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Farrokh Nadim* Thomas Glade†

*International Center of Geohazards, farrokh.nadim@ngi.no

†University of Bonn, Germany, thomas.glade@uni-bonn.de

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On tsunami risk assessment for the west coast of Thailand

F. Nadim[1] and T. Glade[2]

[1] International Centre for Geohazards / Norwegian Geotechnical Institute, P.O. Box 3930 Ullevaal Stadion, NO-0806, Oslo, Norway; PH (+47) 22023000; FAX (+47) 22230448; email: farrokh.nadim@ngi.no
[2] University of Bonn, Department of Geography, Meckenheimer Allee 166, D-53115 Bonn, Germany, PH (+49)(0)228–739098; FAX (+49)(0)228–739099; email: thomas.glade@uni-bonn.de

Abstract

The catastrophic Indian Ocean tsunami of 26 December 2004 raised a number of questions for scientists and politicians on how to deal with the tsunami risk in coastal regions. This paper discusses the challenges in tsunami risk evaluation and presents the results of a tsunami risk mitigation study for the west coast of Thailand. It is argued that a scenario-based approach is particularly well suited for evaluation of the risk posed by tsunamis. The approach consists of considering scenarios of plausible extreme, tsunami-generating events, computing the tsunami inundation levels caused by these events, estimating the possible range of casualties for the computed inundation levels, and estimating the upper and lower bounds on the annual probability of occurrence of the scenarios.

Other challenges related to perceived risk vs. real risk, acceptable/tolerable risk levels, and the use of the results in the decision making process are also put into perspectives.

Introduction

The Indian Ocean tsunami of 26 December 2004 was triggered by a gigantic magnitude 9.3 earthquake on the Sunda Arc subduction zone. The tsunami caused over 250,000 casualties, and devastated large areas along the coastlines of Indonesia, Thailand, Malaysia, Myanmar, Sri Lanka, India, the Maldives and even some parts of the east African coast. Along the west coast of Thailand, the tsunami caused about 8,000 fatalities due to inundation levels of 5 to 12 m above the sea level at the most severely affected areas.

In the aftermath of this catastrophic event, the Norwegian Geotechnical Institute (NGI) did a fast-track study (NGI, 2006) for the Department of Mineral Resources (DMR) and the Coordinating Committee for Geoscience Programs in East and Southeast Asia (CCOP). The aim of the study was to assess the future tsunami risk in Thailand, and to help develop a reconstruction and rehabilitation strategy for the tsunami-affected areas of the country. The assessment and quantification of future tsunami risk presented a number of challenges. This caused some difficulties in applying the same methods as commonly used for other natural dangers. The risk assessment approach adopted for the project and the obtained results are presented in the paper.

The risk assessment terminology used in this paper is consistent with the "Glossary of Terms for Risk Assessment" developed by Technical Committee on Risk Assessment and Management (TC32) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) (www.engmath.dal.ca/tc32). Definitions of some of the important terms used in the paper are provided in the following.

Danger (Threat): The natural phenomenon that could lead to damage, described in terms of its geometry, magnitude, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as a tsunami). The characterization of a danger or threat does not include any spatio-temporal probability or forecasting.

Hazard: Probability that a particular danger (threat) occurs within a given period of time.

Consequence: In relation to risk analysis, the outcome or result of a hazard being realized.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, and/or the environment. Quantitatively, Risk = f (Hazard, Potential Worth of Loss). This is commonly expressed as "Probability of an adverse event times the consequences of that event".

Risk mitigation: A selective application of appropriate techniques and management principles to reduce or even avoid either likelihood of an occurrence or its adverse consequences, or both.

Acceptable risk: A risk which everyone impacted is prepared to accept. Action to further reduce such risk is usually not required unless reasonably practicable measures are available at low cost in terms of money, time and effort.

Tolerable risk: A risk within a range that society can live with so as to secure certain net benefits. It is a range of risks regarded as non-negligible and needing to be kept under review and reduced further if possible.

ALARP (As Low As Reasonably Practicable) principle: The principle which states that risks, lower than the limit of tolerability, are tolerable only if risk reduction is impracticable or if its cost is grossly in disproportion (depending on the level of risk) to the improvement gained.

