Comprehensive Flood Risk Management – Klijn & Schweckendiek (eds)

A multi-layered safety perspective on the tsunami disaster in Tohoku, Japan

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ABSTRACT: This paper presents an assessment of the multi-layered safety system in Tohoku, Japan based on the tsunami disaster of March 2011. The performed analysis has been based on data provided by local researchers and field observations. First an overview of the tsunami behaviour along the affected coastline of Tohoku is presented, which shows clearly that the disaster has site-specific features. The assessment that follows has a descriptive character and it is divided in two parts. First the performance of each safety layer in Tohoku is separately assessed, and conclusions are drawn for the efficiency of the system. The second part points out some implications of this disaster for the use of multi-layered safety in flood risk management.

Keywords: multi-layer safety; disaster management; tsunami

1 INTRODUCTION

The tsunami that hit the north pacific coast of Japan on March 11, 2011 has been characterized as a mega disaster. It inundated over 560 square kilometers of land, devastating a large number of coastal communities, causing over 19,200 casualties and huge economic damage in Tohoku region. As many catastrophic tsunamis have been recorded in the history of Tohoku and seismologists had remarked the high probability of a major earthquake that could generate a tsunami in Japan, the region was considered highly prepared against tsunami. However the event of March 11, whose return period has been suggested to 1/500–1/1000 years (Fujita 2011), exceeded all pre-disaster assumptions used in the Japanese disaster management (CDMC 2011). Being designed to resist much smaller tsunamis, the primary defences, such as breakwaters, tsunami walls and coastal levees were overtopped and suffered severe damage. As an overload of primary defences is not uncommon in tsunami-prone areas, a variety of measures for the mitigation of damage and casualties, such as allocation of important community functions in higher grounds and emergency plans were combined with primary defences in Tohoku. This compound of measures that focus on both the reduction of risk probability and mitigation of damage in case that a disaster occurs, signifies a so-called multi-layer safety system.

Multi-layer safety is a flood risk management concept that introduces the integration of probability-reducing and loss-mitigating measures in a flood protection system. The same concept can be found in international literature under similar terms, such as "multi-level approach" or "multiple-lines of protection". The term "multi-layer safety" is mainly used in the Dutch flood risk management, and also appears in the National Water Plan of The Netherlands. The concept is being further developed in The Netherlands, where a rational framework for the cost-efficient use of multiple layers of safety is studied.

The theoretical basis of multi-layer safety in The Netherlands is the classification of measures in safety layers, which can be described as follows (Hoss et al. 2011):

- Layer 1—Prevention: Prevention is defined as preventing river and seawater from inundating areas that are usually dry. This is done by building flood defenses or preventing high river discharges.
- Layer 2—Spatial Solutions: Spatial solutions mean using spatial planning and adaptation of buildings to decrease the loss if a flood occurs.
- Layer 3—Emergency Management: This layer focuses on the organizational preparation for floods such as disaster plans, risk maps, early-warning systems, evacuation, temporary physical measures such as sandbags, and medical help.

The three safety layers can be graphically presented as follows:

Figure 1. Graphical representation of multi-layered safety (Kolen et al. 2010).

This paper presents an assessment of the Japanese flood protection measures in Tohoku during the tsunami of March 2011, considering a multi-layer safety perspective. The record of such a major disaster offers ample opportunity to investigate and assess the response of the multiple layers of safety. The performed analysis has been based on data provided by local researchers and field observations. First an overview of the tsunami behaviour along the affected coastline of Tohoku is presented, which shows clearly that the disaster has site-specific features. Next a descriptive assessment of the performance of each safety layer during the disaster is discussed based on field observations and information provided by Japanese institutes, with respect to the basic principles of multi-layered safety. This process is facilitated by the questions "what went wrong" and "what performed as expected". The assessment ends with a discussion about the general attributes of multi-layered safety in Tohoku, which allows for a comprehensive understanding of the overall performance during the disaster. Based on this discussion some conclusions about the further development and improvement of the multi-layer safety concept are drawn.

