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Efficient Energy Storage and Distribution
Resilience against Disasters

RAPSODI Project

Risk Assessment and design of Prevention Structures
fOr enhanced tsunami DIsaster resilience

Deliverable D9- Guidelines for
design of structures and risk
management strategies

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Client:	CONCERT-Japan Joint Call Secretariat
Client's contact persons:	CONCERT-Japan Coordinator
	The Scientific and Technological Research Council of Turkey (TUBITAK)
	Ms. Filiz Hayirli (filiz.hayirli@tubitak.gov.tr)
	concertjapan@tubitak.gov.tr
	Phone: + 90 312 468 5300 (ext.1910)
	CONCERT-Japan Joint Call Secretariat
	Centre national de la recherche scientifique (CNRS)
	Ms. Lucie Durocher (lucie.durocher@cnrs-dir.fr)
	Phone: + 33 (0)1 44 96 47 14
	Fax: + 33 (0)1 44 96 48 56
	http://www.concertjapan.eu
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For NGI

Project manager:	Carl Bonnevie Harbitz
Prepared by:	Andreas Kortenhaus; Agnieszka Strusinska-Correia;
Reviewed by:	Carl B. Harbitz

Publishable summary

The 2011 Tōhoku tsunami showed the potential for massive destruction of buildings, infrastructure, and coastal protection by tsunamis. A huge amount of data has been collected after the event, allowing a retrospective analysis. Within the CONCERT-Japan RAPSODI project (Risk Assessment and Design of Prevention Structures fOr enhanced tsunami Disaster resilience; http://www.ngi.no/en/Project-pages/RAPSODI/) these data were used to develop a framework for the design of tsunami mitigation structures and quantitative tsunami risk analysis to improve resilience against tsunami impacts.

RAPSODI focused on various research issues such as the analysis of loads on structures and their various failure modes (deliverable D1), post-tsunami field surveys of the 2011 Tohoku tsunami (deliverable D2), comparison of coastal protection structures in Europe and Japan (deliverable D3), comparison of mitigation strategies against tsunamis in Europe and Japan (deliverable D4), numerical modelling of tsunamis (deliverable D5 and D6), laboratory experiments on breakwaters in wave flumes (deliverable D7), as well as quantitative assessment of tsunami mortality (deliverable D8). These issues should intentionally lead to improved infrastructures, coastal protection measures, and overall preparedness of coastal communities exposed to tsunamis.

In more detail, a matrix presenting different failure mechanisms of coastal protection structures exposed to tsunamis (in terms of water level difference and wave force) was produced based on field data and experiments by various research groups. The tsunami mortality risk analysis included numerical modelling of tsunami inundation and empirical relations for fatalities as a function of flow depth. The results of the mortality hindcast for the 2011 Tohoku tsunami substantiate that the tsunami mortality risk model can help to identify high mortality risk areas, as well as identify the main risk driver(s). The results of the tsunami wave-flume laboratory experiments were used to assess structure resilience against tsunami impact.

This report summarises the key findings of the previous deliverables, but also seeks to provide lessons learned from this analysis and specific guidance for both researchers and practitioners. In addition, two parallel guidance documents on tsunami mitigation are cited which are the Japanese guidelines on tsunami-resistant design of breakwaters (MLIT, 2015) and a chapter by the American Society of Civil Engineers on 'Tsunami Loads and Effects' (ASCE, 2015).

Overall, this report and the aforementioned guidelines provide key recommendations for researchers, policy-makers and practitioners on various aspects of tsunami impacts in coastal areas. These aspects include guidance on a) surveys and their analyses after a tsunami event, b) the performance of tsunami defence structures and buildings, c) casualties and preparedness of people; d) coastal defence strategies against tsunami and storm surge; e) numerical model simulations; f) hydraulic model tests for tsunamis; and g) vulnerability and risk analyses.

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1   Introduction

The Japanese word "Tsunami" is composed of two Chinese characters where 'Tsu' means harbour or port and 'nami' means wave. Therefore, "tsunami" means 'harbour wave' in Japanese. Tsunamis are defined as water waves generated by large-scale short duration energy transfer to the entire water column by earthquakes, coastal and submarine landslides, volcanic eruptions, caldera collapse, or meteor impacts. Tsunamis and landslide waves may attain large amplitudes in closed basins or shallow regions (see e.g. Yalciner et al., 2007). They are generally classified as long period waves and now all are referred to as tsunamis. Landslide generated waves are normally have shorter wavelength than tectonic tsunamis, and their initial amplitude depends on the length, thickness, and initial acceleration of the triggering slide as well as the water depth. The amplitude of tectonic tsunamis depends on the width of fault rupture and the slip as well as the water depth. The runup distribution on adjacent shorelines is so different between landslide and earthquake tsunamis that it often allows discrimination of the source (Okal and Synolakis, 2004).

The interest in tsunami research has increased in recent years after the devastating consequences of the 2004 Indian Ocean tsunami and of the 11th March 2011 tsunami in Japan. The Great East Japan Earthquake which induced the 2011 Tohoku Tsunami was of magnitude 9.0 and the largest earthquake ever recorded in Japan. Its focal region extended over a wide area from the coast of Iwate Prefecture to the coast of Ibaraki Prefecture, and since the breakage of the fault was over 450 kilometres long and about 200 kilometres wide it resulted in a tsunami of a scale that has rarely been seen before. This event clearly showed the potential for massive destruction of buildings, infrastructure, and coastal protection by tsunami waves. Moreover a huge amount of data has been collected during and after the event, allowing a retrospective analysis. The 2011 Tohoku tsunami impact caused failures of foundations and prevention structures, which are not yet fully understood.

Moreover, today's tsunami vulnerability and risk models are descriptive and limited; some are based on simple empirical relationships between tsunami flow depth and structural damage or fatalities. Thus, better understanding of the overall vulnerability to tsunamis, the specific mechanisms that lead to or contribute to the collapse of buildings and infrastructure as well as the performance of selected coastal structures must be analysed in detail to develop efficient mitigation measures against future tsunami events.

With this background the European-Japanese research project RAPSODI (**R**isk Assessment and design of **P**revention **S**tructures f**O**r enhanced tsunami **DI**saster resilience) aims to provide design guidance for tsunami mitigation structures to improve resilience against tsunami impacts. In more detail the key objectives of RAPSODI are:

1. Assess structural and, socio-economic vulnerability based on detailed analyses of damages of infrastructure and coastal protection as well as

analyses of fatalities; compare tsunami mitigation strategies in Japan and Europe.

2. Update numerical tsunami models with new modules to analyse current velocities and fluxes around structures and in complex topographies/urban areas; the results will be used in the design of prevention structures and for quantitative risk assessment.

3. Perform detailed laboratory analysis of tsunami impacts on coastal protection to analyse loads and functionality for various foundations and design of tsunami prevention structures; test new or improved tsunami mitigation measures; establish a matrix for different types of structures and buildings with their potential failure modes.

4. Develop a framework for the quantitative assessment (GIS-based) of tsunami vulnerability and risk, including the assessment of structural and socio-economic vulnerability.

5. Exchange experience, knowledge, and scientific results between Japanese and European tsunami experts; disseminate project outcomes through joint workshops or seminars.

RAPSODI has produced eight deliverables to date which address these objectives and provide a background for various aspects in tsunami research with a special focus on similarities and discrepancies between tsunamis in Europe and Japan. Most of the deliverables have been generated using the extensive exchange between European partners (NGI, METU, TU-BS) and Japanese colleagues (PARI). The list of these aforementioned deliverables in RAPSODI is given as follows:

- D.1: Existing tools, data, and literature on tsunami impact, loads on structures, failure modes and vulnerability assessment (METU, 2013)

- D.2: Database on post-tsunami field surveys (run up, flow depth, flow velocities, fluxes), damages, and fatalities of the 2011 Tohoku tsunami (PARI, 2015)

- D.3: Comparison of coastal structures in Europe and Japan (METU, 2014a)

- D.4: Comparison of mitigation strategies in Europe and Japan (METU, 2014b)

- D.5: Computed tsunami parameter values in shallow waters and around structures (METU, 2015a)

- D.6: Numerical modelling of tsunamis in harbours and bays (METU, 2015b)

- D.7: Results of the laboratory analysis and wave flume tests (LWI, 2015)

- D.8: GIS tsunami vulnerability and risk assessment model (NGI, 2015)

All these deliverables have focussed on specific aspects of the joint tsunami research and have brought together relevant information which has not yet been collated before. However, this new knowledge has not yet been translated into an end-user friendly design guidance document that consistently can advise potential readers on any mitigation (structures) of tsunamis or risk analyses strategies and assist in improving the current tsunami threat for European and Japanese coastlines.

