Java Trench. If $Te$ is positive, inhabitants close to high hills or away from shoreline have more chances to reach a safe site before the tsunami arrives, as long as they act immediately - with preparation times and evacuation times close to those we estimate.

Wave arrival times at the coast ($Tw$) and practical evacuating times ($Tp$) for the coastal communities that we have evaluated are provided in Table 5. Residents of Pangarangan, Bayah, Ciwaru, Ujung Genten, east Sukabumi, Cianjur, west Garut, and Pameungpeuk have a $Tw$ of around 15 minutes due to the deeper bathymetry immediately offshore, which allows for the tsunami waves to travel faster, and/or longer distance from Java Trench. The communities at greatest risk, based on the number of people inhabiting the death zone, are Ujung Genten, east Sukabumi, Cianjur, west Garut, and Pameungpeuk.

The death zones are where coastal inhabitants in inundation zone are too far away from an evacuation site (Fig. 24). The evaluation of the death zones considers the evacuation distance of 1) the brisk walk speed for less populated areas, 2) the half walk speed for highly populated areas, and 3) the extra 5 min evacuation time that inhabitants away from coastline have before waves arrive. Besides, the suitability of an evacuation site is also taken into account assuming a capacity of 3 people per square
meter (Still, 2017), in which all of the evacuation sites are able to accommodate surrounding refugees.

The death zones require additional resources for constructing evacuation sites within the community. We are encouraged by the construction of one of these facilities in Pangandaran. Our models show that without this facility, most of the inhabitants in this large coastal community would reside in the death zone. The 2006 tsunami that struck Pangandaran claimed hundreds of lives with modest run-up heights (5 m).

9.3 Evacuation Plans and Suggestions

Based on the results of our tsunami hazards risk assessment, we have started a training program in community-based risk reduction with local disaster mitigation agencies for most of the major coastal communities in West Java. The training program involves best practices in effectively communicating risk through questionnaire surveys, presentations and other community-driven activities, and evacuation drills. The results of the surveys we conducted in Pelabuhan Ratu and Pangandaran show participants in the Pelabuhan Ratu had a lower perceived risk of a tsunami than those in Pangandaran, which is not surprising considering Pangandaran experienced a tsunami in 2006. However, the majority of participants at both locations do not distinguish between length and severity of shaking. The earthquake in 2006 was hardly felt even though it shook for more than 30 seconds. More people in Pangandaran have participated in evacuation simulations than Pelabuhan Ratu, but most of Pangandaran participants did not remember the evacuation principles. The results show that evacuation drills helped participants know where to evacuate, but not under what circumstances. The results suggest the need for a simple guiding principle, such as 20-20-20 to help participants 1) make the connection between the
length of time an earthquake shakes, 2) the amount of time they have to evacuate and to where they need to evacuate.

For communities with negative Te scores, where it is nearly impossible to evacuate before a tsunami arrives, we suggest the following: 1) where practical, move villages inland or to a higher location. However, this mitigation strategy is the least likely to be enforced or to sustain. 2) Erect natural barriers between the coast and where residents live using mangrove, palm or casuarina tree groves that will significantly slow the wave as it makes landfall. These types of barriers have proven effective in many coastal communities (Alongi, 2008; Tanaka, 2009). 3) construct evacuation shelters in the most populated areas and the death zones, which has already been accomplished in Parangdaran. For communities in the death zones, suggestions 2 and 3 should be applied as well. The only places where Indonesia has constructed evacuation shelters are in areas frequented by tourists, such as Pangandaran. Few tourists travel to Pelabuhan Ratu or most other populated coastal cities facing the Java Trench, and none of these areas have evacuation shelters.