2 TSUNAMI BEHAVIOUR ALONG TOHOKU COASTLINE

Some significant morphological variations can be noted along the coastline of Tohoku, which are responsible for the variation of the coastal tsunami behaviour. In particular two coast types can be distinguished, along which different disaster patterns can be identified (Mori et al. 2011 & 2012); 1) the rias coast in the northern half of Tohoku, and 2) the flat plains coast in the southern half (Fig. 1). It should be noted that the primary coastal defences were also of different type in the two regions. The coast types and their characteristics regarding the tsunami behaviour and the type of structures in each coast type are presented below.

2.1 *Rias coast*

The rias coast extends along Iwate prefecture and the northern half of Miyagi prefecture. Rias are fyord-like shaped coastal inlets formed by the submergence of former river valleys. The rias coasts are therefore extremely irregular and indented in places, forming narrow and steep bays. At this type of coast, due to bathymetry focusing effects, the tsunami height increases. The narrow bays are surrounded by high grounds that face the ocean with steep cliffs, and relatively deep sea in the front. The basin created by the high grounds obstructs the intrusion of seawater far inland, which, combined with the increased tsunami height, resulted in large inundation and run-up heights.

Most urban and industrial areas in the rias are built in the basins that surround the narrow bays; hence the majority of coastal defences in this part are concentrated in the bays.

2.2 *Flat plain coast*

Large low-lying areas fronted by mild-sloped sandy beaches characterize the southern half of Tohoku, starting from the coast of Sendai city in Miyagi prefecture, extending to Fukushima and further to the south. Unlike the case in the rias, the tsunami intrusion is not obstructed by high grounds in the

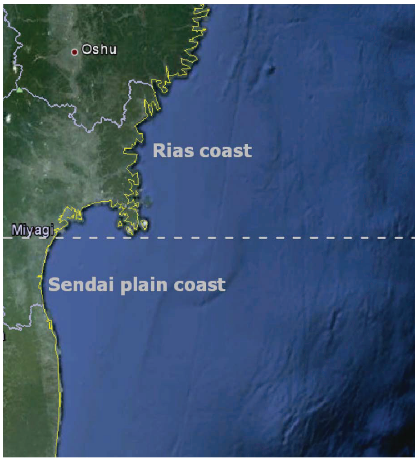

Figure 2. Coast types in Tohoku.

Figure 3. Inundation area in Minamisanriku, rias.

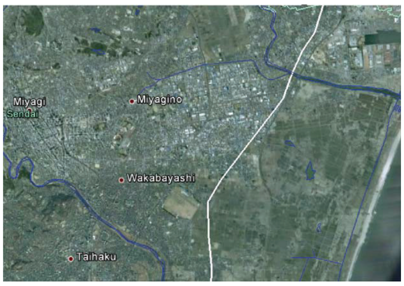

Figure 4. Inundation area on the frontage of Sendai.

flat plains. At this type of coast, the tsunami broke near the shore and propagated inland, inundating large areas of flat land, while much lower inundation heights were recorded.

At this type of coast long lines of land-based coastal levees protect the inner land, where agricultural, urban and industrial functions can be found. Fukushima Daiichi nuclear power station, where the major nuclear catastrophe took place due to the tsunami inundation, lies in the flat plain coastal area.

3 RESPONSE OF TOHOKU MULTI-LAYERED SAFETY

A combination of structural and non-structural measures, representative of all the three layers of multi-layered safety can be found in Tohoku region. Their role is to prevent inundation or to mitigate its impact if prevention fails. Most structural measures belong to layers 1 and 2 of multi-layer safety. The types of structures and the degree of safety they provide are not uniform along the entire coastline, but they vary depending on the coastal morphology and the social and economic value of the protected land. Layer 3 consists mainly of non-structural measures, and also presents variations along the different coastal types regarding the type of measures and the degree of safety they provide. An overview of the most common flood risk countermeasures in the two coast types of Tohoku are shown in the Figures below. They are further described in the following paragraphs.

The entire flood protection system of Tohoku region was overwhelmed by the tsunami of March 11, 2011. This section presents a qualitative interpretation to the response of the multiple layers of safety in Tohoku during the tsunami attack, based on field observations and information provided by Japanese scientific institutes. The presented assessment has a preliminary character. Due to the variations of measures and safety levels along the coastline, a detailed assessment of multi-layered safety would require the performance of site-specific analyses.