Therefore, this report, Deliverable 9 - *Guidelines for design of structures and risk management strategies,* aims to provide guidance with respect to coastal protection structures against tsunamis in Europe and Japan and compares them. It also provides guidelines on risk analyses strategies and how to develop them.

The report is structured as follows: in chapter 2 an overview of the current state-of-the-art knowledge on tsunami mitigation is given, Chapter 3 provides an overview of the post-tsunami data from the 2011 tsunami. Chapters 4, 5, and 6 suggest guidance on mitigation structures for tsunamis, numerical and physical model studies, respectively, for tsunamis due to the experience gained within RAPSODI. Chapter 7 summarises lessons learned from vulnerability and risk assessment studies and Chapter 8 finally summarises these findings.

2 State-of-the-art in tsunami mitigation

This chapter provides an overview of the current state-of-the-art knowledge in tsunami mitigation. It commences with relevant definitions as used within RAPSODI (section 2.1) such as run-up height, inundation height and inundation depth which were often are inconsistently used in literature and then reviews the current literature in the field (section 2.2).

2.1 Definitions

Definitions of various terms for tsunami impacts have varied over different publications in the past and therefore need a consistent definition to clarify the terminology. In this report, inundation height is defined as the observed level of the water above the tide level at the time of the event at intermediate locations, and run-up height denotes the elevation above the tide level at the time of the event at the maximum distance from the shoreline. Note that inundation depth is defined as a height of tsunami above the ground (Figure 1).
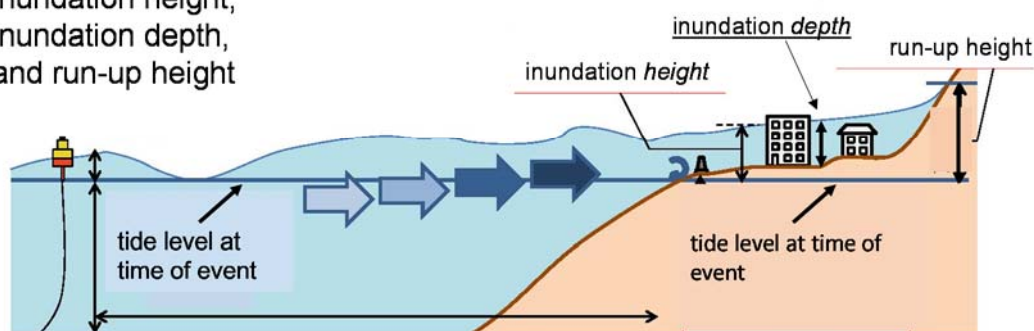

Figure 1: Definitions of tsunami height, inundation depth, and run-up height (PARI, 2015)

2.2 Literature review

Numerical models are often used to model the generation, the propagation, the run-up and the inundation by tsunamis. The number of numerical models developed is significant (e.g. TUNAMI, NAMIDANCE, MOST), a comprehensive overview of the models together with their essential features is provided in METU (2013). Some of these models are developed for a wider range of applications such as nearshore wave processes, advection-dispersion or sediment transport that can be used for tsunami modelling (e.g. BOSZ, MIKE21, etc.). Different equations such as shallow water, Navier-Stokes and Bousinessq equations are solved with a variety of numerical schemes. Each of these solutions requires a set of assumptions that could affect the performance of the models. Structured, unstructured and nested meshes are the most common types of meshes/grids in the models. The type of grid used by the

model can determine the accuracy of representing the bathymetry/topography, the accuracy of the inundation, as well as the computation duration. Nested meshes have become widely used in the recent years, as different resolutions could be used in the model that can decrease the computation time. Almost all of the numerical models have the capability of modelling earthquake generated tsunamis. Some of the tools can model landslide generated tsunamis and only a few of them consider other tsunami generation mechanisms. The numerical tools have been applied to several different tsunami events around the world. Especially, after the 2004 and 2011 events, more attention has been paid to the accuracy of inundation modelling including the velocity and fluxes considering different roughness patterns, which turned out to be very important.

The assessment of the **impact of tsunami on structures** requires the calculation of tsunami forces, even though many building codes do not generally consider tsunami loading. However, a significant amount of damage has been observed during the 2011 Great East Japan Earthquake (GEJE) tsunami which puts an emphasis on proper planning of buildings under tsunami flow. Forces associated with tsunami consist of: (1) hydrostatic force, (2) hydrodynamic (drag) force, (3) buoyant force, (4) surge force and (5) impact of debris. To model the tsunami forces, three parameters are essential: (1) inundation depth, (2) flow velocity, and (3) flow direction. The proposed formulas to calculate the forces mostly depend on accurate prediction of tsunami velocity and flux. Tsunami velocity at different locations under inundation is one of the topics that has to be further studied to increase the force calculations in the design of structures. The proposed formulas all have empirical coefficients thus there is a range of values for numerical prediction of tsunami velocity. One can either use conservative values – or work with a range of values which may give result in up to 100% difference in terms of velocities. Additionally, the effects of run-up, backwash and direction of velocity are not addressed in current design codes. Thus it is important to have more experimental data on the forces generated by tsunamis acting on various types of structures.

Two **failure mode matrices** showing failure mechanisms of coastal structures and different land structures such as reinforced concrete and steel buildings, walls, columns, wooden structures according to tsunami impact pressure or the standing tsunami pressures were derived from the present state-of-the-art literature and presented by METU (2013). Debris impact is commonly observed in wooden structures and buildings whereas overturning, bending and punching shear failure and 1st story collapse are the other failure modes seen under impulsive tsunami loading. In case of standing tsunami pressure, scour and rebar fracture are the most common failure modes and overturning, rebar yielding and wash-away due to sustained force are the other present forms of failures. The analysis shows that the static and dynamic effects of debris on structures is significant in addition to tsunami pressures which requires further study to understand the exact effects on the overall damage. Also, the design approaches against erosion around concrete structures should be improved and extended since it has been observed in most of the cases where failures occurred.

Considering **tsunami loads on coastal structures** such as breakwaters, the available design codes do not integrate tsunami loads explicitly. Thus the performance of these structures is assessed in the field as in the case of 2011 tsunami. The main function of coastal structures against tsunamis is to prevent overflow. Thus most of the time the design consideration is based on historical events or model results from possible tsunami scenarios. However, tsunami loads can cause damage on the structure (e.g. slope instability, see previously mentioned failure mode matrix as well) and in return initiate overtopping during later stages due to long duration of tsunami waves. Additionally, once overflow occurs, other types of failure modes can be observed such as scouring which may further increase the damage. Design codes for coastal structures such as breakwaters are focused on wind waves and storm surges since the tsunami events does not occur frequently. Since experiments on the performance of coastal structures under tsunami loading and overflow have gained attention recently, most of the information on failure modes are based on the observations and field surveys of the latest tsunami events. Water level differences across the structure and wave impact on the structure are the two main processes that initiate the failure. The former can generate a functional failure of the structure (overflow) initiating several of the other failure modes and eventually the final damage observed. However, the exact sequence of the failure modes for many of the failures require more experiments and/or real time observations to accurately understand the overall damage caused by tsunami. Most of the missing information is about performance of rubble mound breakwaters since they are not common in Japan. Additionally, failure modes due to tsunami wave impacts have not been investigated much in the literature. Another important outcome of the analysis was that soil conditions and soil-structure interaction is very important in the case of overflow. Many of the observed failures were based on scouring on either side of the structures occurred during the tsunami event. Additionally, some of the failures were due to the tsunami drawdown (outflow) which was not considered in the design of these structures before 2011 observations.

