Assessment of tsunami risk to offshore platforms in Indonesia archipelago

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Abstract. Earthquakes are unpredictable natural disasters that need to be taken into serious consideration in the design criteria of offshore platforms, particularly in regions of high seismicity. The Indonesia Archipelago is characterized by extensive zones of seismic activity where large earthquakes can be extremely dangerous to the safety and reliable performance of offshore platforms. Tsunamis generated by the larger earthquakes in the region present an additional extreme danger to offshore oil production and need to be assessed and considered in the design criteria of offshore platforms.

1. Offshore platforms; design loads and forces

Proper sitting and design of an offshore oil platform must take into consideration all the environmental criteria and all available oceanographic and meteorological data. Such information includes: storm wave heights and wave periods; storm wind speeds and gust conditions; tides; swells; ocean bottom scouring or slides; currents; icing conditions; earthquakes, etc. The most important design considerations for an offshore oil platform are the storm wind and the storm wave loading the structure will be subjected to during its service life [1,2].

2. Tsunamis; causes, nature, and damages

Tsunamis are long water waves (with wave periods of 5 to 60 min., or even longer) generated impulsively by such mechanisms as submarine volcanic explosions; submerged landslides; rock falls into bays or the ocean; tectonic displacements associated with earthquakes, and underwater explosions of nuclear devices. The word “tsunami” is now generally used to describe these waves, in preference to terms such as "seismic sea wave", or "tidal wave", the latter being clearly a misnomer. The major cause of catastrophic tsunamis is the tectonic displacement of the ocean floor associated with shallow focus earthquakes with magnitudes greater than 7 on the Richter scale. Tectonic ocean floor displacements must have a substantially vertical component in order to generate tsunamis of larger magnitudes. Larger tsunamis are important natural hazards and can cause great loss of life and vast property damage. One of the worst tsunamis in historical times occurred in Japan on June 15, 1896. The largest of the waves reached elevations of 75 to 100 ft above sea level, engulfing entire villages. More than 27,000 persons were killed, and 10,000 houses were destroyed [3]. Many other tsunamis in the Pacific Ocean and the inland seas have caused appreciable destruction, but with lesser loss of life. For example, the April 1, 1946, tsunami generated by an earthquake in the Aleutian islands killed more than 150 persons, seriously injured another 163 persons and caused about $25 million in property damage in the Hawaiian islands [4]. Large destructive tsunamis have also occurred in many other parts of the world, including the Bay of Bengal, the Caribbean Sea, the Celebes Sea, the Java Sea, the Mediterranean Sea, the Sea of Japan, and the South China Sea [3]. As an oversimplification,
the displacement of the ocean floor by an earthquake can be visualized as a huge paddle shoving a vast amount of water. The vertical movement of the ocean floor and the disturbance of the water column above it create potential energy on the ocean's surface, which in turn radiates out in all directions. This energy travels as potential energy and only becomes kinetic energy near the shore when the water depth is shallow.

The magnitude of an earthquake is related to the maximum ground displacements over the affected area and the length of its surface rupture. Most of a quake's aftershocks in the ocean usually occur within an area which usually corresponds with the tsunami generating area. Initial tsunami height and period will depend on the extent of seafloor vertical displacements and the water depth in the generating region. The larger the generating area and the vertical seafloor displacements, the greater will be the magnitude of the associated tsunami. The size of a tsunami and its run-up at a particular location will depend upon the shape and orientation of the generating source area as well as the amount of earthquake energy that went into tsunami generation.

In the open ocean where the water depth is deep, tsunami waves are very long and relatively low in height, e.g., of the order of 50 miles or more in length and less than about 2 ft in height. They travel at speed, which is controlled primarily by the depth of the water. This term can be expressed by Equation 3 ft/sec, where g is the acceleration of gravity and d is the water depth [3]. Based on the variation of water depth in the ocean, the speed of the tsunami will vary and the wavefronts will bend. This process is known as wave refraction. In some areas, the offshore topography may cause tsunami waves to refract in such a manner that the wave energy will converge, thus increasing wave heights. In other areas such as bays. The underwater bathymetry will cause the wave energy to diverge, thus accounting for lower wave heights.

When a tsunami wave reaches the coast, it may run inland, past the land sea boundary, for a considerable distance. The elevation above the mean sea level reached by the tsunami inundation is called the run-up elevation. The run-up elevation is not the same as the tsunami wave height observed offshore or recorded by a tide gauge. Tsunami height, as observed or measured on a tide gauge record, is the vertical distance between the crest and the trough of the wave (figure 1). Depending on the distance from its source, a tsunami approaching a coast will usually cause a drop in sea level before it arrives. The extent of the vertical distance of the drawdown will vary depending on the underwater topography and the characteristics of the tsunami wave. A tsunami's drawdown may not be as great as its ensuing run-up. Other than tide gauge records, there is very little information on drawdown elevations with which to substantiate this phenomenon. Tide gauges usually filter the waves, depending on their period, so the recordings may not be representative of what actually happens on an open coast. Most tide gauges are located close to shore, in harbors, usually within a fraction of one tsunami wavelength of the shore [4].