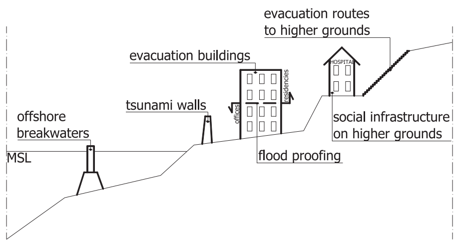

Figure 5. Flood risk countermeasures in the rias.

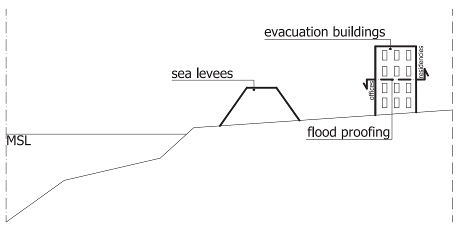

Figure 6. Flood risk countermeasures in flat plain region.

3.1 *Layer 1: Prevention*

The measures of layer 1 encountered in Tohoku were structures of different types along the rias and along the flat plain coastal zone of Sendai region. The primary defences along the rias consisted mainly of offshore breakwaters and tsunami walls, while along the flat plains coastal levees on the sandy frontage were the most common defence.

These structures suffered severe damages with some of them failing catastrophically. Based on this fact, it becomes clear that their structural resistance was exceeded by the tsunami of March 11, 2011. It is also notable that although all of them were located on a tsunami-prone coast, there was no consistency in their design specifications. Some of them were designed to withstand tsunamis, such as the offshore breakwater of Ofunato in the rias, while others were designed against storm waves, such as the breakwater of Onagawa in the rias and most of the coastal levees in Sendai area. These variations could be justified by a general tendency in the Japanese flood risk management to design new defences based on previously occurred extreme events. The difference in time that those structures were constructed and the available amount of knowledge at the time in terms of recorded extreme storms and tsunamis can explain the inconsistency in design specifications. Some structures were much younger than others and possibly designed to resist higher loads. Moreover, depending on the preparedness and the value of the protected area in terms of population and wealth, it is expected to have variations in the design specifications of coastal defenses. In any case the tsunami of March 11, 2011 was an exceptional event with a low frequency, and it is quite possible that preventing inundation by rising high enough and strong defences is not cost-effective. This could only be proved by means of a cost-benefit analysis.

It should be noted that although most of the coastal defences failed, they seem to have played a role in the mitigation of inundation heights in the protected land (Mori et al. 2011). Some further research on this topic might have interesting outcomes. It is characteristic that the recorded inundation heights in Ofunato that was protected by a tsunami breakwater were much lower than other cities with similar morphologies and no tsunami breakwater.

3.2 *Layer 2: Spatial solutions*

Due to the fact that the tsunami exceeded the design specifications of prevention measures, urban areas were exposed to inundation. Hence layer 2 had to play a crucial role in the mitigation of damage and the prevention of casualties. As spatial solutions are applied in a smaller geographical scale than measures of layer 1, a thorough assessment of the response of layer 2 measures to the tsunami in Tohoku would require a more detailed observation of the affected urban areas with separate visits and detailed data for every town and settlement. The following assessment is only based on general characteristics of the urban areas in Tohoku that could be distinguished during the field observations, and on information provided in the post-event reports of Japanese institutions.

The spatial arrangements that seem to be part of layer 2 measures are the allocation of important social infrastructure buildings in higher grounds, and the flood proofing of high buildings by accommodating the most important functions in higher floors. Among the functions that need to stay unaffected during a tsunami are schools, as the exposure of kids is usually considered much more costly than the rest of population. A case of compartmentization was also noticed in the area of Sendai, where the existence of a highway seemed to have limited inundation of Sendai plain. It is unlikely though that its flood risk mitigating function was ever considered.