Challenges in tsunami-risk assessment

In modern engineering practice, buildings, infrastructure and lifelines are designed to withstand environmental load effects, such as earthquake acceleration, flood level, ground movements or wind velocity, which are caused by an event with a given annual probability of exceedance – and preferably defined spatial extent. For example, Eurocode-8 recommends a return period of 475 years (10% probability of exceedance in 50 years) at a given location for the design of normal residential buildings against earthquake loads, and somewhat higher return periods for schools, hospitals, fire stations and buildings where many people might be gathered and potentially affected (CEN, 2002). The framework behind this methodology is a reliability-based design approach which assumes that the annual extremes of the load effect in question have a well-behaved, continuous distribution. The code-specified design return period and associated partial safety factors indirectly imply a target (acceptable) failure probability for the structure, or the set of structures in question.

The tsunami load effects do not lend themselves easily to this simplification. The physical process characteristics of the potential triggers of a tsunami are such that there exists a lower threshold return period, below which the expected tsunami wave height is insignificant in terms of likely consequences, and above which it increases rapidly up to an upper threshold level. If this upper threshold is exceeded, total loss is unavoidable. Such thresholds have already been discussed for other natural processes, such as landslides and debris flows (e.g. Wieczorek & Glade 2005).

These threshold characteristics make the tsunami an 'ill-behaving' load in a probabilistic framework, i.e. tsunami wave height vs. return period (on a log-scale) is expected to be *highly* non-linear. Other challenges related to tsunami risk assessment are dealing with low hazard events that have extreme severe consequences, whether an effective tsunami warning system will be in operation, uncertainties in estimation of tsunami load effects due to scarcity of data, communication of the warnings to the potentially endangered society, issues related to risk perception by different groups of potentially affected society, and, in terms of preventive measures, on acceptable societal risk criteria. Four issues are especially important to keep in mind while addressing these challenges:

1. Risk mitigation measures should be for potential future tsunamis, not for the tsunami that happened on 26 December 2004.
2. Tsunamis with similar or even larger magnitudes have occurred in these areas long before humans settled. Thus tsunamis are part of the general “set” of natural processes operating in these regions and consequently, it is just a matter of time until the next tsunami of even greater magnitude will occur.
3. It is vital to have a long-term view of the problem. The actions taken today will affect the exposure of future generations to tsunami risk.

4. If the present trends in population growth and development along the coastlines continue, the exposure of the societies along the coastlines to tsunami risk will increase.

Characteristics of tsunami from an engineering design perspective

Most common environmental loads and load effects, such as the stresses induced in a structure by earthquake, wind, and snow, or the highest water level in a river during a flood event, can be classified as 'well-behaving' loads in a probabilistic sense (Figure 1). These loads exhibit a more or less linear characteristic on a plot showing the load-level vs. the logarithm of return period.

The well-behaving loads fit nicely into the partial safety factor format of modern design codes. The code defines the return period of the design event and the partial safety factors that are used to obtain a target reliability level (i.e. an acceptable annual failure probability).

Unfortunately, the tsunami wave height falls into the category of 'ill-behaving' loads from an engineering design perspective as it exhibits a highly non-linear behavior in the type of plot shown on Figure 1. Such characteristics are known from other natural process and are currently investigated in terms of non-linearity, complexity, chaos, and emergence (e.g. Harrison, 2001; Phillips, 2003). Due to the characteristics of the physical processes governing the tsunami, there exists a threshold return period below which the expected tsunami wave height is insignificant (earthquakes with magnitude less than 7.5 rarely trigger a tsunami), and above which it increases rapidly.

