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Triggering mechanism of gas hydrate dissociation and subsequent sub marine landslide and ocean wide Tsunami after Great Sumatra –Andaman 2004 earthquake

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ABSTRACT

Tsunami generated by Great Sumatra and Andaman earthquake in 2004 with Mw of 9.3 is greater than the size of the earthquake magnitude. The southern 400 km rupture was a fast slip and northern 900 km rupture was a slow slip. Time window is inadequate to alert the public about the generation of ocean wide tsunami for earthquakes > Mw 8.5. To compare the size of the tsunami caused by this earthquake with other great earthquakes tsunami magnitude , 'Mt', and body wave ' mb ' surface wave , 'Ms', moment magnitude ,'Mw' and seismic duration ,'T' of earthquake are considered. The larger differences between 'Mt' 9.1 and 'Mw 9.3 ' and the variation between 'mb 7.25 and Mw 9 3 can be accredited to the abnormal nature of source of slow faulting or submarine slide. Multiple focal mechanisms in subduction zone and uplift of western and submergence of eastern margins of Nicobar –Andaman islands appears to have slipped 10 m can be accounted for by seismic model with time scale of ~ 1 hour. Nevertheless, no such strong seismic waves' were observed in aftershock zone. But satellite observations of tsunami waves in Bay of Bengal after 2 to 3 hours of the rupture, constrain on the slip distribution in the aftershock zone. This aftershock zone is directly perpendicular to that tsunami waves that stoke along coasts of Sri Lanka, India and Thailand. Huge methane gas hydrate deposits reported in off shore of Andaman. Triggering of 2004 earthquake increased the pore pressure of the gas hydrate, free sediment gas; seepage –mud volcanoes and unroofed sediments and initiated slope instability and submarine landslides in consequent to that catastrophic ocean wide tsunami devastated Indian Ocean countries in 2004.

Key words: 2004 Sumatra Andaman earthquake, ocean wide tsunami, slow faulting, multiple focal mechanism, gas hydrate, slope instability, submarine landslide

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INTRODUCTION

Earthquake generated tsunamis are causing more damages to megacities, nuclear power plants, airports and harbours in coastal areas . 2004 Great Sumatra –Andaman tsunami was the most catastrophic tsunami in the 20^{th} century. Not only tsunami caused several morphological changes along the coast, but also affected economic activity such as aquaculture farming, coastal agriculture, coastal forestry and so on[1]. Tsunamis originated by submarine landslides and subsequent development of turbidity currents have repeatedly broken submarine cables. Our society significantly depends on submarine cables and protection of submarine cable systems is highly demand for cable companies and government organizations.

The overall size of the tsunami generated by the Great Sumatra and Andaman earthquake 2004 is somewhat greater than the size of the earthquake magnitude, Mw of 9.3 ruptured 1300 km long subduction zone between the Indo-Australian and Eurasian plates [2]&[3]. The duration of the fast slip in the 400 km long ruptures in Sumatra region varies from 400 to 600 seconds and slow slip along 900 km rupture zone of Nicobar – Andaman has extended to 3000 seconds with directional pattern. The slow slip ruptures developed with low energy frequencies > 5 Hz in the areas of Nicobar – Andaman with magnitude of M 9.3 earthquake is astonishing.

The characteristic of tsunami generated by submarine landslides depend primarily upon the volume and the dynamics of the sliding masses as well as water depth. In general , Tsunami generated by submarine landslides often have very large run up height close to landslide area , but have more limited far field effects than earthquake tsunami [4] . Indeed, 26th December 2004 tsunami in Indian Ocean is truly the first global tsunami, as it propagated into the Atlantic and Pacific oceans in addition it has covered rim of the Indian Ocean countries The inferences of maximum earthquake tsunami amplitudes that battered the coasts of India , Sri Lanka and Thailand lacked radial damping and had propensity of linear features that propagated perpendicular to the fault sources of earthquakes rupture zones from Nicobar –Andaman segment .

Tsunami Geology

Similar to earthquake magnitude (Mw), tsunami magnitude (Mt) is also computed from tsunami wave heights (H2) from tide gauge stations in Indian and others coasts, epicentre distances (X) from the respective locations of the tide gauge stations by using the formula; Mt= log H2+ log X+ 5.55 (Abe, 1979). The average tsunami magnitude of Mt=9.1 of Great Sumatra Andaman earthquake for near field of Indian Ocean rim countries like India was computed. Bivariate plots of earthquake magnitude (Mw) versus local tsunami intensity that occurred in different parts of the world reveal that size of the local tsunami increases with the magnitude of the earthquake . The average tsunami run ups of Andaman – Sumatra earthquake were recorded as of 22 m and hence this earthquake is considered as tsunami earthquake not as anomalous tsunami earthquake.[5] .