Concerning the allocation of community functions on higher grounds, it should be noted that not all essential functions stayed unaffected. There were schools and hospitals located on high enough grounds that stayed unaffected or less affected than the majority of buildings. Such case is a school in Minamisanriku on 47 m-ground elevation. Another case is the hospital of Onagawa on a ground elevation of 15 m, where only the ground floor was inundated. The location of those buildings may have been decided taking into account the risk of a tsunami, but only the local authorities can confirm this. On the other hand, there were important administration buildings that were severely damaged and could not be used anymore, such as the city hall of Rikuzentakata and Watari. The city hall of Rikuzentakata is located on 7 m-ground elevation, which means that the building would be exposed even if a much smaller tsunami occurred. It is therefore doubtful in which degree attention was paid in the use of spatial planning for the enhancement of flood protection. As for the flood proofing of buildings, some occasional measures could be found, such as the case of an eight-floor building in Kamaishi city, where residencies were concentrated in the higher floors, while the lower floors were only used as offices. This seems to be a measure for the reduction of vulnerability. Another measure that could be classified in layer 2 is the construction of tsunami-resistant buildings. Although the design of tsunami-resistant buildings is not mandatory, there were a few buildings designed against tsunami loads, such as the evacuation building on the frontage of Minamisanriku that survived. Nevertheless not only tsunami-resistant, but also conventional concrete buildings withstood the tsunami forces, which could be possible due to their anti-seismic design. Although a different type of loading is taken into account for earthquake proofing of buildings, it is possible that designing for a very strong earthquake makes the building resistant to the strong hydrodynamic tsunami forces, although buoyancy effects of hydrostatic pressure on buildings are not well considered for the most of existing anti-seismic designed buildings. Yet the majority of buildings in urban areas was made by wood and was swept. Furthermore most concrete buildings were not higher than 4 floors, therefore completely inundated in the areas that inundation reached 15 m, and their internal was completely destroyed. This fact implies the need for a careful consideration of risk in the choice of evacuation building, which is addressed in a following paragraph.

A general remark about layer 2 measures in Tohoku is that although they were distinct in urban areas, it is unknown if they were a deliberate choice with the purpose of reducing flood risk.

3.3 *Layer 3: Emergency management*

As many devastating tsunamis have been recorded in the history of Tohoku, the local communities were considered well prepared for the case of a catastrophic event, with early-warning and evacuation schemes playing a central role in the prevention of casualties, which is the greatest concern of all communities. Apart from that, the authorities responded immediately after the event for the recovery of victims, with the establishment of massive rescue missions and shelters.

The early warning system worked effectively, as the tsunami alarm was issued only three minutes after the earthquake (Shaw et al. 2011). The expected inundation heights though, as issued by the Japan Meteorological Agency, were exceeded. It should be remarked that despite the effectiveness of early warning system, some people had less than 30 minutes available to evacuate, which is an extremely short time, comparing to the time available for evacuation during other extreme coastal events. The inhabitants of New Orleans had 48 hours available after a mandatory evacuation was issued for the landfall of hurricane Katrina, while the same time is the expected early warning time in The Netherlands as well (Kolen et al. 2012).

Due to the frequent tsunami attacks in Sanriku region, the local society was well prepared and willing to evacuate. Moreover the so-called "tendenco" local culture of mutual trust may have prevented a

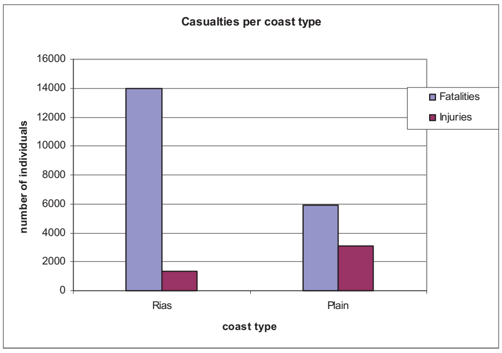

Figure 7. Recorded casualties in the rias and in the plain region (November 2011).

lot of casualties. The literal meaning of it is that people trust that their families will also be properly sheltered, and as a consequence, during a tsunami alarm, they shelter themselves immediately without looking for their family members first, which could take some precious time (Shaw et al. 2011). This is not the case in The Netherlands and New Orleans, or even in other coastal areas in Japan.

Concerning evacuation, different schemes were followed in the rias than in the flat plains. The morphology of the rias allowed evacuation both to the top of high buildings and higher grounds, which could be reached in relatively short time. In that area, due to the extreme inundation heights, that reached 20 meters in some locations, the local evacuation plans were overwhelmed, and many evacuation buildings were overtopped, exposing evacuees to further risk. A characteristic special case is an overtopped four-storey evacuation building on the waterfront of Minamisanriku, where luckily all evacuees survived, as the building was only just overtopped. It is notable that in that area a significant subsidence took place during the earthquake, which might have been crucial for the failure of the building as evacuation centre. These sort events should be taken into account for the improvement of both evacuation schemes and the design regulations of evacuation buildings.