Tsunami risk is defined here as the product of the probability of a tsunami hazard and its consequences where the latter is essentially triggered by the vulnerability of a region subject to tsunamis. Therefore, the **vulnerability assessment** of the region plays a crucial role not only in the tsunami risk assessment but also in tsunami disaster reduction. Some of the vulnerability assessment methods have been provided in METU (2013). Many of these vulnerability assessments start with determining the inundation area and depth calculated by numerical models in order to understand the extent of structural damage (buildings specifically) as well as the number of people affected by the tsunami. There are models which also include other aspects of vulnerability such as ecological or environmental impacts, impacts on the economy, social or political aspects influencing the vulnerability of a region, which are aspects not depending on water depths alone. If more parameters defining vulnerability are included in the models, for example in terms of indicators, weighing methods have been applied to quantify vulnerability. However, in general, the weights are either gained by expert judgement or depending on available data, which increases the uncertainty of the overall results. Moreover, this affects the applicability of the

models to different regions negatively. Most vulnerability assessments use historical tsunami events or possible scenarios to determine the inundation area. Additionally, probabilistic approaches have been used to determine the input tsunami event to predict the possible risk of a region. Almost all of the vulnerability assessment models use GIS and the reliability of the results depends on the resolution of data as well as the accurate representation of the tsunami event. Most of the predicted vulnerability or the damage is associated with inundation depth although recent research has shown that velocity and fluxes associated with the inundation could be more significant for accurate predictions. Tsunami fragility curves drawn to represent the relationship between the damage level and the inundation have been widely used in the literature. Fragility curves gained from field surveys after real events are useful sources to understand and map tsunami damage. However, the classification of the damage levels is still to a large extent subjective as it is based on the field assessments. Additionally, the classification of damage levels is not universal as different definitions are used by different research groups at different events. Many of the vulnerability assessments are part of the mitigation studies. However, for the 2011 tsunami many of the assessments underestimated both the structural damage and the population at risk. Although this underestimation is believed to be due to an underestimation of the magnitude of the hazards involved, the uncertainties related to the methodologies of vulnerability assessment including the fragility concept also influenced the reliability of the results. Working towards common approaches in determining the vulnerability and risk as well as key definitions used in the assessments should therefore be an objective of the scientific community.

2.3   *Conclusions for the RAPSODI project*

Considering the information summarised above and the details such as provided by METU (2013), it was concluded within RAPSODI that the available literature could be enhanced through the following work:

- Provide an overview of available post-tsunami data from the 2011 Tohoku tsunami for further use of these data especially for numerical models and the vulnerability assessment for this event (see chapter 3).
- Propose and discuss improved methods for tsunami mitigation strategies based on the lessons learned from the 2011 Tohoku and earlier events, and distinguish between cases in Japan and Europe. Identify the commonalities and the differences and provide guidance on the relevance of each of the measures (see chapter 4).
- Enhance numerical models such as NAMI-DANCE focusing on the modelling of tsunami parameters in high resolution geometries (e.g. urban areas) as well as accurate computation of flow patterns (see chapter 5).
- Perform hydraulic model tests on tsunami impacts on rubble mound breakwaters (with and without crown wall) focusing on wave loading and the respective failure modes of different type of armour material, slope, and type of wave generation (solitary, bore), see chapter 6.

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- Enhance the vulnerability analysis model developed by NGI by integrating building fragility curves and detailed socio-economic, environmental, and physical information collected after the 2011 tsunami in the model in order to improve a quantitative tsunami risk analysis (see chapter 7).
- The RAPSODI failure mode matrices for coastal structures and buildings (deliverable D1, see METU (2013)) have proven to be useful tools to correlate information on structures and buildings with different types of loadings. It has, amongst others, indicated that there is a knowledge gap on failure modes and loading of coastal structures, especially rubble mound breakwaters, subject to tsunami loading.

3   Overview of post-tsunami data from the 2011 Tohoku tsunami

This chapter summarises the findings of the surveys performed after the 2011 Tohoku tsunami and which are summarised in more detail by PARI (2015). Section 3.1 provides this overview with specific information on run-up heights, damages to coastal structures and buildings, and casualties. Section 3.2 then seeks to summarise the lessons learned from this study and provides some guidelines for improved tsunami resilience.

3.1   Overall results

The Tohoku earthquake Tsunami Joint Survey Group assembled 50 organizations (more than 150 people) for a field study. From March 12th to May 22th, 2011, tsunami-affected areas along the Pacific coast from Hokkaido to Okinawa Prefecture were surveyed. **Tsunami run-up heights** exceeded a height of 10 m on a 530 km stretch of coastline centred on Iwate Prefecture. In addition, tsunami trace heights exceeding 20 m were recorded in most locations along the Sanriku coast, which is formed as a Rias coast. Furthermore, run up heights of 40 m were confirmed in Ryori Bay at Ofunato City, making this the maximum tsunami height ever recorded in Japan. Comparing with past tsunami events, tsunami heights in the Iwate prefecture were similar to levels observed in the 1896 Meiji Sanriku tsunami, whereas those in the southern Tohoku region were much larger. In the Iwate prefecture, the run up points are near the coast because mountains near the shoreline. In contrast, the topography of Sendai area is flat, hence the end of inundated area is very far from shoreline. This may account for the difference in casualty rates between the two prefectures.

The extent of **damage to coastal structures** including bay mouth breakwaters, common breakwaters, and seawalls was documented during field surveys. Laboratory experiments have also been conducted to investigate the mechanism of the failure and to explore solutions for improving the resiliency of such protective structures. Details of these field surveys have been presented in PARI (2015) as representative examples: one for bay mount breakwaters (Kamaishi Bay) and another for common breakwaters (Hachinohe Port). In the latter example, researchers

concluded that implementing countermeasures for overflow scouring is the most important design task for future breakwaters. Finally, the damage to shore protection facilities was surveyed by Kumagai et al. (2011) on 20 districts in 7 ports in Miyagi and Iwate prefecture.

PIANC (2013) shows the relation between the design wave height-tsunami height ratio and the **damage ratio for breakwaters**. The damage ratio is defined as the ratio of the damaged length to the total length. If the tsunami height at the front side of the breakwater is divided by the design wave height, the damage ratio can be predicted with some accuracy by the logarithmic normal cumulative distribution function.

For **seawall structures**, the relationship between the damage ratio and the wall height was investigated at 60 structures in Iwate Prefecture where the cross-section profiles were known. Analysis showed that the safety factor for sliding was generally lower than the safety factor for overturning. Furthermore, the safety factor for sliding dropped below 1.0 around where the relative height exceeded 3 meters.

A survey of **building damages** throughout the region struck by the 2011 tsunami has shown that in districts where the inundation depth exceeded 2 m, the percentage of buildings that were completely destroyed (including those washed away) was high. Many buildings were washed away by the horizontal force or the buoyancy of the tsunami. Buildings were categorized by construction type: wooden or concrete, steel frame buildings, and others. Field surveys conducted in Natori City, Miyagi Prefecture were discussed to analyse and compare the impact of tsunamis on these different categories of building. MLIT (2012) investigated the proportion of affected buildings in six of the tsunami-impacted prefectures. In total, 250,000 buildings were affected, out of which about 140,000 were completely destroyed. Buildings were sorted into seven categories based on their condition after the disaster, ranging from completely destroyed (washed out) to no damage. Wooden structures accounted for 70% of buildings that were completely destroyed, reinforced concrete structure for 2%, steel frame structure for 4%, and others for 7% (weight steel frame, soil structure, and block structures). The analysis showed a significant relationship between inundation depth and the condition of a building after a disaster. The proportion of buildings completely destroyed in the case of inundation depth of 2 m or below tend to be significantly lower than above that value. Building type also has a significant role. The proportion of buildings completely destroyed was 5% in the case of reinforced concretes structures for inundation depth 1.5 m – 2 m. In contrast, at least 20% of wooden structures were completely destroyed at this depth, which is not necessarily a low proportion. Data were further used to analyse the relationship between inundation depth and disaster condition of buildings by structure and by number of floors.

A 2011 report form the Central Disaster Management Council of Japan (CDMC, 2011) provided **casualty rates** in each affected prefecture. The working definition of the casualty rate used was "the ratio of total number of casualties (fatalities and missing persons) to the total population living in the inundated area." The casualty

rate was highest in Iwate Prefecture at 5.9%, followed by 3.5% in Miyagi Prefecture and 2.7% in Fukushima Prefecture. The larger the tsunami height on the coast was, the higher was the casualty rate. When the relation between the tsunami height and casualty rates is compared to those observed in past tsunamis, the casualty rate of Iwate prefecture in the 2011 Tohoku tsunami was much smaller than in earlier tsunami events in the same prefecture and smaller than that in other locations in the same event. There, the tsunami preparedness education was more effective, and the hazard mapping was more in-depth and accurate. In comparison, the casualty rate in Miyagi prefecture was larger than that of Iwate prefecture. Some suggested explanations include differences in topography or hazard map accuracy. In Miyagi prefecture, the hazard map in many area underestimated inundation area. This comparison indicates that the preparedness of vulnerable populations is very important.