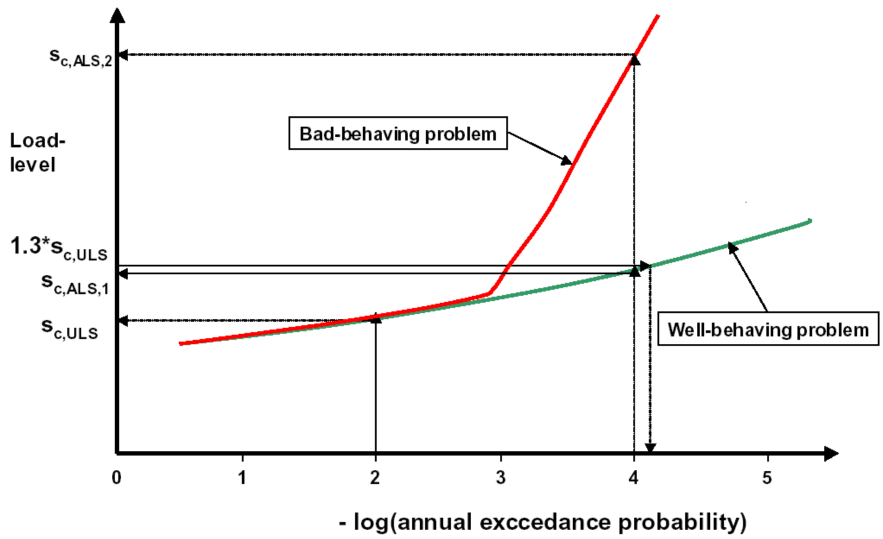

Figure 1. Theoretical examples of "well-behaving" and "ill-behaving" loads with respect to engineering practice (Haver, 2005).

There are other types of geohazards, for example debris flow, for which the magnitude or intensity of the triggering mechanism should be above a threshold value before the process is initiated. All the 'threshold-dependent' processes would fall into the ‘ill-behaving’ load category from an engineering design perspective, and they do not fit well into the design formats developed for well-behaving loads.

On the other hand, there are several aspects of the tsunami load which are well defined. The direction of the loading is given, and the area affected by the load is, in most situations, limited to a few hundred meters from the shoreline. This makes the tsunami problem ideal for scenario (what-if) studies. By considering a few plausible scenarios of extreme events, the geographical extent of the potentially affected areas can be identified, risk reduction measures can be suggested and locally adopted, and accepted strategies can be implemented. The physical consequences of the scenario tsunami events (i.e. maximum water level, water flow velocity and inundation distance from the shoreline), combined with the physical and social constraints as well as coping possibilities in the areas of interest, form the basis for risk mitigation measures as part of long-term risk management strategies. The knowledge of the potential consequence of a future tsunami event might support decision-makers at regional (municipality), national (government) or global levels (United Nations organizations) of governmental as well as non-governmental organizations (e.g. Red Cross, Terre des hommes) in their decisions for preventive actions (e.g. education, land-use planning) as well as for immediate responses to a forthcoming event.

Risk and its perception

The most complete description of the possible losses (risk) is quantitatively in terms of a “probability distribution”, which presents the relative likelihood of any particular loss value or the probability of losses being less than any particular value. Alternatively, the “expected value” (i.e., the probability weighted average value) of loss can be determined as a single measure of risk. A general scenario-based risk formulation is given by:

$$E[Loss] = \sum_{All\ S} \sum_{All\ \underline{C}} \underline{C} \cdot P[\underline{C} \mid S] \cdot P[S]$$

where $\underline{C}$ is particular set of losses (of comprehensive and mutually exclusive set of possible losses), S is particular scenario (of comprehensive and mutually exclusive discrete set of possible scenarios), P[S] is probability of occurrence of scenario S, P[$\underline{C}$ | S] is the conditional probability of loss set $\underline{C}$ given that scenario S has occurred, and E[Loss] is the “expected value” of loss. “Loss” may refer to any undesirable consequence, such as loss of human life, economic loss, loss of reputation, etc., in terms of its direct and indirect effects (e.g. local damage of railway tracks and related interruption of industrial traffic), its affects on different social groups (e.g. individuals, community, insurance, government) as well as its short- and long-term influences on a society (e.g. fatalities could include all children of a community, the tourist industry might collapse). The focus of the present study was on the loss of human life.

Calculation of the terms in the above equation is not trivial. As it will be shown later, the hazard term in the above equation (i.e. P[S]) is not constant with time. Moreover, the expected number of fatalities depends on many factors, for example on which week-day and what time of the day the tsunami occurs, whether the tsunami occurs during high tide or low tide, whether or not an effective tsunami warning system is operative at the time of the tsunami, how the issued warning is communicated to the respective groups and individuals, public awareness on what to do if tsunami warning is issued, etc. An implicit assumption in the study is that an effective tsunami warning will be in place in Thailand and other countries around the Indian Ocean within a few years. Although various organizations and institutions work on the implementation of such an early warning system, this assumption may prove to be problematic.

