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Research paper

Review of Year 2004 Sumatra-Andaman Earthquake Tsunami Fault Parameters

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Abstract

This paper reviews the fault parameters used in the literatures of tsunami source simulations for the 26 December, 2004 Sumatra–Andaman tsunami, as well as understanding of the geology and geography of the Sunda Trench. Although the source of tsunami generation is exclusive, the parameters used in the simulations differ according to source of data, method of parameter derivation and modeling experiences. Hence, identification of possible future source generations and results for best fit parameters obtained from literature review are integrated to be used for future simulations. Based on the literature review conducted, it is clear that the parameters of tsunami source generation play a vital component and indication in amplifying effects in the coastal areas. Hence, earlier identification of possible fault rupture parameters in the Andaman Sea provides an information about the effects of the future risks of tsunami towards the west-coast of Malaysia.

Keywords: *Fault parameters; 2004 Sumatra – Andaman tsunami, Sunda Trench, source simulations*

1. Introduction

It was more than a decade ago that the megathrust year 2004 Andaman tsunami shocked the entire world with its devastating aftermath effects. The deadly tsunami killed more than 250 000 people with 68 of it were in Malaysia. The source of subduction megathrust rupture for Sumatra–Andaman earthquake was identified to be in the Andaman part of the Sunda Trench, where the Bay of Bengal is located [1]. Subduction zone of the earthquake in the Sunda Trench is where the India Plate is subducted by the Burma Plate. The trench of 1300 km long covers the south end of Sumatra and north of the Andaman. Based on data from GPS stations of Southeast Asia [2], the vast coverage of the event can be proven when co-seismic readings from 5 to 10 mm are clearly detected as far as 3000 km from the epicenter such in Kunming (China), Bangalore (India) and Sabah (East Malaysia). Sumatra-Andaman region is prone to seismic activities due to its location. It has experienced several earthquake events; from impactful to less. Historical data support the claim that greater earthquakes are reported to occur along the Sumatran section of Sunda subduction zone in 1797 (M_w = 8.4), 1833 (M_w = 9) and 1861 (M_w = 8.5) [3, 4]. Nicobar and Andaman Islands in the northern part have also experienced earthquake-generated tsunamis in 1881 (M_w = 7.9) and in 1941 (M_w = 7.7). Based on past literature reviews [3, 5], however, no historical records of past occurrences are comparable to the year 2004 event located in the Bay of Bengal.

The convergence rate of the plates along the Sunda Trench differs with the age of the lithosphere. On the northern part of year 2004 epicenter, where Nicobar and Andaman Islands are located, the convergence of old lithosphere is moderate [6]. The convergence rate in this region is about 14 mm/year, which can be considered as moderate, compared to 40 to 50 mm/year at the rate of convergence near epicenter of northern Sumatra [3]. Rate at both ends of year 2004 rupture epicenter agreed well with the empirical correlation between properties of megathrust earthquake and corresponding subduction zones. This relationship can be manifested as the maximum earthquake magnitude increases linearly with convergence rate and decreases linearly with the subduction plate age [6]. This relationship explains the historical records, where Sumatran region experiences more devastating earthquakes since the past hundreds of years as compared to the region of Nicobar and Andaman Islands. Just after the earthquake in December 2004, another earthquake at Mw 8.7 occurred further south of Sumatra trench, where the epicenter is located between simile and mainland of Sumatra. This is believed to be caused by inflicting stresses on the adjacent partly ruptured segment of the previous quake. This can be further justified due to stress instantaneous transfer (Coulomb stress failure) or delayed in time [2]. Fig. 1 depicts the historical earthquake occurences along Sumatra-Andaman trench with convergence rate of individual plates.

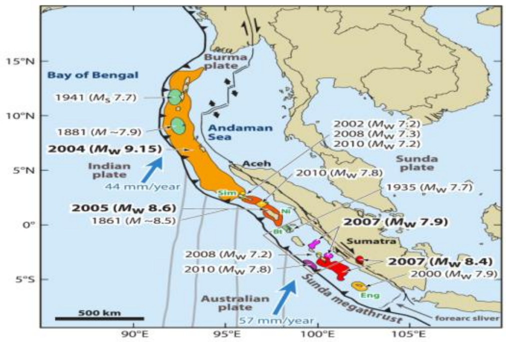

Fig. 1: Historical ruptures along Sumatra-Andaman trench and convergence rate of plates [7].