3.2   Lessons learned and guidance

In summary, the analysis of the field survey after the 2011 Tohoku tsunami has provided the following lessons learned:

- Data from field surveys after tsunamis are still scarce, but represent very valuable and necessary information for any further assessment and mitigation of tsunami impacts.
- Information from the field should be as comprehensive as manageable and as objective as possible.
- Information on run-up heights after the tsunami could help to calibrate and check numerical models for tsunami generation, propagation, and inundation simulations. As much as possible information should be collected in as many as possible locations.
- Considerable damage of coastal structures occurred during the 2011 event and were mostly due to sliding when the relative wave height exceeded 3 m. However, this cannot be easily generalised and some failure mechanisms are still not fully understood.
- Damages to buildings mostly depend on the construction type and material and appeared to be full damages when the inundation height exceeded 2 m. Very often, scour due to the strong flow patterns around buildings has caused additional damages.
- The number of casualties depends to a large extent on the tsunami height and the preparedness of people in the hazard prone areas. Although, again, this cannot be generalised this observation was found to be extremely relevant to avoid casualties in the future.

The aforementioned findings allow for the following guidelines related to post-tsunami surveys:

- **Surveys** should be performed at a relatively short time after the tsunami to allow collecting relevant information. Surveys should be performed by experts and in the most objective way. It should be noted that all relevant information needs to be compared to data available from before the tsunami. Therefore, frequent surveys of relevant information should be collected in regular intervals.
- Various **information** should be collected during the survey if not already available otherwise such as (incomplete list):
  - Topography of area, incl. the built environment
  - Tidal water level during the event
  - Flow depth/inundation height and runup height (inundation distance)
  - Construction type, material, and age of defence structures and buildings
  - Damage (proportion) of defence structures and buildings
  - Countermeasures for preventing damages and scour
  - Number of people present in the area
  - Level of preparedness of people
  - Number of casualties
- **Analysis** of tsunami surveys should be made available at the earliest possible time after the event to allow for a most effective post-tsunami mitigation
- **Coastal tsunami defences** should be built in a way to possibly withstand sliding even though they are overtopped. Likewise, scour protections around these structures should be further investigated and it should be assured that tsunami currents cannot erode too much support material around these structures.
- **Buildings** in tsunami-prone areas should at least withstand tsunami heights of 2 m. For higher tsunamis there should be buildings available which may serve as vertical escape structures built from reinforced concrete to withstand higher tsunamis.
- **Number of casualties** in tsunami-prone areas can be reduced if people are well-prepared. Increasing the preparedness of people by all sorts of information (leaflets, radio, TV, personal teaching, etc.) and regular training should be considered for this purpose.

4 Coastal mitigation strategies for tsunami in Europe and Japan

This chapter summarises the key results from two research lines within RAPSODI which include an overview and comparison of coastal structures in Europe and Japan (METU, 2014a) and a comparison of mitigation strategies against tsunamis in Europe and Japan for both hard structures and soft techniques (METU, 2014b). The key findings from this review are provided in section 4.1 whereas the lessons learned and potential recommendations are given in section 4.2.

4.1 Overall results

Before summarising the key strategies against tsunamis in Europe and Japan the **key characteristics of these regions** should be noted as follows:

- The main tsunami source mechanisms differ significantly in Japan and Europe. The most common tsunami sources in the Northeast Atlantic are submarine landslides as well as subaerial rockslides in lakes and fjords, while the active tectonics of the Mediterranean have also caused numerous tsunamis generated by offshore earthquakes. In Japan, co-seismic tsunamis are most common because of its position along a subduction zone.
- The bathymetries in front of the European coasts vary significantly from steep to very mild foreshores providing very variable conditions for either storm surges or tsunamis to attack the coastlines. In Japan the bathymetry comprises steep foreshores with large water depths close to the coastlines.
- Tidal variations are very different in Europe ranging from almost no tidal range in the Baltic Sea and the Mediterranean to some of the largest tidal ranges in the world at the French coast of Normandie with up to 16 m tidal range. In Japan, tidal ranges are from less than 1 m to several meters.
- Meterorological conditions in terms of storm surges may be regarded similar where storm surges in the North Sea reach even larger wave heights than storms in the Japanese Sea. However, considering the aforementioned bathymetry, larger waves may reach the Japanese coastlines as compared to the North Sea coasts in Europe.
- People's awareness along the coasts in Europe are very different dependent on the region they live. There is a history of storm surges though and people have suffered significantly from casualties and land losses up the last centuries whereas the protection level has been increased more recently. In Japan, people are aware of both storm surges and tsunami and the frequencies of occurrences of these hazards is higher than in Europe. Policies to make people aware of these hazards are also different in these regions.

Based on these principal characteristics, RAPSODI has identified the existing structural and non-structural tsunami mitigation strategies in Japan and Europe where the focus has been mainly on structural protection against tsunamis in terms of structural mitigation (see METU, 2013).

In Europe, the **type of coastal hazards** that are typically considered in the management strategies are storm surges and coastal erosion. Storm surges may result in flooding and hence the type of structures designed for protection aims to either prevent water from overtopping the defences or prevent the progress of the flooding. Consequently, the scale of loadings on structures is very different from the case of tsunamis which are typically considered in Japan.

With respect to **defence strategies,** coastal protection structures have been the first line of defence against many of the coastal hazards and problems in these regions. There is a variety of protection structures that has been implemented in terms of hazard mitigation. The functionality, design, and construction of these structures depend significantly on the type of hazard they are built against as well as the site specific conditions. Therefore, different types of structures perform well under different hazard conditions. So, although similar structure types are constructed all around the world, not every location that has a protection structure is resilient against all types of hazards.

These differences in functionality are reflected in the materials and the design process of the protection structures. While Japanese structures are mostly vertical type structures or seawalls which are built of concrete, European structures are usually either sloping structures with rock armours or seawalls designed for erosion mitigation. The performances of these different structures under tsunami loading, especially in the case of European structures, should be further investigated even though they are considered efficient in case of storm surges. Although tsunami risk is low in many parts of Europe, several historical tsunamis occurred which were not generated by earthquakes but by landslides.

Coastal dikes are the primary coastal structures built against tsunamis in Japan as well as other four main types of structures such as tsunami barriers, water gates, breakwaters and green belts. The Japanese design approach includes mainly the historical records of tsunami heights, but it is based on storm surge predictions as well in some areas. They have also followed a two-level approach for the design parameters after the Great East Japan Earthquake event. This approach requires all the coastal protection structures to resist a tsunami of a 100-year return period. On the other hand, the design should resist as long as possible for much larger tsunamis such as an event with a 1000 year return period.

Information about tsunami mitigation structures in Europe is very limited where only in Norway, constructing dikes against tsunamis is encountered as a structural measure. Although in Europe neither such a variety of coastal structures nor a developed design approach specifically against tsunamis exist, there are extensive storm surge protection measures designed for extreme (100 to 10000 years) events.

Typical protection schemes against storm surges in the Baltic Sea are shown in Figure 2 (METU, 2013) whereas tsunami countermeasures in the Tohoku region are illustrated in Figure 3 and Figure 4 (Tsimopoulou, 2012) which show the various

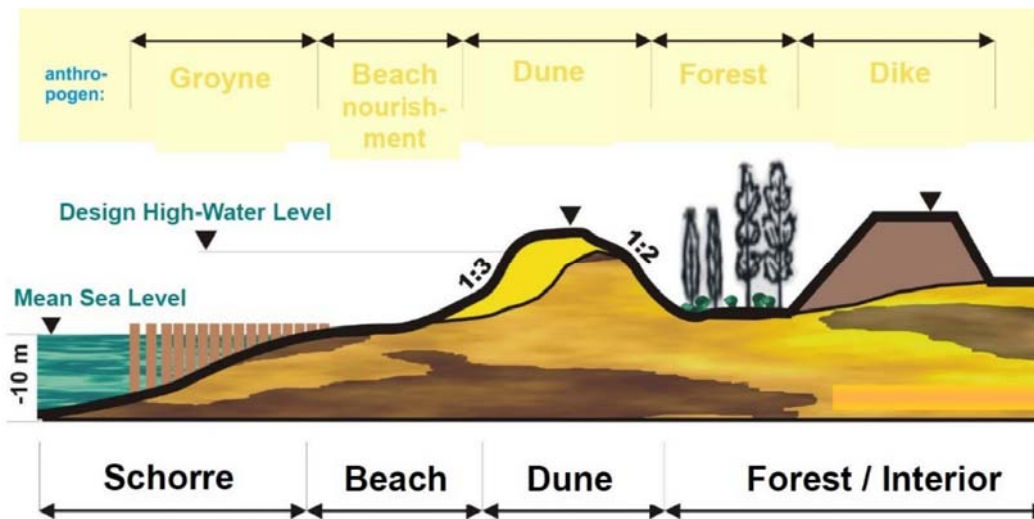defence lines against tsunami attack, dependent whether the topography is either steep or rather flat.