10.0 CONCLUSIONS

The west Java Trench may have accumulated up to 30 m of potential slip, which is enough to generate a megathrust earthquake and giant tsunami. Coupling along the trench is manifest by uplift of coastal terraces and other geomorphic features. In our search for giant tsunamis that may have struck the coastline of West Java in the past, we found 5 candidate tsunami deposits in Pelabuhan Ratu and 2 in Banten. Candidate Tsunami deposits in Pelabuhan Ratu are correlated to events A and B. Deposits of event A contain obvious marine materials such as shells and coral fragments at depths that range from 2 – 5 m in the cores. In Banten, the outcrop of an uplifted terrace
exposes a chaotic deposit of coral debris overlying uplifted coral. The age of the coral fragments varies with the youngest at around 1053 AD, which is a maximum age for an earthquake that may have generated a tsunami that deposited the coral. This earthquake would correlate with event D. If the earthquake was along the Java Trench, it could have caused considerable co-seismic coastal subsidence. However, at the high uplift rates measured along the western Java coastline, more than one co-seismic earthquake event may be required to account for the present elevation of the uplifted coral terrace. Another candidate tsunami deposit in Banten is correlated to event C and consists of coarse sand and shell fragments.

Three different numerical models of Java Trench earthquake scenarios were used to account for where the candidate tsunami deposits were found. The severest modeling scenario is 30 m of slip on the whole 1,000 km seismic gap, which generates an earthquake of Mw 9.5. The tsunami it produces will likely trap nearly half a million residents that live too far from a suitable evacuation site to avoid the tsunami. Our education efforts can help those who inhabit areas where there is enough time to escape to high ground before a tsunami arrives. However, in the areas too far from high ground for coastal inhabitants to escape, more resources are needed to slow the wave, such as tree barriers or the construction of tsunami evacuation shelters.
11.0 REFERENCES


Internet World Stats, 2017. World Population.


Figure 1. Tectonic setting of Java (modified from Google Earth). Coasts of Banten Province and West Java Province are the focus study areas. Yellow dots show Mw > 7.0 earthquakes since 1900 (USGS, n.d.). Most of the earthquakes (those further from inland from the Java Trench) were too deep to rupture the surface and cause a tsunami or much damage. The West Java seismic gap is at least 1000 km in length, and is defined as the distance between possible segment boundaries identified from Enggano Island and subducting sea mounts in East Java. The white boxes are index map of figure 15.

Figure 2. Contours of displacement velocity estimated from slip rate motion of active faults (modified from Meilano et al., 2014). Red arrows are the convergence vectors of the Australian Plate with respect to the Sunda Plate. The arrow east of Java is about 75 mm/a. Notice the slip deficit along the entire length of the Java Trench. The internal shortening across Java is less than 10 mm/a. Deformation is 2-3 times large than in Java, the central of Sunda Trench, to the west due to the motion of Sumatra strike-slip fault zone, and to the east due to strike-slip motion along the eastern boundary of the Sunda Plate.
Figure 3. Population density of the flow depth area of 30-m scenario of inundation modeling in each regency of Banten and West Java Provinces (Fig. 1.) The density above 60 people/0.01 km$^2$ (red) is considered as highly populated. The boxes (a)-(i) are the focus areas of estimating evacuating times in Figure 24 and Table 5.

Figure 4. Augering and trenching locations in Pelabuhan Ratu. The xx’ profile line gives the locations shown in Figure 8. The yellow profile #1 and #2 lines of GPS measurements are shown in Figure 5, which are 300 m and 400 m inland, respectively.
Figure 5. GPS elevation measurements of the profile #1 and #2 in Figure 4, showing ridges (R) and swales (S) from the high tide level (0.5 m above sea level). Ridge 1 is well correlated in two profiles.

Figure 6. Augering and trenching locations, the red profile lines yy’, and the yellow GPS measurement profile lines of Banten. Profile #3 and #4 is 300 m and 800 m inland, respectively. The white box shows the location of figure 15.

Figure 7. GPS elevation measurements of the profile #3 and #4 in Figure 6, showing ridges (R) and swales (S) from the high tide level (0.5 m above sea level). Ridge 1, 2, 5 and swale 1,2 are correlated in two profiles.
Figure 8. Stratigraphic cross section of line xx’ in Figure 4. Deposits of event A, at 2–5 m depths, are bluish grey mud or sand, and contain noticeable shells and coral fragments. Deposits of event B are thick sand sandwiched between mud or silt layers without marine materials by visual observation.
Figure 9. Augered core samples from location C – D (Fig. 4.) (a) Bioturbation in mud in location C. (b) Organic mud in location C. (c) Organic sand with shell fragments in location D. (d) Blue clay with shell fragments in location E. (c) and (d) are tsunami candidates for proposed Event A.