The potentially affected population could be divided into three groups based on their temporal exposure to the tsunami danger, and their choice in exposing themselves to risk: 1) people who live in the exposed areas permanently, 2) tourists who only live in the exposed areas one or two weeks each year, and 3) locals who do not live in the exposed areas, but work there during the tourist season. The risk considerations for the 3 groups are not the same. What matters for the first group is the "real risk" (which might be impossible to quantify) which is taken deliberately or unconsciously, while the "perceived risk" influences heavily the behavior of the second group, because their exposure to the "real risk" is much lower than the first group due to their limited temporal exposure. The number of people comprising the third group is strongly correlated to the number of tourists, so for this group both the real risk and the perceived risk are important.

The real risk and the perceived risk for the tsunami are likely to be quite different. The tsunami modeling studies done for the project showed that the most likely source for a tsunami on the west coast of Thailand is a major shallow earthquake on the northern section of the Sumatra-Andaman subduction zone. Considering that this section of the fault experienced a magnitude 9.3 earthquake in December 2004 and a magnitude 8.7 earthquake in March 2005 (Nias earthquake), it is not likely that a similar event would occur in the next few hundred years. One of the key conclusions of the present study is that much of the energy stored on the fault is already released and it will take several hundred years before the fault has the potential of being the source of a magnitude 9+ earthquake again. Consequently the scientifically derived annual probability of a major tsunami event in western Thailand during the next fifty to hundred years is extremely low. However, the *perceived risk* of a tsunami in that area is much higher because of the event that did happen recently, and this is what really matters for various social groups, including the decision-makers and the tourist industry in Thailand. In addition, social groups were affected globally, as the fatalities included also Europeans, Americans, Japanese, etc., and were not limited to local population only – which is the case in most other extreme events such as earthquakes or floods. Consequently, there is a global involvement of a locally occurring event.

A rare event with extreme consequence

As the Indian Ocean tsunami of 26 December 2004 tragically demonstrated, a rare, extreme tsunami event might cause thousands of fatalities. When the probability of occurrence of an undesirable event (e.g. hazard) is extremely low and the consequences have the potential to be extremely high, the calculated risk in terms of expected human fatalities is highly uncertain. The calculated risk is essentially a zero times infinity problem. This implies that an outcome could change by several orders of magnitude due to very small variations in the initial assumptions. To a lesser degree, this issue is also a problem for estimating the risk posed by an extreme earthquake or landslide. An argument that is sometimes used to distinguish earthquakes or large landslides, which are relatively rare events, from other, more frequent natural hazards, such as storms, floods, etc., is that latter often have a stronger place in societal memory. Tsunamis are further up on that same scale.

Calculation of tsunami hazard and risk in Thailand

In contrast to other process investigations, not enough data are currently available to establish the magnitude-frequency statistics for tsunamis in the Indian Ocean. Therefore, to establish such relationships, other techniques, such as the Probabilistic Tsunami Hazard Analysis (PTHA) approach (Thio *et al.*, 2005), should be employed. Although PTHA has the potential to provide a rational framework for tsunami-resistant design in the future, there are too many weak links in the model at present to form the basis for making decisions, the most important of which is the link between the earthquake magnitude and depth, and seabed dislocations. Developing a reliable PTHA framework for the coastal areas of Thailand and other countries around the Indian Ocean was considered beyond the scope of the project.

The approach that was adopted for the study was to consider several scenarios of plausible extreme, tsunami-generating earthquakes (and/or tsunami-generating submarine slides, e.g. Tappin *et al.*, 2001), compute the tsunami wave heights triggered by these events, and estimate the upper and lower bounds on the annual probability of occurrence of the scenarios. It involved the following steps:

1. Define scenarios for tsunami-generating earthquakes.
2. Compute the tsunami inundation levels for the scenario earthquake events.
3. Estimate the tsunami risk for the different scenarios.
4. Compare the estimated risk with tolerable or acceptable risk levels.

As mentioned earlier, this scenario-based approach is particularly well suited for tsunamis because of their physical characteristics. For example, the direction of the tsunami wave and potentially affected areas are known beforehand, and reliable software for calculation of the propagation of the tsunami waves resulting from sea floor displacements due to a fault movement or a submarine slide is available.