Considering the future risks of tsunami originating from Andaman Sea towards the west-coast region of Peninsular Malaysia, an intensive study on fault parameters of the year 2004 Sumatra-Andaman tsunami will follow in the later part. The reasons for choosing this particular event as a reference for the forecast are due to the magnitude of the rupture that was considered as mega and the location which had affected Malaysia by causing 68 casualties. Seeing the capability of the event in causing destructions and loss of lives in the west-coast of Peninsular Malaysia, studies in potential risks of tsunami to our coastal areas need to be conducted. Hence it is appropriate action to study the parameters of the potential rupture, which is the main component and the start of a tsunami event in order to provide knowledge on the risks and its implications towards the study area. From reviewing the fault parameters used by researchers to simulate the last 2004 Sumatra-Andaman tsunami, an insight of possible locations and parameters of rupture source can be identified. While addressing this matter, the authors managed to find the gap in the previous simulations done in assessing the worst-case scenario in the west-coast of Peninsular Malaysia. The past researches were forecasting the catastrophe scenario by adopting the fault parameters from the year 2004 Sumatra-Andaman earthquake. However, for the purpose of forecasting the worst-case scenario, the authors will be using fault parameters of potential source ruptures different from the one in 2004, as highlighted in section 4.

2. Fault Parameters of Year 2004 Sumatra-Andaman Tsunami

Numerous studies with regards to the disastrous year 2004 Sumatra-Andaman tsunami has been conducted by researchers all over the world since the year of the event. Literatures on simulations of tsunami generation obtained from different numerical models have been presented in the past years. Although the subject matter was established, the source parameters differ depending on modellers' preferences. This study reviews the prominent fault parameters used in past literatures of tsunami simulation modelling.

Fault parameters are important input data to model a tsunami generation. The parameters include longitude, latitude, focal depth, rake angle, dip angle, strike angle, number of segments, width of the segment and rupture length. These parameters are to be taken at the source of generation and at the epicenter of the earthquake. Types of parameters needed to model the generation may differ from one numerical model to another. The accuracy of the simulations generated from the models depends heavily on the fault parameters used.

United States Geological Survey (USGS) is a scientific agency in the United States that studies natural hazards. It has been proven to provide reliable source of data where many researchers worldwide use USGS as their platform to obtain data concerning geography and geology. As for the year 2004 Sumatra-Andaman tsunami event, USGS has issued, the location and a focal depth of the tsunami source on its website [8]. The USGS provided the location of the source generation to be at 3.316 ºN and 95.854 ºE with a focal depth of 30 km.

A study was conducted by Lay et al. in 2005, where it adopted the USGS data for source location and focal depth into their seismic inversion model [3]. The study proceeded by using 8º dipping plane and strike of 329º from Harvard centroid-moment-tensor (CMT) solution which indicated predominant thrust faulting. The rake angle is used as 110º, which has been verified legit to be used when the slip direction and long-term partitioning of right-lateral motion were compared. The 1315 km fault rupture zone was divided into three segments not because of the clear physical fault segmentation, but in accordance with the inferred run-up process. Illustration of the fault rupture is represented in Figure 2. Although the study was conducted immediately after the event, where reliable information is scarce, this model is able to simulate the rupture that travelled from the south to north of the source with diminishing speed going to the north.