Figure 10. Trench profiles for Location F (Fig 4.) The red and white sections on the measuring stick indicate 10 cm.
Figure 11. Stratigraphic cross section of line yy’ in Figure 6. Vertical scale in meters. Event C deposit is a bluish gray, thick sand layer with shell fragment, which might be correlated to event A. Event C may age 10,588 BP with a sedimentation rate 0.17 mm/a in Lebak Regency (personal communication with Purna Sulastya Putra, Indonesian Institute of Sciences.) The coral debris overlying uplifted coral is regarded as event D.
Figure 12. Outcrop of location I (Fig. 6). (a) two distinctive layers in the debris formation, tsunami deposit, on top of the coral reef with a sharp contrast. (b) Radiocarbon dating sampling sites.
Figure 13. Augered core samples from location K (Fig. 6.) At 2 m depth, are thin (0.5 cm) layers of indurated sand with shell fragments. At a depth of 2.2 m we encountered some thin layers (1.5 cm) of angular gravel.

Figure 14. Augered core samples from location M (Fig. 6.) (a) (b) Silt. (c) Shell fragments in medium-grained sand layers between 1.8 – 3.82 m depth.
Figure 15. Contour map of the marine terrace at SE Panto Cape (Fig. 6.) The blue star specifies Location I (Fig. 6). The elevation contours are 0.5 (black), 1.5 (yellow), and 2.5 (brown) meters.

Figure 16. The profiles for lines shown in Figure 15 of the Panto Cape terrace.
Figure 17. Change elevation of the coral reef terrace at Panto Cape, or location I, from 1053 (event D) to the present.

Figure 18. Unit sources, or grids, for tsunami scenarios. Each unit is a grid that is 100 km * 50 km. The numbers on each grid are for reference. Unit sources used for the 2004 Sumatra earthquake (scenario 1) and theoretical slip (scenario 2) and paleo-earthquake reconstruction model (Ch 8.6) are in red and for 2011 Japan earthquake (scenario 3) in yellow dash line area. See slip for each unit source for the two earthquake scenarios on Table 2 and 3.
Figure 19. Max wave amplitude for the scenario 1 modeling. Each of the dots labeled A-K represent positions of simulated tidal gauges shown below. The dark line shows the coastline. The star indicates the maximum amplitude location on land.
Figure 20. Time series of tsunami wave amplitude for the scenario 1 modeling. The locations of each simulated tidal gauge is shown in Fig. 19.
Figure 21. Max flow depth for the scenario 1 modeling. The star shows the location of maximum flow depth.
Figure 22. Maximum wave amplitude for the scenario 2 modeling. Each of the dots labeled A-K represent positions of simulated tidal gauges shown below. The dark line shows the coastline. The star indicates the maximum amplitude location on land.
Figure 23. Time series of tsunami wave amplitude for the scenario 2 modeling. The locations of each simulated tidal gauge is shown in Fig. 22.
Figure 24. Maximum flow depth for the scenario 2 modeling. Each area (a) – (i) corresponds to Figure 3 (a) – (i) boxes and Table 5. The death zones are the areas where inhabitant may not have enough time to evacuate from the tsunami wave. The star in (h) shows the location of maximum flow depth.
Figure 25. Max wave amplitude for the scenario 3 modeling. The star indicates the max amplitude location on land. The dark line shows the coastline.
Figure 26. Time series of tsunami wave amplitude for the scenario 3 modeling.
Figure 27. Maximum flow depth for the scenario 3 modeling. The star shows the location of maximum flow depth.
Figure 28. Maximum flow depth of a simulated tsunami produced by 22-m slip on the 1,000 km seismic gap section of the western Java Trench. The swamp at location M, with the candidate tsunami sand layers is in the blue box.
Table 1. C13 Radiocarbon dating, Panto Cape, Banten Province. Sorted by calibrated ages. The samples from upper layer are collected at 5 – 60 cm below the ground; those from lower layer are collected at 75 – 95 cm below the ground.