The data set computed for this tsunami not only in near field , but also in the far field reveal that first tsunami wave in eastern Pacific varied from 0.04 m in Hawaii to 0.255 m on the coastal South America and 0.26 m on the Alaskan coast. the amplitude of second tsunami waves that stroked the coasts of Hawaii and South American exhibit higher elevations of 0.08 m and 0.82 m respectively. The height differences between the 2nd and 1st waves are positive everywhere indicates it is not only in the near field in the Indian Ocean that the 2nd wave is the highest in the far field in the Pacific Ocean also [6].

Stalemate to Forecast the Impact of Tsunami from the Size of Earthquake Magnitude

Seismic waves from large earthquake travel much faster and giving very short time window for seismologist to locate the epicentre of earthquake and also to announce the warning processes whether a major tsunami would be generated. The magnitude of the earthquake is a factor that determines the size of the tsunami. Less than < 7.5 Mw doesn't produce destructive tsunami, whereas the magnitude between Mw 7.6; Mw 7.8 and Mw7.9 would generate destructive tsunami nearer to the epicentre; at greater distances small changes in sea level may be observed? Tsunami generation is low for earthquake with Mw < 8.5, and becomes extreme for the earthquake with larger moment magnitude, Mw > 9. Magnitude saturation is a setback for tsunami warning. "Great" earthquakes, usually defined as ones with Ms ≥ 8, can be either too small to generate an ocean wide tsunami or enough that the risk is great.

Computation of body wave magnitude 'mb' and surface wave magnitude 'Ms' around a period of 1 second and at 20 seconds, with commencement of about Mw' 6.3 and not exceeding about 'Mw'8.2 [7] after major earthquake are used to assess the size of the earthquake whether an earthquake is larger enough to spawn a major ocean wide tsunami. It is not easy to compare the size of the tsunami affected area with the size of the tsunami excited by different earthquakes in different periods, because excitation and propagation of tsunami vary with bathymetry of the open sea and coastal areas. Short period magnitude scale 'mb' of 2004 Great Sumatra Andaman earthquake with Mw 9.3 7.25 is lower to 'mb' 7.26 of the Nias Sumatra 2005 earthquake with magnitude Mw 8.5.

It is construed in a table (Table 1) with Ms, Mt, mb, Mw, T (sec), and types of tsunami produced by earthquakes to disclose the relationship of the factors outlined. Though Chile 1960 and Alaskan 1960 earthquakes are considered as great earthquakes even then these earthquakes have generated only normal tsunami, whereas 1992 Nicaragua earthquake with Mw 7.6 caused anomalous tsunami earthquake. This abnormal variability is consistent with the seismic duration. The seismic duration of the great earthquakes occurred in Chile 1960 and Alaska 1964 spanned only 11to 13 seconds [8] whereas, 1992 Nicaragua was slow slip earthquake has taken 200 seconds [9]

The broad band seismogram observation of the 1992 Nicaragua earthquake clearly reveals the nature of the rupture measurement and concluded that the earthquake was slow thrust earthquake that last for 200 seconds that energized for larger anomalous tsunami. [9] . Similar to that slow slip ruptures in the northern sector with magnitude of Mw 9.3 took more than 600 to 3000 seconds to generate ocean wide tsunami , whereas, the 2005 Nias earthquake with Mw 8.6 has created only local tsunami because the duration of the events was limited to 120 seconds.

Single or multiple focal mechanisms for initiation of fast and slow slip ruptures in subduction

The slip process of the 2004 Sumatra Andaman of earthquake occurred between Indian and Eurasian plate. The Sumatra segment has 5-20 m rapid slip with no slow slip. Nicobar segment has moderate slip with 5 m for the duration of 230 -360 seconds , in this sector the slow slip took about 230 to 3500 + seconds .In Andaman sector rapid slip < 2 m occurred within the duration of 350 to 600 seconds ,but ~ 5 m slip as slow slip duration extended from 600 to 3500+ seconds [3].

From this analysis, it is perceptible that the rupture in the northern sector with long source –process time has generated little or no seismic waves. But Andaman and Nicobar sector exhibited well documented uplift in the western and submergence in the eastern coasts and that can be taken as considerable slip more than 10 m along 160 km wide thrust plane in the half of the northern rupture zone took more than 3000 seconds even, it has not generated strong seismic wave's radiation.