In the low-lying areas of the Southern half of Tohoku, people could mostly evacuate to the top of high buildings, as higher grounds could not be reached in due time. Although inundation heights were lower in low-lying areas, and therefore the height of evacuation buildings sufficed for the protection of evacuees, it has been recorded that many people did not succeed to evacuate in time, as there were only a few evacuation centres covering too large areas.

Despite the degree of preparedness for evacuation among population, the death toll was much higher in the areas where inundation heights were very high. According to casualties' records available in November 2011, the fatalities in the plain region was 0.32% of the total population, whereas in the rias it reached 2.15%, which is about 7 times higher. The following graph, which is based on the same records, shows that fatalities in the rias outnumber fatalities in the plain region, while the rate of injuries over fatalities is lower. The inundation of evacuation centres can be one of the reasons for the much higher fatalities in the rias. The higher rate of injuries over fatalities in the plain implies that most people exposed to the tsunami flow in the rias died, while in the plain many of them survived.

It is important to note that the efficiency of evacuation cannot be substantially assessed based on the overall statistics of Tohoku. Site-specific analyses of facts are necessary. Although one could claim that evacuation was relatively effective, considering the total number of casualties compared to the magnitude of inundation, not all inundated land was urban or needed to be evacuated, while the number of casualties varies along the affected coast. A site-specific analysis of facts concerning evacuation would also contribute in the identification of needs in local, regional and national level, and therefore in the formulation of effective strategies for the future.

3.4 *Overall assessment*

The coastal zone of Tohoku is an area that has experienced several times in its modern history the devastating effects of a tsunami. Hence the idea of combining probability reducing with loss mitigating measures against tsunami had been reaching consensus even before the event of March 11, 2011. Measures of all three layers were present in Tohoku, yet layers 1 and 3 were much more developed than layer 2. Considering that layer 3 measures are mostly non-structural, and the fact that in an urban area most spatial interventions, i.e. layer 2, would require the consent and cooperation of the local inhabitants, who might have to accept major transformations in their properties, layer 2 measures can be characterized much less flexible and more costly than layer 3. Hence investing more in layer 3 seems to have been a reasonable choice for the increase of safety in the already developed coastal communities of Tohoku. It should be noted though that the uncertainty inherent in the functionality of layer 3 during an emergency are much higher and difficult to define in tsunami-prone areas, where the time available for evacuation is very short. In this case the functionality of layer 3 depends a lot on the behaviour of the local population, which can vary significantly in the different moments of the day. In this respect, layer 2 solutions can be much more reliable in tsunami-prone areas. Some further research on this topic could give interesting outcomes.

Due to the catastrophic impact of the tsunami in large parts of the coastal urban areas, a great opportunity has been created for Japan to develop layer 2 measures, which can have a significant contribution in the increase of water safety. Such measures could be the relocation of residencies and social infrastructure buildings in higher grounds or on mounds in the plain region, and the flood proofing of buildings in low-lying areas by locating most important functions in higher floors that are less possible to be inundated. Another measure that could be classified in layer 2 is making buildings resistant to the tsunami hydrodynamic forces. Concrete buildings seemed to have functioned very well against the forceful tsunami of March 11; it would be therefore good to consider the use of merely concrete buildings in low-lying areas. Although the damage within the buildings cannot be easily prevented, making buildings that cannot be swept by a tsunami will significantly decrease the amount of debris, which imposes additional loads that increase the damage. The choice of investments in different safety layers and measures should always be supported by cost-benefit analyses.

Given the magnitude of the event of March 11, it could be claimed that although overwhelmed, the multi-layered safety system of Tohoku performed reasonably good. However, looking at the system from a risk perspective, it is clear that an essential aspect was absent, which could possibly be responsible for a failure in the system even if a less extreme event occurred; the synergy of the three safety layers related to an acceptable level of risk. This can only be achieved if a common reference point for the evaluation and comparison of different measures and safety layers is used, which can only be the degree of safety that each measure adds to the system. As mentioned before, flood protection measures in Japan used to be built based on the effect of previously occurred extreme events. As a result, measures implemented in different time periods, hence designed to withstand different extreme events can be found within the same system. Moreover the return period of the design events is not accurately defined. This approach does not allow for the analysts to assess how much each measure and layer contributes to the final safety of the system.