<table>
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<th>Layer</th>
<th>Lab ID</th>
<th>Sample ID</th>
<th>d^13C corrected Age (BP)</th>
<th>Calibrated Age (AD)</th>
<th>Calibrated 95% Confident Interval (AD)</th>
<th>Material</th>
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<td>UVU Km1b-1</td>
<td>1425 ± 22 BP</td>
<td>1053 AD</td>
<td>990 - 1153 AD</td>
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<td>Upper</td>
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<td>991 AD</td>
<td>908 - 1050 AD</td>
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<td>Lower</td>
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<td>UVU Km1a-3</td>
<td>1493 ± 22 BP</td>
<td>989 AD</td>
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<td>coral</td>
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</table>

*Calibration weighted mean ΔR= 76, standard deviation = 20
*The analysis is performed at the Center for Applied Isotope Studies of The University of Georgia. Radiocarbon dates calibrated using CALIB program, shell and corals corrected for the marine reservoir.
Table 2. Parameters of the fault unit source for the 2004 Sumatra scenario (scenario 1). The theoretical slip scenario (scenario 2) and paleo-earthquake reconstruction model (Ch 8.6) are also use the same unit source but with different slip amount. Each fault plane is 100 km in length and 50 km in width, and matches to the numbering shown in Figure 18. The location of each fault plane is at the center of the subsidence side of each rectangular.

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<th>Rake (deg)</th>
<th>Strike (deg)</th>
<th>Depth (km)</th>
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<td>36.19</td>
<td>10.9</td>
</tr>
<tr>
<td>17</td>
<td>(-8.048, 106.6421)</td>
<td>12</td>
<td>90</td>
<td>305.4</td>
<td>25.79</td>
<td>10.9</td>
</tr>
<tr>
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<td>(-8.4061, 106.3845)</td>
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<td>305.4</td>
<td>15.4</td>
<td>10.9</td>
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<td>296.87</td>
<td>36.19</td>
<td>10.9</td>
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<td>296.87</td>
<td>25.79</td>
<td>10.9</td>
</tr>
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<td>90</td>
<td>296.87</td>
<td>15.4</td>
<td>10.9</td>
</tr>
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<td>90</td>
<td>289.34</td>
<td>36.19</td>
<td>10.9</td>
</tr>
<tr>
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<td>(-8.6916, 107.9223)</td>
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<td>90</td>
<td>289.34</td>
<td>25.79</td>
<td>10.9</td>
</tr>
<tr>
<td>24</td>
<td>(-9.1062, 107.7745)</td>
<td>12</td>
<td>90</td>
<td>289.34</td>
<td>15.4</td>
<td>10.9</td>
</tr>
<tr>
<td>25</td>
<td>(-8.4763, 108.7623)</td>
<td>12</td>
<td>90</td>
<td>283.23</td>
<td>36.19</td>
<td>21</td>
</tr>
<tr>
<td>26</td>
<td>(-8.9039, 108.6608)</td>
<td>12</td>
<td>90</td>
<td>283.23</td>
<td>25.79</td>
<td>21</td>
</tr>
<tr>
<td>27</td>
<td>(-9.3316, 108.5585)</td>
<td>12</td>
<td>90</td>
<td>283.23</td>
<td>15.4</td>
<td>21</td>
</tr>
<tr>
<td>28</td>
<td>(-8.5653, 109.3704)</td>
<td>12</td>
<td>90</td>
<td>273.71</td>
<td>36.19</td>
<td>21</td>
</tr>
<tr>
<td>29</td>
<td>(-9.0038, 109.3416)</td>
<td>12</td>
<td>90</td>
<td>273.71</td>
<td>25.79</td>
<td>21</td>
</tr>
<tr>
<td>30</td>
<td>(-9.4422, 109.3121)</td>
<td>12</td>
<td>90</td>
<td>273.71</td>
<td>15.4</td>
<td>21</td>
</tr>
</tbody>
</table>
Table 3. Parameters of the fault unit source for the 2011 Japan scenario. Each fault plane is 100 km in length and 50 km in width, and matches to the numbering shown in figure 18. The location of each fault plane is at the center of the subsidence side of each rectangular.