The seismic hazard evaluation performed in the study concluded that within the next 50 to 100 years, the largest credible earthquake to be prepared for is a magnitude 8.5 event (Harbitz *et al.*, 2006). The event could cause a tsunami which at the most gives an inundation level of 1.5 to 2.0 m above sea level. If the tsunami occurs at high tide, the inundation level could be 2.5 to 3.0 m above the mean sea level (Harbitz *et al.*, 2006). After about 100 to 200 years, the potential for earthquakes greater than M 8.5 will increase gradually, and so does the potential for generating larger tsunamis than that for the M 8.5 earthquake scenario (NGI, 2006; Karlsrud *et* *al.*, 2005). The return period for the tsunami-generating M 8.5 event was estimated to be 200 to 800 years.

The estimate of the return period of a magnitude 9.3 earthquake, similar to the one that caused the tsunami on 26 December 2004, vary between 400 years using the subduction rate, and 1140 years using the seismicity statistics (Harbitz *et al.*, 2006). A key issue regarding the return period is the timing of major earthquake events within the occurrence cycle. The evaluations suggested that an M 9+ earthquake in the Sumatra subduction zone with potential tsunami effects on Thailand will most likely not occur before at least 400 years after the 2004 megathrust earthquake. For the M 8 to 8.5 earthquakes the cyclicity is less predictable (i.e. the occurrence is more random within recurrence interval), but even for such events the probability of occurrence will be quite low for a long time after 2004, increasing gradually with time. In the long-term perspective (100 – 200 years), risk mitigation measures should protect the exposed population from a tsunami similar to the one that occurred on 26 December 2004, i.e. 5 to 12 m above the mean sea level. It should be noted, however, that the maximum tsunami wave heights along the west coast of Thailand and their spatial variation for a future M 9.3 earthquake may be quite different from those observed during the 26 December 2004 event. The possible range of characteristics of a future extreme tsunami event needs further investigation.

Is the tsunami risk in Thailand acceptable?

A part of risk assessment and risk management is to deal with risk acceptance criteria. In the context of the present study, one of the key questions was “Is tsunami risk level in Thailand acceptable?” Here, it is important to recognize the difference between acceptable and tolerable risks defined earlier. This differentiation is often reflected through the use of the so-called ‘F-N curves’. The F-N curves relate the annual probability of causing N or more fatalities (F) to the number of fatalities, N. This is the complementary cumulative distribution function. The term "N" can be replaced by any other quantitative measure of consequences, such as monetary measures. Such curves may be used to express societal risk criteria and to describe the safety levels of particular facilities.

It is also important to clarify who defines the levels of acceptance and tolerance: The potentially affected population? A government agency? The design engineer? This is crucial for further decisions on mitigation measures.

The application of societal risk to life criteria is to reflect the reality that society is less tolerant of events in which a large number of lives are lost in a single event, than if the same number of lives is lost in a large number of separate events (e.g. Alexander, 2000). Examples are public concern to the loss of large numbers of lives in airline crashes, compared to the many more lives lost in road traffic or small aircraft accidents (e.g. Alexander, 2002).

The use of cumulative F-N curves to reflect this is not universal. An example which has been tried on an interim basis in Hong Kong to assist landslide risk management of natural hillside hazards is shown in Figure 2 (GEO, 1998; Malone, 2005). The criteria depicted on Figure 2 were used to deem the tsunami risk level in Thailand.

Based on the return period estimates for tsunami scenarios, the recommended design water levels, and the experience from the 26 December 2004 tsunami, the annual risk to human life from a tsunami on the west coast of Thailand, and the changes in this risk with time can be estimated. The Indian Ocean tsunami of 26 December 2004 caused very few casualties (none recorded in the available data-bases) in the coastal areas of Thailand where the inundation level was less than 3 m. The main reason is that the coastal areas in west Thailand reach a level of 4-5 m above mean level at a very short distance from the shoreline. Almost all the fatalities in Thailand occurred in areas where the inundation level was more than 5 m above the mean sea level. This is in contrast to the affected coastal regions in India and Sri Lanka where the elevation of 3 m above sea level is reached several hundred meters from the shoreline, and where many people died in areas where the inundation level was about 3 m.