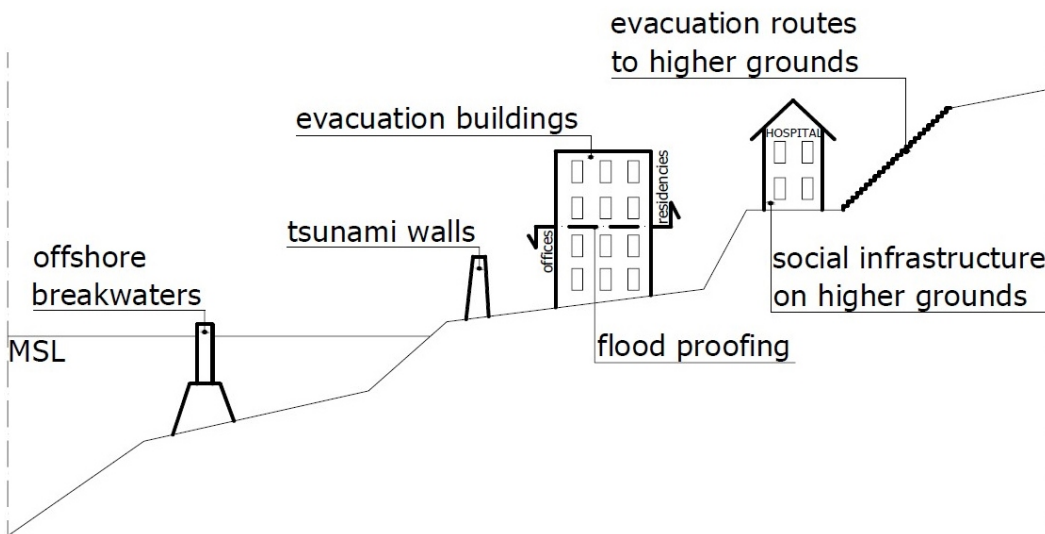*Figure 2 Typical coastal protection scheme at the German Baltic Sea coast*

Figure 3 Tsunami countermeasures in the rias (MSL=mean sea level). (Source: Tsimopoulou, 2012)
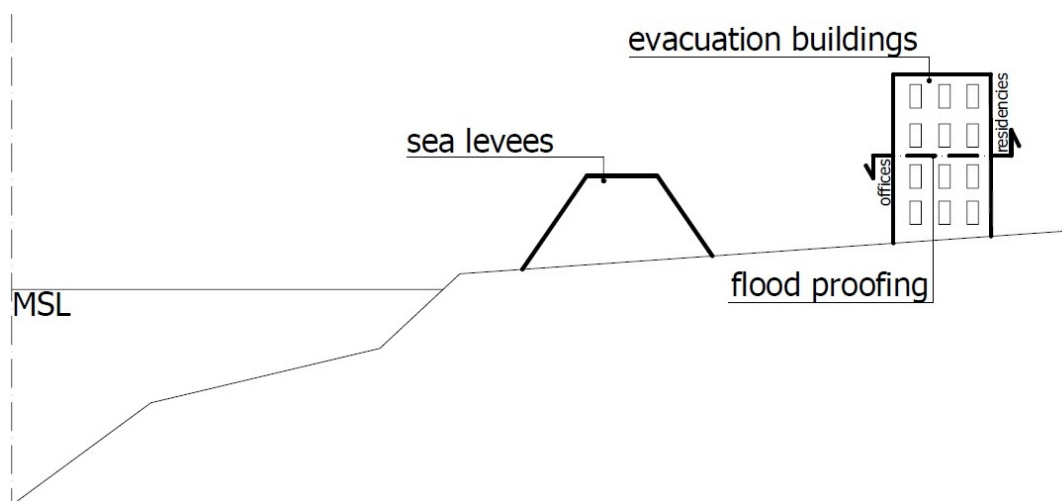
Figure 4 Flood risk countermeasures in flat plain region (MSL = mean sea level). (Source: Tsimopoulou, 2012)

Although none of these examples for mitigation measures represent all of the defence systems which can be found in these regions they already show some key characteristics:

- Systems in Europe and Japan both rely on different mitigation measures rather than just one. At the Baltic Sea this is the high foreshore, groynes, beach nourishment, a dune, a coastal forest and a dike. Note that the number of mitigation options may differ from only one to several ones like in this example. In Japan the defences are typically man-made and ranging from offshore breakwaters over tsunami walls, sea walls, evacuation buildings and buildings on higher ground.
- Large systems in Europe are natural defences like beaches and dunes which are maintained. Therefore, very often the 'mitigation' in Europe means to keep natural systems in their original condition, e.g. by sand nourishments. In Japan, due to the high loadings of defences induced by tsunamis and storm surges, this would in most cases be insufficient to defend the coastal areas so that hard measures (e.g. concrete seawalls) are needed.

It should be noted that in Japan evacuation and the respective buildings is very often a part of the coastal defence strategy whereas in Europe coastal authorities often rely only on natural or anthropogenic mitigation systems. Of course, as said before, there are exceptions to these observations.

Furthermore, in Japan, many **non-structural measures** such as tsunami and earthquake warning systems, community-based disaster risk management, evacuation and land-use planning as well as the use of coastal vegetation exist. The fact that tsunami mitigation must be an integration of several different approaches has been highly recognized. On the contrary, only some of those non-structural measures exist in Europe. In Norway there is monitoring of unstable rock slopes

combined with early warning, and capacity building activities for the population. Land use planning (like limitations for buildings near protection areas or in flood prone areas) are in place in some parts in Europe. Early warning systems are in operation in some urban areas warning the population against coastal hazards (storm surges) such as in the city of Hamburg/Germany. The Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS), is also an initiative worth mentioning. There are currently three National Tsunami Warning Centres functioning as Candidate Tsunami Watch Providers (CTWPs) for the entire region, the Centre d'alert aux tsunami in France, the Kandilli Observatory and Earthquake Research Institute in Turkey, and the National Observatory of Athens in Greece. The Tsunami Watch Providers (TWPs) are in charge of: the observation and the detection of the phenomenon, the analysis of the data received in real time or quasi-real data, and sending warning messages to Tsunami Warning Focal Points (TWFP). Additionally, there are some examples of community based evacuation planning in Portugal and Italy.

4.2 *Lessons learned and guidance*

Overall, it can be stated that structural and non-structural tsunami mitigation measures differ greatly in Japan and Europe due to the difference in existence and perception of the tsunami risk. There is a great variety of measures in Japan extending from constructing coastal dikes of advanced design to community preparedness and protection by coastal vegetation, although some gaps and deficiencies exist. In Europe, tsunami mitigation is rare and limited to a few types of measures and locations. This could be attributed to the fact that the occurrence of most tsunamis in the Pacific region has led to a thought that tsunami hazard in Europe is insignificant, although the hazard is real according to the European records of tsunamis both from documentary evidence and the geological records.

In addition, Europe has a much longer natural coast line which utilizes the concept of soft and hard measures in combination. Natural defences such as dunes are very often integrated into the hazard mitigation strategies. On the other hand, Japanese mitigation strategies usually consist of hard measures leading to a large amount of artificial shorelines.

In conclusion, it can be suggested that more actions on tsunami mitigation should be taken in Europe considering new research on sources, risk, and performance of existing structures under tsunami loading, whereas the mitigation strategies on the Japanese side should be enhanced for a more resilient system against tsunamis.