<table>
<thead>
<tr>
<th>Unit Source</th>
<th>Location (Lat, Lon)</th>
<th>Dip(deg)</th>
<th>Rake(deg)</th>
<th>Strike(deg)</th>
<th>Depth(km)</th>
<th>Slip (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>(-6.1857, 103.418)</td>
<td>12</td>
<td>90</td>
<td>300.22</td>
<td>25.7912</td>
<td>9.54</td>
</tr>
<tr>
<td>7</td>
<td>(-6.1731, 104.3297)</td>
<td>12</td>
<td>90</td>
<td>296.31</td>
<td>36.19</td>
<td>4.14</td>
</tr>
<tr>
<td>10</td>
<td>(-6.5941, 105.1682)</td>
<td>12</td>
<td>90</td>
<td>297.5</td>
<td>36.19</td>
<td>12.43</td>
</tr>
<tr>
<td>11</td>
<td>(-6.9838, 104.9639)</td>
<td>12</td>
<td>90</td>
<td>297.5</td>
<td>25.79</td>
<td>17.01</td>
</tr>
<tr>
<td>13</td>
<td>(-6.7936, 106.3703)</td>
<td>12</td>
<td>90</td>
<td>304.18</td>
<td>46.58</td>
<td>17.5</td>
</tr>
<tr>
<td>14</td>
<td>(-7.157, 106.1216)</td>
<td>12</td>
<td>90</td>
<td>304.18</td>
<td>36.19</td>
<td>20.99</td>
</tr>
<tr>
<td>15</td>
<td>(-7.5205, 105.8727)</td>
<td>12</td>
<td>90</td>
<td>304.18</td>
<td>25.79</td>
<td>27.39</td>
</tr>
<tr>
<td>16</td>
<td>(-7.8839, 105.6233)</td>
<td>12</td>
<td>90</td>
<td>304.18</td>
<td>15.4</td>
<td>0.48</td>
</tr>
<tr>
<td>18</td>
<td>(-8.048, 106.6421)</td>
<td>12</td>
<td>90</td>
<td>305.4</td>
<td>25.79</td>
<td>6.31</td>
</tr>
<tr>
<td>19</td>
<td>(-8.4061, 106.3845)</td>
<td>12</td>
<td>90</td>
<td>305.4</td>
<td>15.4</td>
<td>1.91</td>
</tr>
</tbody>
</table>
Table 4. Summary of the tsunami modeling results. The population distribution in the inundation zone of theoretical 30-m slip scenario shown in Figure 3.

<table>
<thead>
<tr>
<th>Model (Scenario #)</th>
<th>Moment Magnitude (Mw)</th>
<th>Max Flow Depth (m)</th>
<th>Location of Max Flow Depth</th>
<th>Max Wave Amplitude (m)</th>
<th>Location of Max Wave Amplitude</th>
<th>Total Inundation Area (km²)</th>
<th>Total Pop in Inundation Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Sumatra (1)</td>
<td>9.3</td>
<td>44.85</td>
<td>7.5112 S, 107.4592 E in west Garut</td>
<td>47.78</td>
<td>7.5112 S, 107.4592 E in west Garut</td>
<td>223.2</td>
<td>182,400</td>
</tr>
<tr>
<td>Theoretical Slip (2)</td>
<td>9.5</td>
<td>61.53</td>
<td>7.5396 S, 107.5125 E in west Garut</td>
<td>67.07</td>
<td>7.5604 S, 107.5667 E in west Garut</td>
<td>642.7</td>
<td>443,365</td>
</tr>
<tr>
<td>2011 Japan (3)</td>
<td>8.9</td>
<td>22.44</td>
<td>6.8514 S, 105.5974 E in Pandeglang</td>
<td>30.8</td>
<td>6.8397 S, 105.6108 E in Pandeglang</td>
<td>99.0</td>
<td>77,776</td>
</tr>
</tbody>
</table>

Table 5. Evaluation of evacuating situation in the focus regions. Sort by population in death zone. The population data is 2015 Indonesia census 100-m distribution from “World Pop” (www.worldpop.org.uk).