Elastic co-seismic modelling was used by Vigny et al. in 2005 to determine fault parameters of year 2004 tsunami event. The results of the simulations were then compared to data extracted from approximately 69 GPS stations located within Southeast Asia. The initial model (model A) was initialized by using parameters from USGS and CMT. It was found that the dipping angle of 8º, dislocation plane of 450 km length and 145 km width, produced a moment magnitude of Mw 9.0, which compares well to the CMT value. This model matched the observed deformation at northern Sumatra and Peninsular Malaysia with an average misfit of 27 mm. Unfortunately, it failed to predict the occurrences at the northern part. Due to failure of the latter, this model was then reconstructed few times until it finally produced satisfactory results when compared to GPS data. The final model (the fourth) was altered to a fixed dip angle of 13º in accordance to USGS determination and a maximum depth of 50 km. The plane was cut into two sections; the southernmost has the length of 450 km and strike angle of 330º while the second has 550 km long with strike angle of 350º. This model was able to produce results at average misfits of 4 mm when compared to the GPS data in Kunming, Manila, Bangalore and Hyderabad [2].

Grilli et al. in 2007 chose to estimate the source for the year 2004 tsunami event in terms of magnitude and timing for co-seismic seafloor displacement of the trench. The estimates were then refined by iteratively constraining the source and simulated tsunami to match prominent features of tide gauge and satellite track records. In the initial modelling of the year 2004 tsunami event, non-identical four fault segments with lengths of 220, 410, 300 and 350 km, summing up to 1200 km of the ruptured subduction zone were established. Each segment was unique in morphology, earthquake parameters, shape and orientation [1]. However, details of the simulation were not well reflected. In order to achieve a better match for observations, further constraints were integrated [2, 3, 9]. To reduce the number of free parameters, Grilli et al. sought to have a small number of sources/segments, thus leading to the replacement of mid two segments into three segments, resulting in a total number of five segments as currently addressed today. As mentioned, the method of estimation and further iterations resulting to the required parameters depend on the modeller's preferences. Hence, the latitude and longitude of the epicenter after several iterations are found to be at 3.83 º N and 94.57 ºE, respectively. In order to reproduce accurate distances between seafloor features, the rake angle and dip angle are assumed to be 90º and 12º, respectively, which were applicable to all segments. Focal depth was fixed at 25 km based on slip distributions as predicted in GPS data [2]. Further details of the five fault tsunami segments source parameters were not shown in this paper and can be accessed from the authors'. Simulation results using the five fault segments source parameters were found to be satisfactory and matched the seismic inversion models with GPS data. In year 2011, Teh and Koh used fault parameters driven by Grilli et al. to simulate the generation and propagation of the year 2004 Andaman tsunami by using TUNA-M2. Results obtained leading to depression N waves were proven to match with the eyewitnesses. [10].

In the study, Koh et al. in the year 2009 has provided a summary of initial tsunami generation sources for Sumatra-Andaman event. Parameters for the sources included length, width and displacement of fault [11]. In order to simulate tsunami generation of the event, the study applied parameters mentioned in a literature by Mishra and Rajasekhar in 2005. The epicenter and focal depth were the same as provided by USGS [8]. Meanwhile, for this single-segmented rupture of 1000 km long and 100 km width, other parameters included are dip angle at 8º, slip angle at 110º, strike angle at 350º and displacement at 20 m [11, 12]. These parameters were applied to the model as source generation and have successfully provided credible results when compared to the eyewitness account in terms of arrival time and wave shape. Due to its credibility in producing consistent simulations to the real event, the fault parameters were further being used in other studies to simulate and forecast the worst tsunami case scenario at Peninsular Malaysia [13, 14].

Ismail et al. in 2012 performed a vulnerability assessment on west-coast of Peninsular Malaysia by adopting three rupture segmentations proposed by Lay et al. As shown in Fig. 2, the three rupture segmentations were used to produce different scenarios originating from each segment (Sumatra fault, Nicobar fault and Andaman fault). This was to identify the worst-case scenario that could affect the study area. However, scenario for year 2004 Sumatra-Andaman tsunami was chosen to be considered in this paper. For this scenario, Ismail et al. simulated the tsunami in a single segment fault spanning at about 1100 km with an epicenter of 1.12 ºN and 96.25 ºE. The remaining parameters were fault width = 150 km, strike angle = 350º, dip angle = 15º, slip angle = 90º, focal depth = 10 km and displacement = 20 m. It was assumed that the initial wave generation was formed by a dip-slip fault mechanism [15]. Although the latitude used in this simulation was outside the range as compared to others [1-3, 8, and 11-14], the results of the simulation were found to match to the eyewitness with concurrent simulated arrival time and wave shape.