However, [10] proposed a Composite Centroid Moment Tensor (CMT) source model of five sources offset in time along the rupture with varying amplitudes and focal mechanism and gives solution of normal mode of 1.2×10^{30} dyne cm corresponding to Mw 9.3 and consistent with surface wave value. The rupture velocity varied from 4 km/sec to less than 2 km/sec with average velocity of 2.8 km /sec without reaching the very low value (1 km/sec. Observed for so called tsunami earthquake). [11]&[12] . Furthermore, it is inferred that single point source model is no longer required, because, it results from interference between energy radiated from parts of the fault rather than purely from the fault size.

More to the point , tsunami with high wave heights that stroked in the coasts of Sri Lanka; India ; Thailand were directly perpendicular to the fault limited in the southern and northwest aftershock zone with slow slip .[13]. Tsunami, thus generated has covered 2, 80,000 – 3, 00,000 square km of the ocean floor.

The transfer of stress from the rupture zone of December 2004 Sumatra Andaman earthquake amplified stress on the segment immediately to the south and resulted Nias earthquake of Mw 8.7 in March 2005 [14] . The Nias earthquake cracked only 300 km long and 100 km wide area in the ocean floor and generated merely 4 m high tsunami that covered 30,000 square km only, but it didn't generated ocean wide tsunami.

Occurrence of Gas Hydrates in Andaman Sea

Drilling and coring in 2006 by National Gas Hydrates Program estimated richest gas hydrates deposits of 230 to 600 m thick in Andaman Sea, below the sea floor through seismic measurement of bottom simulating reflector (BSR) in the sandstone and siltstone dominated gas hydrate reservoir [15]

Catastrophic release of Methane Gas Hydrate and instability of slope in the subduction zone substratum due to seismic excitation

Acceleration of horizontal and vertical loads by multiple focal mechanism of the earthquake in the uneven rupture zones accrued the pore pressure in northern part has enhanced gas hydrate dissociation. Gas hydrate dissociation resulted in loss of solid material, production of free gas and increased fluid pressure and all which have the effect of reducing sediment strength instability and destabilised slope stability [16]. In general it is possible to achieve safe slope by application of appropriate geometry and soil mixture [17]. The Gas hydrates dissociation in the subduction zone dependent on thermal gradient relative to depth and don't exist in the hot zone . [18] &[19] .

Simulation of the development of excess pore –pressure at the base stratum initiated due to the horizontal ground shaking caused by an earthquake and propagated upward. It is assumed that the seismic excitation is sinusoidal, with given frequency, but the amplitude of subsequent cycles may change. Also the soil properties may vary with the depth. In this case, the equation of motion describes the propagation of seismic shear waves in the seabed. It takes the following simple form,

$$\frac{d^2\tau}{dZ^2} + \frac{\zeta}{G}\tau = 0$$

Where τ = non-dimensional shear stress; Z = non-dimensional vertical co-ordinate; G=shear modulus; = certain coefficient that depends on frequency of excitation, density of saturated soil, depth of soli layer, characteristic features of stress and strain. This process requires that unloading of the headwall causes strain concentration, loss of strength in a base layer then propagated upslope along a layer of marine deposits [20]

A detailed study on the submarine landslide through images and identification of 20 m depression that run parallel to the base of fault scarp , existence of remoulded sediments through coring and pore pressure measurements through piezometer in the subduction zone located between Sumatra and Indonesian/Indian water limit indicate active fault features generated at the same time than the 2004 earthquake [21].

Triggering mechanism of December 2004 earthquake increased the pore pressure of the gas hydrate accumulated in the open space in the sedimentary formation and enhanced liquefaction of sediments and reduction of effective stress thus provoked the slope instability as submarine landslides .

Geological data relevant to destabilization of the gas hydrate and rapid release of Methane in the other parts of the ocean bottom in the past that have generated catastrophic submarine landslides are located i) in the Cape Fear slide or mud flow and Black Ridge sediment instability ; ii) The Humboldt slide , Eel River Basin off California ; iii) the Gulf of Cadiz slump and slide off SW Spain iv) the Storegga slope failure complex off Norway [22]&[23]. These regions have extensive observational data to suggest that the four apparently unconnected phenomena of free sediment gas; gas hydrate; seepage – mud volcanoes and slope instability. These independent observational data in some regions are connected into one family of features that interacts with each other and thus spawned large scale submarine landslide due to the pressurization of pore water by gas and gas hydrate that ultimately affected the acoustic and bulk density and compressibility of the sediments [24] .