In most areas, when the tsunami strikes, the water rises like a rapidly rising tide, while at other areas large tsunamis may cause a bore. The terminal characteristics of a tsunami often depend primarily on the source mechanism of the earthquake or the impulsive mechanism that created it. Other significant factors are the distance from the source, the tsunami travel path and the local coastal configuration and bathymetry. Closer to the source, bores are quite common.

A substantial part of the literature on tsunamis is concerned with the very large tsunamis that affect an entire ocean. However, tsunamis in inland seas or smaller bodies of water are also of great importance to local areas. For example, the tsunami of June 15, 1896, which was so disastrous in Japan, was barely detectable at San Francisco. Another example of smaller scale effect is the eruption of Taal Volcano in the Philippines in September 1965. Many lives were lost during that event when the waves swamped, overloaded boats with people fleeing the island. However, since the source was almost a point source of origin, the wave energy and wave amplitude dissipated very quickly with distance.

The historical record indicates that damage caused by tsunamis can be very significant. In addition to the loss of life and damage to coastal buildings and structures, extensive damage often can occur to boats. Tsunami waves may break or drag their moorings and carry these boats inland or pound them against docks, buildings or other vessels. There is substantial documentation in the literature about the destructive effects of tsunamis and on the need for protective systems and measures. Essentially three
types of tsunami damage have been identified for urban sites. John D. Isaac has described these types in the report on damages which occurred in Oahu, Hawaii, during the April 1, 1946 tsunami, to be:

Damage or effect of tsunami which did not exceed that which would be expected from an unusual raise in sea level due to unusual tidal inundation without surf (houses either floated of their foundations or merely flooded, and the vegetation was disturbed to a small extent); Intermediate damage or effect of the tsunami between conditions 1 to 3 (houses were moved some distance and damaged and the ground was eroded to a certain extent); Finally, damage or effect of tsunami, disproportionately great compared with that which would be expected from a tidal inundation of similar height (evidence of high velocity everywhere, with buildings destroyed, considerable erosion, automobiles rolled about, and in areas of gentle slope, extensive inland water inundation).

All of the tsunami damages that had been reported in the literature, there has been no known studies or references on destructive effects of tsunamis on oil platforms, or whether any oil-fields workers were killed during a tsunami. So, the remaining question is: Is it important to study potential tsunami effects on the safety and reliability of offshore oil platforms. The answer to this question is a definitive, yes. Indonesia is located in a very active seismic setting. The historical record demonstrates that large destructive tsunamis have caused considerable destruction and loss of life in the Indonesian Archipelago. Winds, waves, currents, as well as dead and live load forces are predictable. However, earthquakes and their primary and secondary impacts are not very predictable. Structures in localities subject to earthquakes and other extraordinary conditions must be designed with due regard to such conditions [1].

3. Oceanographic condition in Indonesia archipelago
The extreme climatologic conditions in the Indonesian archipelago are dominated by two monsoon seasons. These are the northwesterly monsoons (generally developing during December and lasting until late March), and the southeast monsoons (generally prevailing from late April to mid-November). The extreme ocean conditions caused by the monsoon "storms" are generally responsible for the generation of very high waves in the archipelago.

Fortunately, conditions of extreme wave heights have recurrence periods of 100-years. For example, in the Java Sea, the expected maximum wave heights are between 8 to 9 meters. But nature is not always predictable. There will always be uncertain conditions which may occur suddenly and which may cause extensive damage.

The Indonesian archipelago is also characterized by other extreme natural hazards, such as earthquakes and tsunamis. Earthquakes originate at two principal tectonic sources. The major tectonic feature in the region is the Sunda Arc that extends approximately 5,600 km between the Andaman Islands in the northwest and the Banda Arc in the east. The Sunda Arc consists of three primary segments; the Sumatra segment, the Sunda Strait Segment and the Java Segment. These locations represent the area of greatest seismic exposure, with maximum earthquake magnitudes of up to 7.75 on the Richter scale and with focal depths in excess of 70 km.

According to Dadang Achmad of the Oceanic Geophysical Laboratory of Universitas Hasanuddin, the probabilities of tsunami occurrence in the Indonesian Archipelago, especially in the eastern region, are very high in view that Indonesia is surrounded by four major tectonic plates, i.e. Pacific, Asian, Australian and the Philippine plates. All these tectonic plates are presently active and future movements and earthquakes can be expected. The second primary source of earthquakes in the region is the shallow crustal fault region that generally parallels the Sunda Arc (east-west) with some transform surface faulting marking the north-south trending boundaries of the landmasses. These locations represent the areas of greatest seismic exposure, which can produce earthquakes with a maximum magnitude of 7.0 and focal depths of less than 70 km. Based on data of peak ground accelerations of surface waves (taken from 200-year peak accelerations that have been recorded), the Indonesian Offshore area can be divided into three major zones (figure 2), where "g" is gravitational acceleration.
There are:
Zone 1, Ground Peak Acceleration (Gm) = 0.05 g (0.15 g)
Zone 2, Ground Peak Acceleration (Gm) = 0.15 g (0.25 g)
Zone 3, Ground Peak Acceleration (Gm) = 0.25 g (0.35 g)

Figure 1. Example of ground peak acceleration map for Indonesia Archipelago [3].