In order to use safety as a reference, a risk based approach to flood protection needs to be engaged, i.e. a probability of failure to be used as the main target of design of every particular measure, every safety layer and the entire system. This allows for an accurate determination of the degree of safety that every measure adds to the system, and ultimately for the evaluation of design specifications and the comparison of different types of measures. The first step towards a risk-based approach to flood risk management is the determination of exceedance probability curves for a tsunami in Tohoku. This requires a thoughtful statistical analysis of tsunami records, and a probabilistic analysis of the tsunami generation mechanism, which should combine the knowledge and experience of hydraulic engineers and seismologists. As an overall indicator of the tsunami magnitude the deep-water tsunami characteristics need to be used, i.e. the tsunami height in deep waters, its period, and its total energy.

It should be noted that the target probability of failure of the layer 1 defences, which is proportional to the return period of a tsunami, should be the outcome of a cost optimization, in which the effect of damage mitigation measures and evacuation plans in the risk reduction should be taken into account. The risk reduction of both loss of life and material damage should be considered. In the end determining consistent target reliabilities can ensure the synergy of the three layers. That is to ensure that if layer 1 fails, the probability that layers 2 and 3 also fail will remain low.

A simple expression of the total cost based on which the optimization can be realized is as follows:

$$TC = C_1 + C_2 + C_3 + \sum P(i)D(i) \qquad (1)$$

where C_1 = investment cost of layer 1 measures, C_2 = investment cost of layer 2 measures, C_3 = investment cost of layer 3 measures, P(i) = probability of occurrence of scenario i, and D(i) = damage corresponding to the occurrence of scenario i.

4 IMPLICATIONS FOR MULTI-LAYERED SAFETY

Based on the above discussion, it is made clear that a rational utilization of multi-layered safety is only possible with a risk-based approach to design and assessment of a flood protection system. Besides the concept of multi-layered safety has been suggested and is being developed in the Dutch flood risk management, which is a characteristic case of a risk-based approach to flood protection. The coastal zone of Tohoku constitutes a case less familiar to the Dutch. It is a coast where multi-layered safety does exist, albeit not rationalized by a cost-benefit perspective. The response of the multi-layered safety system of Tohoku to the tsunami of March 11, 2011 could therefore teach some important lessons, which would possibly be useful for the improvement of the Dutch multi-layered safety concept.

4.1 *The role of risk aversion*

The choice of multiple layers of safety in Tohoku could be justified by the risk aversion of the local society, due to the relatively high frequency of tsunamis, which allowed consecutive generations to experience its devastating consequences. The occurrence of a tsunami is therefore dealt as a "high frequency-high consequence" event. In order to find out if frequency and consequences are high enough to make high investments in layers 2 and 3 economically beneficial in the long term, a cost-benefit analysis is necessary. Nevertheless making a decision based on the result of a cost-benefit analysis would only be the choice of a rational decision maker. In reality the decision makers' choices reflect the level of risk aversion in the society, which is a time-dependent parameter. It should be therefore realized that no matter what the choice of a rational decision maker would be, the future safety scheme of the system will depend a lot on the occurrence and impact of extreme events over time, which will determine how risk-averse the local society will be. Yet the insight into the economically optimal solutions should always be given.

It should be noted though that the role of risk aversion diminishes in less developed societies, where the available economic resources mostly drive the distribution of investments. Developed countries that have not experienced a large scale disaster in recent times, hence being more rational than risk averse, usually aim at decreasing the probability of flooding by building large scale structural defences. Developing countries that have other priorities than investing in prevention of floods usually focus on mitigating damage and fatalities, i.e. layers 2 and 3, which are less costly investments and of smaller scale.