Mud Volcanoes

There are eight mud volcanoes erupted on 26th December 2004 with concomitant gas flow of Methane fired more than week in North and middle Andaman. The mud brought out as seismogenic liquefied sediments formed at the time of earthquake to the surface through the fractures driven by deep pressure [25]. There are many numbers of mud vent or conduit outlets to drain away the excess pore water identified as mud volcanoes in the form of crater and build up mounds along the fractures /fault zones in North and middle Andaman Mud volcano deposits of consists of clay, clay silt matrix with rock clast of heterogeneous boulders and pebble sized material. The intermittent eruptions of mud volcano with Methane, Nitrogen and Radon gases at the time of tectonic movement and earthquakes are still continuing.

DISCUSSION AND CONCLUSION

The 2004 December Sumatra Andaman earthquake rupture appears to have been a compound process of seismic energy release involving, variable slip amplitudes, rupture velocities and slip durations. Uplift of western margins of Andaman and Nicobar Islands and submergence in the eastern parts appears to have slipped 10 m can be accounted for by the seismic model with time scale of ~ 1 hour or larger. In the northern part no such strong seismic wave's radiation was generated to cause ocean wide tsunami. But the arrival times of tsunami waves around the sea of Bengal provide additional constrain on the slip distribution in the North. This suggests that estimation of tsunami source consistent with satellite altimetry observation of the deep water waves obtained by satellite after 2 to 3 hours after rupture occurred.

Along the subduction zone, the multiple focal mechanisms of earthquakes shaking increase the pore pressure and dissociated the gas hydrate. The seismic shaking and tilt of Andaman and Nicobar islands had eventually resulted in loss of solid material, production of free gas and increased fluid pressures which have the effect of reducing sediment strength and leads to of slope instability . Reporting of mud volcano eruption with simultaneous gas flow of Methane fire continued for a week time were formed as the direct result of connection of high pressure fluid at depth initiated the fracture triggered by earthquake [25].

In most cases for normal earthquake, Mt and Mw values computed are close [26]. Since Mw 8.6 and Mt 8.5 of Nias 2005 earthquake are more or less identical and generated merely 4 m high tsunami. An obvious exception is 2004 Great Sumatra Andaman earthquake which had exhibited a large difference between Mw 9.3 and Mt 9.1. This difference is generally attributed to the anomalous nature of source either slow faulting or large scale ocean bottom slumping. The ocean wide tsunami generated by Andaman – Sumatra earthquake based on field observation has revealed highest ever recorded tsunami run ups 22 m to the epicentre distances. Still; it has not been included in the list of

Anomalous tsunami earthquake

The short period body wave 'mb' 7.25 for the Great Sumatra Andaman earthquake is considerably lower to that of other great earthquakes. As already seen that the tectonic environment of the rupture zones of other Great earthquakes of 1960 – Chile and 1964 –Alaska earthquakes were entirely different from the December 2004 Great Sumatra Andaman earthquake. Whereas , the earthquake at Nicarague in 1992 generated slow tsunami earthquake

, and spawned disproporнately larger tsunami for its seismic magnitude [9] which had an ‘mb’ which is significantly smaller than that of ‘Mw’. In that order the difference between ‘mb’ 7.25 and ‘Mw’ 9.3 of Great Sumatra Andaman earthquake is very large indicates earthquake as *tsunami earthquake.* This differentiation can also be accredited to the anomalous nature of the source, either extremely slow faulting or a large scale ocean bottom slumping.

The non-roofing of the overburden materials in the slope area has suddenly released confining pressure of the gas hydrate admixture in the sediments and ultimately burst and liberated about 164 m3 of methane from 1 m^3 of gas hydrate at standard pressure and temperature. Consequent to that large scale submarine landslides occurred on the continental slope in 2004 spawned disproportionately larger tsunami. Understanding of the mechanism of less frequent, but potentially catastrophic mega slide of Great Sumatra Andaman in 2004 that has spawned 30 m high, involved plate tectonic mechanism for Methane hydrate release along the subduction zone.

Table 1: Computation of various types of magnitude spectrum of earthquake duration and types of tsunami

Location	Ms	Mb	Mw	Mt	T (second)	Types of tsunami
1960 Chile	8.1	7.9	9.5	9.4	11	Normal tsunamigenic earthquake
1964 Alaska	8.4	7.9	9.2	9.1	13	Normal tsunamigenic earthquake
1992 Nicaragua	7.0		7.6		200	Anomalous tsunami earthquake
2004 Great Sumatra Andaman	8.5	7.25	9.3	9.1	Fast slip=300to 600 and slow slip 3000 +	Ocean wide tsunami
2005 Nias		7.60	8.6	8.5	120	Local tsunami

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