The aforementioned considerations suggest the following guidelines related to coastal hazard strategies:

- Hazards along coasts may result from very **different sources** and result in very different impacts along coasts. Altough some principal characteristics can be found for European and Japanese coasts, it is advisable to perform a detailed analysis (hindcast or scenario simulation) rather than use a generic approach.
- **Coastal areas** in Europe and Japan are very diverse and may differ significantly from each other. It is therefore advisable to carefully investigate all potential options for mitigation measures against tsunami and storm surges and design any measures on a case to case basis.
- **Strategies (hard measures)** for protection against tsunami and storm surges are often based on a multiple-step approach and not based on single measures. It is generally advisable to build on such a 'stepwise' defence strategy rather than relying on single hard structures.
- **Soft strategies** should also be considered and included in the defence strategy against coastal hazards. Such strategies comprise early warning, training exercises and teaching, evacuation of people, vertical escape structures, risk analyses and landuse planning, and many more.

5   Numerical model studies for tsunami

This chapter introduces analyses performed with numerical models for tsunami propagation and run-up and the behaviour of tsunamis in harbours. Different numerical models were used to hindcast case studies and check model results against measurements. Details of these analyses are discussed (section 5.1) and have led to some concluding observations and guidelines (section 5.2).

5.1   Overall results

In METU (2015a) the **key tsunami parameters** are summarised and discussed which describe and characterise the tsunami impact. It has been noted that the behaviour of tsunami when approaching the coast can be significantly different depending on the tsunami height, the bathymetry and topography and various other boundary conditions. The relevant output parameter like the maximum and minimum wave elevation, the maximum flow depth, and the current speed are usually simulated by numerical models.

Furthermore, various forces can act on any structure or building in tsunami-prone area. These forces are:

- Hydrostatic Forces: This force is due to an imbalance of pressures from differences on water depths on opposite sides of a structure. Hydrostatic force can act laterally on an object.
- Buoyant forces: This force acts on partially or totally submerged objects and will act vertically through the center of mass of the displaced volume.
- Hydrodynamic forces: Hydrodynamic force will act on the structure due to water flow around a structure.
- Surge forces: When the leading edge of a surge of water impinging on a structure it causes surge forces.
- Impact forces: When tsunami inundation occurs, objects like boats, pieces from houses, cars, or other debris are transported in the water and may strike structures or buildings which will cause large impact forces.
- Breaking wave forces: Here two breaking wave load conditions are of interest; wave breaking on small-diameter vertical elements and wave breaking against walls.

The study has also looked into three different numerical models which were used to hindcast a case study where hydraulic model tests were performed in a 3D tsunami basin simulating the tsunami impact on a small town (scale of 1:50). The models showed principal abilities to model several of the aforementioned parameters with partly large differences to the measured data. More details can be found in METU (2015a).

Numerical modelling of **tsunamis in harbours** are discussed in two categories which are i) the harbour damage and ii) the harbour resonance (METU, 2015b). First, an

overview of those possibilities was introduced and described. In order to determine the level of tsunami hazard and to develop measures to increase resilience, the effects of the key tsunami hydrodynamic parameters in the shallow water zone and at land area were investigated. The resilience against disasters in harbours, the water level and current amplifications and some examples of tsunami induced hazards in harbours from different prefectures during the 2011 Tohoku event were compiled and presented based on an extensive literature survey.

The main tsunami hydrodynamic parameters were found to be (i) the maximum positive amplitude, (ii) the maximum current velocity, (iii) the maximum flow depth, (iv) the maximum hydrodynamic forces, (v) the maximum of momentum flux, (vi) the maximum negative amplitude, (vii) the arrival time of the first wave, (viii) the arrival time of maximum wave, and (ix) the duration of the inundation and withdrawal of tsunami. Since basins' depths are shallow at all long wave conditions, the tsunami surge modelling in a harbour becomes applicable by using the governing equations under long wave conditions. Those were used to compute and evaluate the effects of main tsunami hydrodynamic parameters in shallow zone and at land in order to determine the level of tsunami hazard and to develop the measures to increase the level of the resilience of the study area.

Ocean waves cannot generate enough energy to affect open coasts by resonance amplification. However, they can cause hazardous oscillations when they enter enclosed or semi-enclosed basins and harbours. Wave radiation via semi-enclosed basins is an important factor in decaying energy. On the other hand, making the harbour entrance narrower, an amplification of the arriving wave may occur. Therefore, dams, dikes and other harbour protecting structures could tighten the entrance width, and then intensive resonance oscillations take place inside the harbour, this phenomenon is called the 'harbour paradox'. Hence both the harbour resonance period and the harbour damage parameters could be related to the layout of harbour structures which determines the harbour geometry.

To conclude, resonance inside harbours due to tsunami waves can exacerbate the damages by amplifying the water level changes, currents and momentum fluxes. An example of assessing possible amplifications due to resonance is presented in METU (2015b). The presented study focused on the distribution of water level and current velocity amplifications due to the long wave motion inside Haydarpasa harbour. The fully reflective boundaries inside the ports (such as Haydarpasa port) should be considered as the critical locations under the extreme wave conditions. The regular shaped inner basins with reflective boundaries can also become critical regions such as the case in Haydarpasa port.

5.2   *Lessons learned and guidance*

Key parameters for tsunami impacts have been identified and benchmark tests for numerical models on tsunamis have been performed. This included a tsunami wave run-up study and a case study looking into harbour resonance and damages. These

studies have suggested that numerous numerical models are available for modelling tsunami sources, tsunami propagation over the ocean, and wave run-up at the coasts. However, due to the complexity of the bathymetry, the large extent of the model needed, and further necessary limitations the model results need careful checks and calibrations. Most of the models are capable to produce the identified key parameters characterising the tsunami impacts on the coasts although the quality of prediction may differ significantly from model to model and from case to case.

With respect to modelling tsunamis in harbours the studies have shown that the highly reflective boundaries in harbours can generate reflections so that resonance in harbour basins can occur. It is therefore required for a design of a harbour to consider these loading cases to avoid both harbour resonance effects and harbour damages.

From these findings the following guidelines on the use of numerical models can be suggested:

- **Numerical models** are in principle able to produce reliable outputs for the simulation of tsunamis. However, the accuracy of these models is limited due to the complexity of the simulated problem and the usual dimensions of the area. If possible, numerical models should therefore be calibrated using available hydraulic model studies or field data.
- **Key tsunami impact parameters** which should be modelled or generated are:
  - the maximum positive amplitude,
  - the maximum current velocity,
  - the maximum flow depth/inundation height,
  - the maximum momentum flux (to assess hydrodynamic forces),
  - the maximum negative amplitude,
  - the arrival time of the first wave,
  - the arrival time of maximum wave, and
  - the duration of the inundation and withdrawal of tsunami
- When **designing harbour layouts** under tsunami impacts, numerical (or hydraulic) models should be used to test for resonance problems. This will assist in minimising the resonance and avoid any damages in the harbour.

6 Guidance on physical model studies for tsunamis on coastal structures

This chapter summarises results from different hydraulic model tests performed in Japan at PARI and in Europe at TU-BS (LWI, 2015). It provides an overview of what has been performed (section 6.1) and seeks to derive lessons learned and some guidance on hydraulic model tests from these tests (section 6.2).