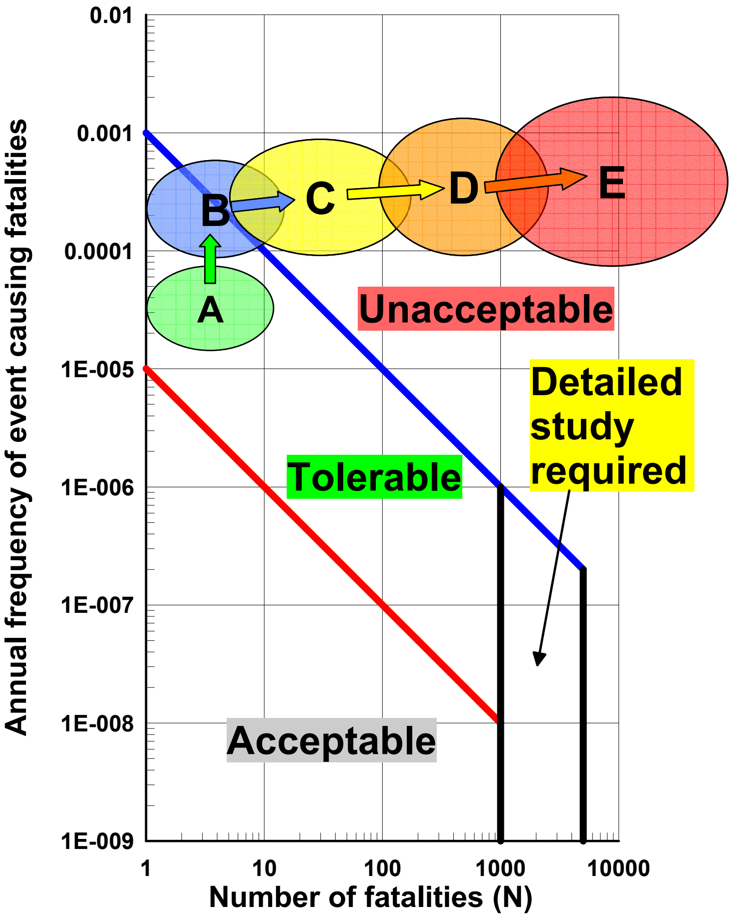

Figure 2. Estimated risk of tsunami in Thailand plotted against the societal risk tolerance criteria of GEO (1998) of Hong Kong. Zone A represents the best estimate of the tsunami risk in Thailand today. Zone E represents the situation prior to the tsunami of 26 December 2004 and also the long-term situation after four to five hundred years if no risk mitigation is done. Zones B, C and D are respectively representative of the situations after 50-100 years, 150-200 years, and 250-300 years if no risk mitigation is done.