Zone 1 has experienced the highest tsunami ever recorded. This was the Flores Tsunami of December 12, 1992, with waves almost 26 meters high [6]. So based on this data, it is conceivable that almost all the earthquakes that can happen at the Offshore Indonesian region can produce an extremely dangerous tsunami. The major question is, how can we predict such tsunamis.

Figure 2. Tsunami zones in Indonesia Archipelago [7].
4. Tsunami forecasting

To forecast tsunamis and determine their terminal run-up characteristics and their destructiveness potential, one must be able to evaluate the parameters of the tsunami source mechanism in real time and often from inadequate data. Tsunami source mechanism analysis is difficult given the time constraints of a warning situation. It will suffice to say that forecasting the occurrence, run-up and potential destructiveness of a tsunami at a distant shore, will depend greatly on determining the seismic parameters of the source location such as magnitude of the earthquake, its depth, orientation, length of the fault line, size of the crustal movements and the depth of the water in the generating region [5].

Based on limited data, one can only forecast future tsunami events by applying some basic statistics to the historical tsunami data. Dr. Imamura and Mr. Hamzah Latief, at Disaster Control Research Center, Tohoku University in Japan conducted a study of historical Indonesian tsunamis recently. They have successively reorganized the existing data on Indonesian tsunamis for the last 400 years, from 1600 to 1998. The International Tsunami Information Center believes that based on historical data and by applying basic statistical principles, Indonesian tsunamis cannot be predicted but at least approximate estimates of tsunami recurrence, as with earthquakes, can be obtained. Also, he has stated that near real-time tsunami warnings, that is tsunami warnings within 15 minutes or less after an earthquake has occurred, are presently impossible for Indonesia. Even if the International Tsunami Warning System disseminates a tsunami warning to Indonesia within 15 minutes or less, present communication infrastructure in Indonesia may not be capable of further disseminating the tsunami warning to any of the threatened communities, in time to be of use for evacuation or protective measures. An early local or regional tsunami warning system, a thorough public education program and an improved tsunami warning dissemination capability will be needed for Indonesia to provide near real-time tsunami warnings in the future.

5. Conclusions

Based on the history of past earthquakes and tsunamis that have occurred in Indonesia, it is important that the design of offshore platforms for Indonesia's oil fields always take into consideration the threat of potential tsunamis. At the present time, tsunami events, just like earthquakes, cannot be predicted with any degree of accuracy for the short term, that is in weeks, months or even years. However, such events are very likely to occur again along the above designated hazard zones. Real time tsunami warnings cannot be effectively issued at the present time for Indonesia because a regional tsunami warning system and the warning dissemination capability are not presently in place. However, regardless of whether tsunami warnings can be issued or not, it is possible to design properly offshore platforms that will withstand the effects of earthquakes and tsunamis.

A promising proposition in understanding further the tsunami hazard in Indonesia will be to conduct research on how to forecast tsunamis in any certain hazard zone, such as the above-designated A, B, C zones or elsewhere. If the forecast of the tsunami in that certain region can be conducted, then Prof. R. Bea's conclusions in his paper entitled "Risk Based, Oceanographic & Earthquake Load and Resistance Factor Criteria for Design and Requalification of Platforms Offshore Indonesia", which includes earthquake design and requalification criteria as basic to the desired reliability of the offshore platforms, needs to add consideration of tsunamis as a secondary hazard of earthquakes. Recently, Mr. Hamzah Latief, Nanang Puspito, and Fumihiko Imamura from the Disaster Control Research Center at Tohoku University, Japan [7], made a tsunami occurrence map in the Indonesian Archipelago. They divided the archipelago into six tsunami zones, including causes (figure 3). Each zone has its own characteristics such as magnitudes, probability of recurrence, run-up heights, etc. These results can certainly facilitate the long-term tsunami forecasting in the Indonesian Archipelago and the analysis of design adequacy and the safety and reliability of offshore oil platforms.

Finally, W. J. Graff recommended that providing offshore oil platforms with air gap deck clearance of about 5-10 ft could reduce the risk of losing a structure because of a freak wave higher than the maximum design wave appreciably. But considering the threat of the tsunami hazard in the region, perhaps the deck clearance of oil platforms should be higher. At this time, an exact value of deck
clearance cannot be suggested. Experimental laboratory work must be undertaken at the Maneuvering and Ocean Basin (MOB) facility.

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