The studies mentioned above were conducted immediately after year 2004 tsunami [2, 3] and several years after the event [1, 10, and 13-15], hence these explained the differences of parameters chosen for the studies conducted over the years. However, there is no established method to indicate the suitable derivation of the fault parameters for simulation purposes since the uncertainty in fault orientation remains a contributing source of errors in tsunami forecast [10].

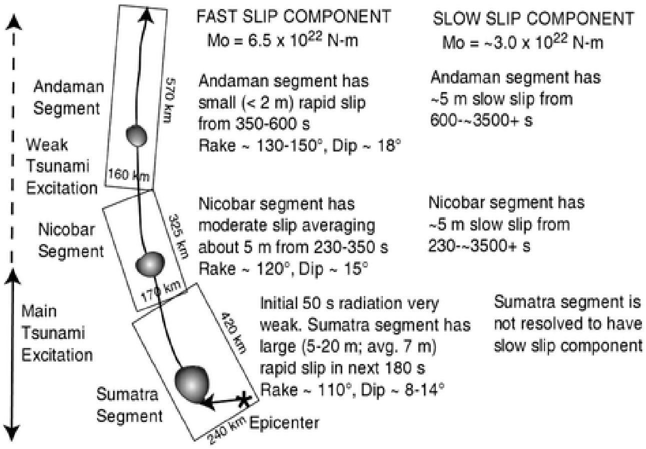

Fig. 2: Three segments rupture proposed by Lay et al. [3]

3. Expected Future Earthquakes Along Sunda Trench

The subsequent M_w 8.7 Nias tsunami event occurred in March 2005 was triggered three months after the great Sumatra-Andaman tsunami of year 2004. This was the causal aftershock of the earlier event. With both earthquakes occurred at the same Sunda megathrust, the pattern that has been observed for more than century can be proven right. Aftershocks do occur in the locality of the main shock rupture zone [16]. With that in mind, it calls for further investigation of the stress changes along the Sumatra-Andaman Trench since there is a concern of fault failures that have been identified in the region [17].

As mentioned, the southern region of the Sunda Trench covers the Sumatra region. The Mentawai segment of Sunda megathrust is known for its seismic cycle, hence placing it as the best location of interest for the next failure. The second rupture from the Nias tsunami in the year 2005 had caused occurrences of megathrust at the south, under Batu and Mentawai Islands which are closer to the rupture since the area of increased stresses have expanded resulting to Mentawai segment being the closest threat [17, 18]. Furthermore, giant earthquakes and tsunami in this area were found to repeat at every 200-230 years, with recent occurrences in year 1861 (M_w = 8.5) [18].

Meanwhile, at the northern part of Sunda Trench, the tsunami convergence rate is not as worrisome as on the opposite side. Historical records do not show active seismic activities in the areas, the fact that too little is known of the area is risky. Hence, the behaviour of this area should be studied in order to provide a meaningful assessment of the risks. In the area where the convergence rate is low such as in the north, the estimated repeat time of the year 2004 earthquake would occur at every 140-420 years. However, this estimate ignores the case of smaller events such as in 1881 (M_w = 7.9) and 1941 (M_w = 7.7) [9].

4. Chosen Parameters for Future Simulation

Considering the study area for future simulation lies on the west-coast of Peninsular Malaysia, the potentially ruptured Mentawai segment in the Sumatra region has to be neglected. Tsunami from the source in Mentawai segment will not pose harm to the west-coast of Peninsular Malaysia since this area is hidden by Sumatra [10]. The potential devastating tsunami in the study area will originate from the Nicobar-Andaman Sea region, as suggested by several studies [13-15].