4.2 *Definition of failure*

As mentioned in a previous section, a risk-based approach to multi-layered safety means that the degree of safety, which is equivalent to the risk in terms of exceedance probabilities, is used as a reference point for the assessment and comparison of measures and safety layers. The benefits associated with the addition of a measure or a safety layer, are therefore expressed as risk reduction to the system. It should be realized though that risk is a compound parameter consisting of two discrete variables; (1) the probability of an event and (2) the consequence due to the occurrence of this event. Accordingly, the measures taken for the reduction of flood risk focus on the reduction of either the probability of flooding or the damage in case that the flooding occurs, and not on both parameters simultaneously.

The forceful tsunami of March 11, whose magnitude exceeded previous design assumptions, overwhelmed the multi-layered safety system in Tohoku, causing consecutive failures of the safety layers. The primary line of defences, i.e. layer 1, failed to prevent inundation of the protected areas, the spatial arrangements against tsunami did not prove as efficient to mitigate damage and casualties to an acceptable level, while the same counts for crisis management. Having described the meaning of failure in each safety layer and the variability in the function of different flood risk reduction measures, it becomes clear that a certain type of measure with a certain function has a certain type of failure, which is in fact different than the failure of the entire system, or at least it still needs to be explicitly defined what is the failure of the system.

According to previous research on multi-layered safety (Jongejan et al. 2011), a multi-layered safety system is not a serial system but it resembles a parallel system, without being a parallel system either. If described in terms of failure, the failures of a serial and a parallel system can be respectively expressed as:

$$F_{serial} = F_1 \cup F_{2/1} \cup F_{3/1} \quad (2)$$

$$F_{parallel} = F_1 \cap F_{2/1} \cap F_{3/1} \quad (3)$$

where, F_1 = failure of layer 1, $F_{2/1}$ = failure of layer 2 given the failure of layer 1, $F_{3/1}$ = failure of layer 3 given the failure of layer 1, while F_2 = failure of layer 2 in a system that only layer 2 is present, and F_3 = failure of layer 3 in a system that only layer 3 is present.

Using Venn diagrams, the failures of a serial and a parallel multi-layered safety system can be depicted as in the following Figure.

Based on the serial system definition, the system fails immediately after the structural resistance of layer 1 measures are exceeded and water flows in the protected area. Based on the parallel system definition, a system failure occurs only when all three layers fail, whereas the failure of two out of three layers is equivalent to non-failure. For multi-layered safety systems none of the two definitions is correct, while a valid definition has not been indicated yet.

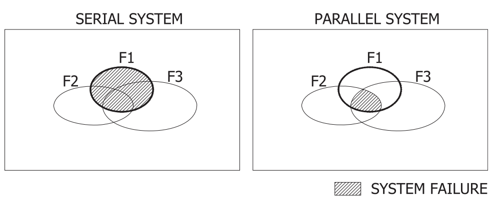

Figure 8. Failure of a serial and a parallel system.

The explicit definition of failure in each safety layer might be essential for the management of multi-layered safety systems, which is addressed in the coming paragraphs. It is remarked that the boundaries of F_1, F_2 and F_3 in the above-presented Venn diagrams can vary depending on the definitions of failure assigned to each safety layer. The definitions suggested in this paper and to which the above Venn diagrams apply are the following:

- F_1 = structural resistance of primary defences exceeded; inundation of protected area,
- F_2 = total cost of material damage exceeds a threshold and total number of casualties exceeds a threshold,
- F_3 = total number of casualties exceeds a threshold,
- F_{system} = inundation of protected area, and material damage exceeds a threshold, and casualties exceed a threshold.

The basic benefit of using these definitions is that the risk reduction due to a certain investment can be classified in reduction of damage, of casualties and probability of flooding, which are the ultimate parameters determining the risk. Subsequently the type of safety added to the system, i.e. safety against damage, casualties or flooding is also defined, which is essential for ensuring synergy in the safety layers. Assuming for instance a dike ring area in The Netherlands where expenditures on an evacuation scheme are decided. If the probability of failure of the evacuation scheme, once evacuation is necessary, turns out to be higher than the probability of failure of the dike, then there is no synergy between layer 1 and 3, as layer 3 will most probably fail in case of a flooding. Hence investing in the evacuation scheme is not going to pay off, and should not be made.