6.1 Overall results

Laboratory experiments on the performance of a rubble mound breakwater under tsunami impact, with the focus on the induced breakwater damage, were performed in a wave flume at TU-BS in a framework of the cooperation between METU and TU-BS. This investigation was a continuation and extension of the tests conducted at PARI (Figure 5), in which the stability of the Haydarpasa Breakwater in the Haydarpasa Port in Istanbul (Turkey), subject to impact of solitary waves and constant overflow, was analysed. Three additional variations of the breakwater prototype with simplified geometry were examined at TU-BS, resulting in a total of four breakwater geometries considered (Figure 6): (i) breakwater with a berm and a crown wall unit (configuration 1), (ii) breakwater without crown wall unit (configuration 2), (iii) breakwater with crown wall unit (configuration 3, corresponding to the prototype), (iv) breakwater with shifted crown wall unit (configuration 4). Two breakwater configurations were always examined simultaneously (configurations 1 and 2, 3 and 4) to optimize the performance time. Apart from the additional breakwater configurations examined, the extension of the reference experiments at PARI encompassed also larger load induced by solitary waves (wave height range from 0.05 to 0.15 m in the model scale) and another flow regime - the tsunami bore, representing a broken, propagating tsunami (with a water depth in front of the bore gate of 0.20 m and behind the bore gate of 0.75 - 0.85 m).
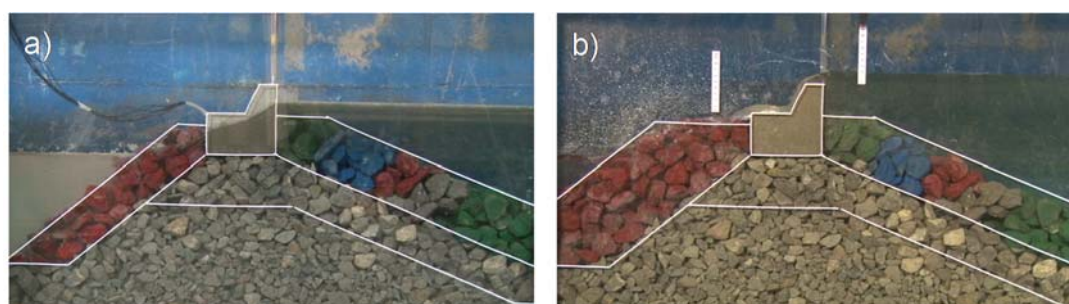

Figure 5 Layout of armour layers in reference tests at PARI: a) for original configuration, b) for improved configuration (Guler et al., submitted)
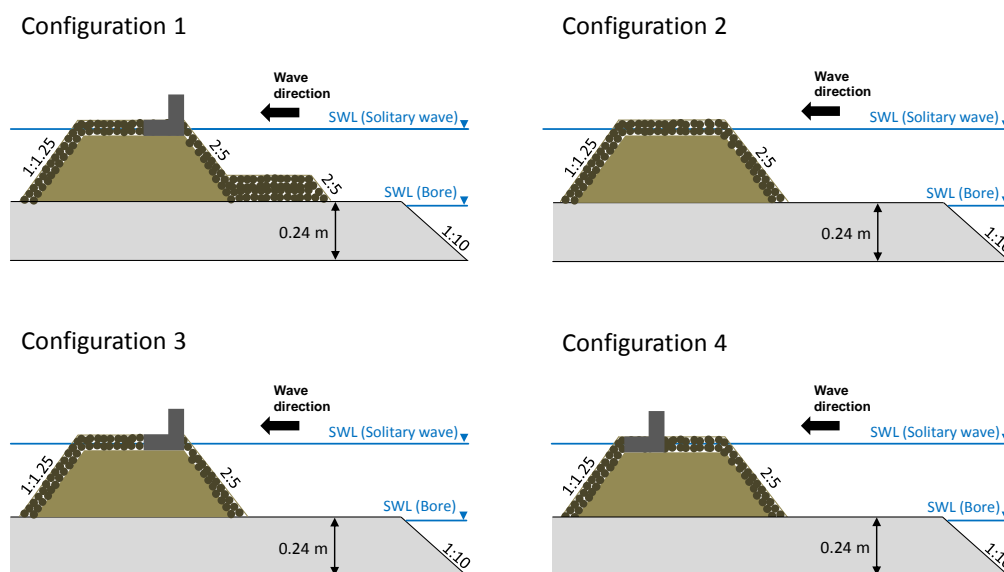
Configuration 1

Configuration 2

Configuration 3

Configuration 4

Figure 6 Configurations of rubble mound breakwaters tested in hydraulic model tests at TU Braunschweig (LWI, 2015)

For the comparison purposes of the experimental results, the model scale was kept the same in the tests at PARI and TU-BS (1:30), and the model setup was designed with some minor modifications of the bathymetry/breakwater models geometry, resulting from a limited time for the performance of the investigation (however, keeping the same thickness and mass of the rubble layers, breakwater model height and geometry of the crown wall units).

The determination of the performance of the breakwater models was based on the analysis of the observed processes, the properties of the incident and transmitted wave/flow (including wave height/flow depth, pressure induced on the crown wall unit, and flow velocity) as well as the breakwater damage (damage classification, photo/video analysis, and comparison of the breakwater profiles before and after tests).

The water depth conditions in the tests with solitary wave and tsunami bore, defining the initial breakwater model submergence (i.e. breakwater submerged up to the crown, breakwater emerged, respectively), resulted from the different methods of the flow regime generation and determined the mode of the breakwater failure. The conditions in the tests with the bore corresponded in nature to a very strong withdrawal of the sea prior to tsunami impact (or to an onland embankment), which might not be very realistic. However, change of the water depth conditions by introducing other bathymetry profile was not favoured concerning the comparative result analysis and the limited duration of the experiments.

Breakwater model damage in case of the tests with the bore resulted predominantly from the pressure difference in front of and behind, as the water, released by the

opening of the bore gate, dammed in front of the breakwater models. This led to the effect of blowing out the rubble layers at the harbour side from inside, with the seaside slope almost undamaged. The contribution of the overtopping of the crown wall units/breakwater crown to the overall breakwater model damage was not significant; it led to sliding of the crown wall unit down the breakwater harbour slope. Due to the fact that different damage extension was observed for the different breakwater configurations, not necessarily resulting from the different geometry (e.g. major damage observed for configurations 1 and 2 for bore of h0 = 0.80 m, while minor damage to configurations 3 and 4 for same bore conditions), repetition of the experiments would be recommended to confirm the gained results (Figure 7).
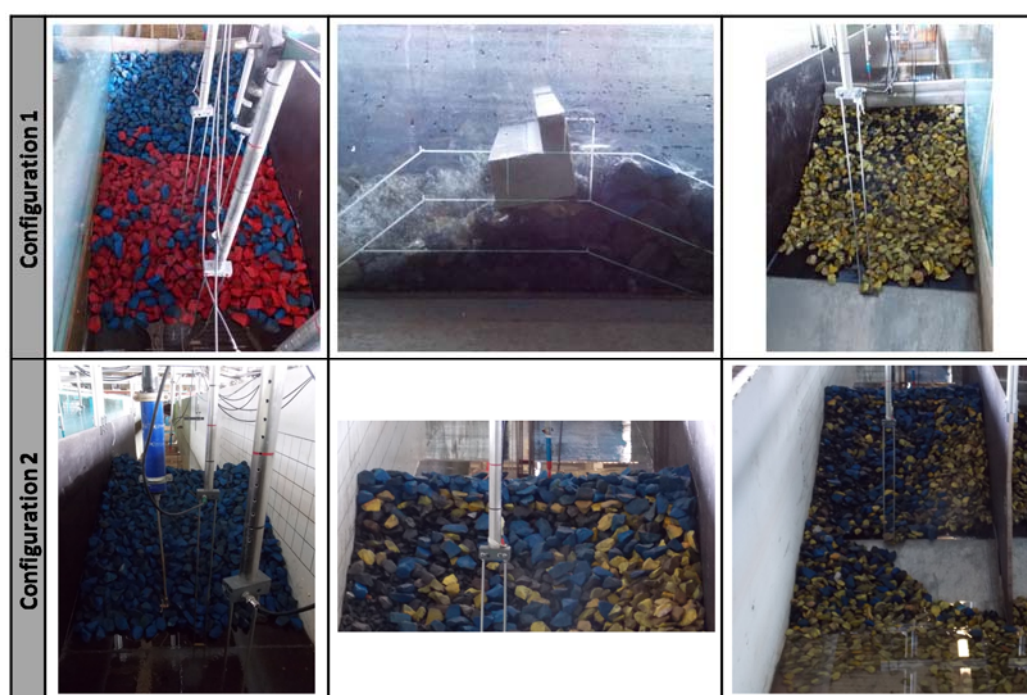

Figure 7 Damage of configurations 1 and 2 due to tsunami bore with h_0=0.80 m and h_1=0.20 m (Test 20140723_02)

In case of the tests with solitary wave, the failure mode of the breakwater models was sliding of the crown wall element and the rubble down the harbour breakwater slope, induced by wave overtopping. Unlike the experiments with the tsunami bore, the seaward breakwater slope as well as the berm remained generally stable under solitary wave attack as they were in submerged conditions.

The presence of the crown wall unit definitely increased the stability of the armour harbour slope, as indicated by the comparative result analysis for breakwaters with and without the crown wall unit. Therefore, the breakwater configuration without the crown wall element is not recommended for practical implementation. No particular advantage of the berm presence (for the geometry tested) was observed. Further tests should be performed to examine berm geometries different from the one applied to

the experiments at TU-BS, including berm lengthening and heightening (i.e. reducing the freeboard over the berm). This would be expected to have more influence on wave transformation over the berm, resulting in a lesser wave transmission to the harbour side.