The areas at the west-coast of Peninsular Malaysia are bound to be hit by tsunami with higher devastating impact as compared to year 2004 event, given the source of the rupture rotated slightly clockwise from the northern part of previous ruptured fault [10]. Hence, Koh et al. in 2009 conducted a study on tsunami source moving directly towards the Straits of Malacca. The results of the study proved that the orientation of the rupture did enhance the run-up wave heights along beaches in Penang and Langkawi [13].

Another study conducted to simulate the worst-case scenario at west-coast of Peninsular Malaysia on tsunami risk mapping simulation was conducted in the year 2011 by Teh et al. In this study, the aim was to ensure that waves from the source would propagate directly towards the northwest of Peninsular Malaysia, but in a different manner from the study conducted by Koh et al. in 2009 [14]. Using the fault parameters from Koh et al. in 2009, the fault was constructed as a single segment rupture of 600 km in length and 130 km in width. The simulation results agreed well with the theory of disastrous direct propagated waves. An alarming run-up height of 8 m was predicted on the beaches in Penang and Langkawi.

Simulations conducted by Ismail et al. in 2012 showed that the worst case scenario at west-coast of Peninsular Malaysia was the combination of source from year 2004 Sumatra-Andaman tsunami that occurred during the highest astronomical tide (HAT) [15]. The study considered four different scenarios with three of it were inspired by the three rupture segmentation proposed by Lay et al. in 2005.

It is important to keep in mind that the criteria of the fault parameters of a source are interdependent and they contribute in defining the intensity of the earthquake that will result in tsunami generation. There is a linear relationship between the water displaced above the source with the dislocation of the rupture as explained by Okal and Synolakis [19]. However, that relationship alone does not define the height of the wave generated from the source since the other parameters are also playing their role in defining the character of the generated wave. Hence, it is fair to say that the character of the generated wave is dependent to the integration of given fault parameters. For example, Teh et al. simulated the 2004 Sumatra-Andaman tsunami with a dislocation of 20 m which generated wave of 7 m height at the source [14]. Lovholt et al. uses a dislocation of 20 m too in simulating the 2011 Tohoku tsunami which resulted in 20 m high of generated wave at the source [20]. These two cases proved that although the relationship between

Table 1: Summary of fault parameters at the epicenter derived from literatures

Source	At the epicenter								Number of Segments
	Lat. (ºN)	Long. (ºE)	Focal Depth (km)	Rake Angle (º)	Dip Angle (º)	Strike Angle (º)	Length (km)	Width (km)	
[3]	3.3	96	30	110	8 - 14	329	420	240	3
[2]	3.3	96	max. 50	110	13	330	650	145	2
[1]	3.83	94.57	25	90	12	323	220	130	5
[15]	1.12	96.25	10	90	15	350	Not available	Not available	1

wave height and dislocation is linear, height of generated wave is also dependent to the other parameters.

From the literature review conducted, fault parameters of the source are able to be identified for future work. Hence, by referring to the Lay et al. segmentation rupture [3] and fault parameters provided by Ismail et al. of the three segments [15], tsunami simulations for each of the segments will be conducted in these cases which are critical in forecasting the tsunami impact into west coasts of Peninsular Malaysia. Details of the parameters are as follows:

1. The source is of a single segment fault, with lengths according to those proposed by Ismail et al. [15]. Results from future work can be compared to these reliable simulation results.
2. The latitude and longitude, strike angle, dip angle, slip angle and focal depth of the segments will be referred to Ismail et al. for each fault segment [15].
3. The dislocation/displacement of each of the segments will be varied by applying the scaling relation. Determination of the dislocations is still in the process which the outputs are to be used in the authors' later work and this will be the novelty of this research as compared to the past studies by [14] and [15].

5 Conclusion

This paper discusses on the geography and geology of Sumatra-Andaman Trench, which resides on the northern part Sunda Trench. Historical data regarding the ruptures at the area were highlighted to further understand the seismicity of the fault lines. Review of the fault parameters used to generate the source models from past literatures were also discussed extensively. Risk locations for future earthquake at north and south regions of Sunda Trench were identified. This will assist in the selection of the best source that will inflict great risk to west-coast of Peninsular Malaysia. This study further finalizes the source parameters that will be used for future tsunami simulation assessment.

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