<table>
<thead>
<tr>
<th>Region</th>
<th>Figure 24</th>
<th>Total Pop¹</th>
<th>Tw (min)²</th>
<th>Te (min)³</th>
<th>De (m)⁴</th>
<th>Pop in Death Zone⁵</th>
<th>Death (%)⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Sukabumi, Cianjur &amp; West Garut</td>
<td>(h)</td>
<td>73,556</td>
<td>12</td>
<td>2</td>
<td>214</td>
<td>37,621</td>
<td>51.1%</td>
</tr>
<tr>
<td>Pameungpeuk</td>
<td>(d)</td>
<td>63,348</td>
<td>13</td>
<td>3</td>
<td>321</td>
<td>36,480</td>
<td>57.6%</td>
</tr>
<tr>
<td>Ujung Genteng</td>
<td>(c)</td>
<td>10,671</td>
<td>9</td>
<td>-1</td>
<td>0</td>
<td>7,944</td>
<td>74.4%</td>
</tr>
<tr>
<td>Tasikmalaya</td>
<td>(i)</td>
<td>35,368</td>
<td>20</td>
<td>10</td>
<td>1,070</td>
<td>4,842</td>
<td>13.7%</td>
</tr>
<tr>
<td>West Pangandaran</td>
<td>(g)</td>
<td>80,676</td>
<td>37</td>
<td>27</td>
<td>2,889</td>
<td>4,622</td>
<td>5.7%</td>
</tr>
<tr>
<td>Pelabuhan Ratu Bay</td>
<td>(e)</td>
<td>54,295</td>
<td>21</td>
<td>11</td>
<td>1,177</td>
<td>3,686</td>
<td>6.8%</td>
</tr>
<tr>
<td>Panggarangan &amp; Bayah</td>
<td>(f)</td>
<td>19,450</td>
<td>15</td>
<td>5</td>
<td>535</td>
<td>3,662</td>
<td>18.8%</td>
</tr>
<tr>
<td>Ciwaru</td>
<td>(f)</td>
<td>18,245</td>
<td>14</td>
<td>4</td>
<td>428</td>
<td>3,635</td>
<td>19.9%</td>
</tr>
<tr>
<td>Pandeglang &amp; Lebak</td>
<td>(a)</td>
<td>30,742</td>
<td>20</td>
<td>10</td>
<td>1,070</td>
<td>1,942</td>
<td>6.3%</td>
</tr>
<tr>
<td>Panto Cape</td>
<td>(a)</td>
<td>7,062</td>
<td>17</td>
<td>7</td>
<td>749</td>
<td>423</td>
<td>6.0%</td>
</tr>
<tr>
<td>Eest Pangandaran</td>
<td>(g)</td>
<td>57,805</td>
<td>40</td>
<td>30</td>
<td>3,210</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>451,218</strong></td>
<td></td>
<td><strong>104,857</strong></td>
<td></td>
<td></td>
<td><strong>23.2%</strong></td>
<td></td>
</tr>
</tbody>
</table>

1 Total population in inundation zones  
2 Coastal arrival time of 1-m height of the first tsunami wave  
3 Coastal arrival time minus 10 minutes (Tp)  
4 Evacuation distance for Te timing brisk walk speed (107 m/min, Vt)  
5 Inhabitants who cannot evacuate in time in inundation zones The evaluation of the death zones considers the evacuation distance of 1) the brisk walk speed for less populated areas, 2) the half walk speed for highly populated areas, and 3) the extra 5 min evacuation time that inhabitants away from coastline have before waves arrive.  
6 Death percentage of total population in inundation zones