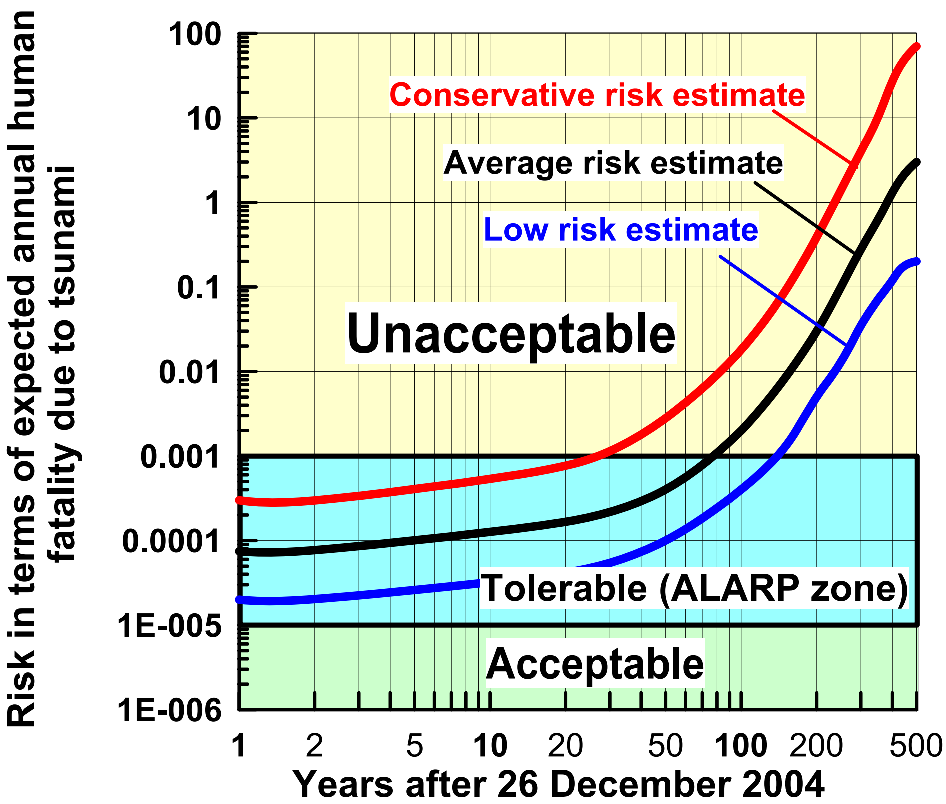

Figure 3 Risk levels implied by the zones in Figure 2 simplified to risk in terms of expected number of fatalities per year (averaged over several hundred years) due to tsunami along the west coast of Thailand (ALARP: As Low As Reasonably Practicable).

Figure 2 shows the estimated risk plotted on the societal risk acceptance criteria diagram for Hong Kong. Zone A represents the best estimate of the tsunami risk in Thailand for the next 50 to 100 years. This risk is associated with the occurrence of an M 8.5 earthquake at a critical location on the Sumatra-Andaman subduction zone. Zone E, which clearly represents an unacceptable situation, represents the situation prior to the tsunami of 26 December 2004 and also the long-term situation after several hundred years if no risk mitigation is done. Figure 3 shows a simplified version of the risk depicted on Figure 2 where the vertical axis represents risk in terms of the expected annual human fatalities (averaged over several hundred years) in Thailand to due a tsunami. The 10^{-5} and 10^{-3} bounds on the vertical axis of Figure 3, which respectively define the boundaries between acceptable vs. tolerable risk, and tolerable vs. unacceptable risk, are based on the bounds defined by GEO on Figure 2.

The main conclusion that can be drawn from Figures 2 and 3 is that, as far as the tsunami risk in Thailand is concerned, the present day situation without risk mitigation measures is marginally acceptable and will remain so for one or two generations. However, a long-term strategy must be implemented to mitigate the tsunami risk by reducing the vulnerability and enhancing the coping potential of the exposed population to an event similar to the one that occurred on 26 December 2004.

Conclusions

The main conclusions regarding future tsunami risk in Thailand are:

1. Within the next 50 to 100 years, the largest credible earthquake to be prepared for is a magnitude 8.5 event. The event could cause a tsunami which at the most gives an inundation level of 1.5 to 2.0 m above sea level. If the tsunami occurs at high tide, the inundation level could be 2.5 to 3.0 m above the mean sea level.
2. After about 100 to 200 years, the potential for earthquakes greater than M 8.5 will increase gradually, and so does the potential for generating larger tsunamis than that for the M 8.5 earthquake scenario. This implies that, as time passes by, the tsunami risk will gradually increase from tolerable to highly unacceptable.
3. Within the next 50 to 100 years, the potential risk from tsunamis to human life and property in Thailand will be small and can be regarded as tolerable. Therefore, in the short to medium term perspective, no mitigation measures would strictly be required. However, already now steps should be taken to reduce the more long term risk of human casualties
4. Despite the calculated low risk in the near future, it is purely a matter of time until the next large tsunami event occurs. This time should be used to develop a strategic plan to increase preparedness of the potentially affected society. Preparedness measures include structural design codes and physical barriers, but range also from land-use planning and early warning systems to education of population and building monuments to remind the future generations of the tsunami danger.

If no risk mitigation measures are planned and implemented in the reasonably near future, it is likely that the long term tsunami risk will be forgotten within one or two generations. No significant tsunamis are expected to occur within the next 50 years or so, and the collective memory of the society in relation to natural hazards that occur infrequently has repeatedly been proven to be short. It is therefore recommended that the authorities in Thailand already now plan for implementation of some mitigation measures that can reduce the risk posed by severe tsunamis to future generations. One cannot influence the earthquake and tsunami hazard, so the only way to reduce the risk is to mitigate their consequences. The mitigation measures that could/should be implemented in the short-term and long-term perspectives are categorized and prioritized in NGI (2006).

Acknowledgments

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