A secondary benefit of the above definitions is that they create a basis for the integration of acceptable levels of damage and casualties in safety standards. Safety standards against flooding exist in The Netherlands, yet they only consist of the acceptable probability of flooding in each dike ring. The acceptable levels of damage and casualties are not addressed (Kolen et al. 2010).

In order to have a complete definition of the failures, the thresholds in damage and casualties for layers 2 and 3 need to be determined, as well as the corresponding thresholds for the entire system. The thresholds of damage and casualties for the entire system might be different than those of layers 2 and 3 separately. Some further research on this topic is necessary.

In a classical structural design of hydraulic structures, where the structure is supposed to be the only measure in a system, and therefore a single safety layer, the choice of target reliability, i.e. target probability of failure is usually based on the results of a cost optimization. When more safety layers are added in a system, whose role is to further reduce the risk by reducing the degree of damage, a cost optimization will also be necessary for the definition of thresholds, yet in this case a new form of cost-benefit analysis will be used, where much more correlated parameters will be involved in the process. It should be remarked though that the role of an economic optimization is expected to be less important in the decision of acceptable thresholds for damage and casualties, because the use of multiple layers is in most cases the choice of a risk averse society, as explained in a previous section.

5 CONCLUSIONS

The coastal tsunami behavior varied, based on the local morphology of the coast. Large inundation heights and long run-up distances along the river basins characterize the tsunami attack in the rias, whereas large inundation areas with smaller inundation heights are the characteristics in the flat plains of Sendai region.

A combination of structural and non-structural measures, representative of all the three layers of multi-layered safety can be found in Tohoku region. The types of measures and the degree of safety they provide vary along the coast, depending on the coastal morphology and the social-economic value of the protected land.

The tsunami of March 2011 overwhelmed the multi-layered safety system in Tohoku, causing consecutive failures of the safety layers.

The structural resistance of primary coastal defenses in Tohoku, i.e. layer 1 was exceeded by the tsunami.

The design specifications of primary coastal defences were not consistent along the coastline of Tohoku. This can be justified by the general tendency in the Japanese flood risk management to design new defences based on previously occurred extreme events.

Although most of the coastal defences failed, they seem to have played a role in the mitigation of inundation heights in the protected land.

Although distinct in urban areas, it is unknown if layer 2 measures were a deliberate choice with the purpose of reducing flood risk.

The early warning system worked effectively, as the tsunami alarm was issued only three minutes after the earthquake. The inundation height expectations though, as issued by the Japan Meteorological Agency, were exceeded.

The tsunami exceeded the expectations of the local emergency plans, as there were cases in the rias that evacuation buildings were overtopped, while in the low-lying areas it has been recorded that many people did not succeed to evacuate in time.

The evacuation project can only be substantially assessed after a site-specific analysis of facts.

Layers 1 and 3 were much more developed in Tohoku than layer 2. Considering that layer 2 measures are less flexible and costly than layer 3, investing more in layer 3 seems to have been a reasonable choice for the increase of safety in Tohoku.

The uncertainty inherent in the functionality of layer 3 during an emergency, are much higher and difficult to define than this of layer 2 in tsunami-prone areas. In this respect, layer 2 solutions can be much more reliable in tsunami-prone areas.

Due to the catastrophic impact of the tsunami in large parts of the coastal urban areas, a great opportunity has been created for Japan to develop layer 2 measures.

Although multiple layers of safety existed in Tohoku, the synergy of those layers was not ensured, which could cause a failure even if a smaller tsunami occurred. In order to ensure synergy, a risk-based approach to flood protection is necessary.

The choice of multiple layers of safety in Tohoku could be justified by the risk aversion of the local society, caused by the fact that consecutive generations have experienced tsunamis.

The future safety scheme of the system will depend a lot on the occurrence and impact of extreme events over time, which will determine how risk-averse the local society will be.

Most measures taken for the reduction of flood risk, focus on the reduction of either the risk probability or the damage in case that the risk occurs, and not on both parameters simultaneously.

The explicit definition of failure in each safety layer could prove to be very beneficial, as it introduces the classification of safety added in a system by means of reduction of damage, reduction of casualties, and reduction of flooding probability.

Failure in layers 2 and 3 can be defined as the exceedance of certain thresholds in material damage and casualties. In order to have a complete definition of the failures, those thresholds need to be determined.

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