Both the experimental investigations at PARI and TU-BS indicated that the conventional breakwater design (i.e. configuration 3 in tests at TU-BS with the crown wall unit placed at the seaside edge of breakwater crown) is stable under weak tsunami conditions (up to ca. 3 m in prototype - 0.1 m in model scale). Further improvement of breakwater stability under more severe tsunami impact can be achieved by thickening the armour layer at the harbour breakwater slope as indicated by the experimental results at PARI with the improved breakwater.

6.2   *Lessons learned and guidance*

The literature study (chapter 2) suggested that there is little information available for specific type of coastal structures like rubble mound breakwaters and their performance under tsunami loads. Therefore, this type of breakwater has been tested in two different wave flumes at PARI and TU-BS, the latter in collaboration with METU. The tsunami impact (generated as a solitary wave and a bore at TU-BS and as a solitary wave and constant overflow at PARI) was examined for four configurations: (i) breakwater with a crown wall unit and a berm, (ii) breakwater without a crown wall unit and without a berm, (iii) breakwater with a crown wall unit and without a berm, (iv) breakwater with a shifted crown wall unit and without a berm. The layout of the rubble layers and the breakwater geometry was based on a simplified cross-section of the Haydarpasa Breakwater, protecting the Haydarpasa Port in Istanbul (Turkey), for which tsunami loads were not taken into account for the design.

The experimental results indicated that the harbour (landward) side of the breakwater, regardless the configuration, was most prone to damage (displacement of the armour layers over the harbour slope as well as the crown wall unit). The processes governing the breakwater damage were directly related to the breakwater submergence conditions tested and to the wave generation method: in case of the solitary wave impact (submerged breakwater conditions) wave overtopping was dominant, while in case of bore impact (emerged breakwater conditions) - pressure difference at both sides of the breakwater was dominant.

The most stable breakwater configuration was the one with the crown wall unit and without the berm, however it failed under the impact of higher solitary waves. Further improvement of its stability can be achieved by applying a doubled armour layer on the harbour side, as indicated by the model tests at PARI (however, not examined at TU-BS). Larger overtopping flow depths were attributed to the breakwater configuration without crown wall unit. The configuration with shifted crown wall unit was less stable under wave impact due to the lack of sufficient support of the

unit by the armour layer. The effect of the berm on wave impact was however not clearly observed.

Guidelines with relation to physical model studies on rubble mound breakwaters subject to tsunamis may be concluded from this work as follows:

- **Hydraulic model tests** are valuable tools to investigate the behaviour of structures and buildings under tsunami attack since they allow insight in the performance and failure modes of these structures.
- The **simulation of tsunami waves in wave flumes** can be performed using three principally different methods
  - overflow induced by pumps[1],
  - turbulent bores induced by suddenly opening gates
  - solitary waves

  These methods require different water level conditions in the flume which together with the specific method lead to different loading conditions of the structure.
- Model tests of **rubble mound breakwaters** under tsunami load need to be performed under the most similar conditions to prototype investigating the type of incoming tsunami wave (e.g. broken or not) and the water level at the location (submerged or emerged). Results seem to indicate that the breakwaters crown wall is crucial for stability and so is the armour layer on the harbour side of the breakwater. Both parts of the breakwater could be potentially reinforced to increase the stability against tsunami attack.
- The **analysis of model test results** needs to be done carefully taking into consideration different tsunami scenarios as indicated before, the possible failure modes of the structure, and model and scale effects.

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[1] More recent developments like the HR Wallingford tsunami generation method (Rossetto et al., 2012) have not been tested here and are therefore not considered in these guidelines.

7   Vulnerability and risk assessment studies

This chapter introduces and discusses work within RAPSODI on vulnerability and risk analyses (NGI, 2015) where section 7.1 discusses the overall results of the study and section 7.2 presents lessons learned from this study and the potentials of hazard and risk maps.

7.1   Overall results

The maximum flow depth was obtained by hindcasting the 2011 Tohoku earthquake and tsunami using knowledge of the earthquake source (Løvholt et al., 2012) and combining bathymetry data (GEBCO '08) with very high resolution Japanese digital elevation data. This flow depth was then used in a GIS-based tsunami mortality risk model in order to calculate tsunami mortality risk. The city of Ishinomaki was chosen for the validation of the model results.

The calculated inundation areas and flow depths both agree well with post-event field data. The modelled mortality in Ishinomaki city agrees reasonably well with reported death tolls, even though it was necessary to introduce several simplifications into the model, such as uniform building vulnerability due to lack of available relevant data (the data were obtained too late, were not in appropriate formats, or did not cover relevant areas). It should also be noted that reported death tolls vary considerably (3000-4000, some sources, though of non-verifiable nature, report even higher numbers).

Our study showed that the GIS-based tsunami mortality risk model reasonably hindcasts mortality for the 2011 Tohoku earthquake and tsunami event, even with all the assumptions that had to be made. With the help of the model it is possible to identify high mortality risk areas, as well as identify the main risk driver(s) in high-risk areas, which often can be attributed to either high to very high flow depths, high population concentrations (causing high exposure), vulnerable building mass, or a combination of these factors.

Based on these positive hind-casting results we are confident that our model could form a useful tool within a tsunami risk reduction framework. The model can be run for different tsunami scenarios potentially impacting a given tsunami threatened area or town. The results of the model can be used e.g. to produce maps showing different mortality risk scenarios that would have to be expected for different flow depth scenarios with corresponding probabilities. This could help in meaningful urban planning, allowing for the identification and selection of evacuation routes, evacuation locations, planning of mitigation structures, etc.

Accessing the large amount of presumably available post-disaster field data was more challenging than expected when carrying out the tsunami mortality risk modelling in the RAPSODI project. Several of the databases where relevant data are stored are in Japanese only, something which obviously hampers the access of the data for non-

Japanese speakers. Other relevant data are stored without geographical information (e.g., in tables or as maps in PDF- or JPG-format). It would have required disproportional resources to convey this information into a utilisable format for use in the RAPSODI project.

Deliverable 7 "Results of the laboratory analysis and wave flume tests" (LWI, 2015) describes the RAPSODI laboratory experiments with various tsunami breakwaters under tsunami impact. The well-functioning design is recommended for possible implementation in the numerical model to study the influence on inundation and mortality risk. However, as overflow without breakwater failure is not realistic and because there is considerable flow through the structure (in addition to the overflow) it was decided not to implement synthetic breakwaters in a numerical model that presently cannot handle breakwater failure or permeability.

7.2   Lessons learned and guidance

7.2.1   Lessons learned

The design of the GIS-based tsunami mortality risk model allows for the expansion of the model with new or other parameters, as well as for the refinement of already implemented parameters.

The flow depth modelling can be refined by including obstructions such as buildings and infrastructure. Such obstructions may locally increase the flow depths or canalise the water, hence locally intensifying the water current velocities and the wave loads. On the other hand, they may also increase the flow resistance and thus reduce the inundation distance. The specific momentum flux per unit width (expressed by the product of flow depth and water current velocity squared) is often considered the best damage indicator (Tsunami Pilot StudyWorking Group, 2006). Comparing the computed specific momentum flux per unit width and damage data may enable further validation and improvement of the numerical model.

In addition to structural vulnerabilities, new parameters could e.g. be the inclusion of economic, ecological, or societal vulnerabilities, as well as indirect impacts. Experience on these issues can probably also be gained from storm surge and coastal flood risk analysis (see e.g. Burzel et al., 2015; Ujeyl and Rose, 2015; for a survey, see NGI, 2014). Also the awareness, education level, and preparedness of the people, as well as existing warning systems and design of mitigation structures influence on exposure and risk, and should be integrated in future analyses. Implementation of breakwaters in the numerical models should consider failure as well as flow through the permeable structure (Cappietti et al., 2012). This could be achieved by replacing the breakwater by a "high roughness zone" or assign current velocities and surface elevation behind the breakwater of recommended design from the laboratory experiments. Possible examples with inclusion of seawalls/breakwaters should anyhow be presented with caution, as the present structures have a minimal effect on the worst-case scenarios like the 2011 Tohoku tsunami.

Building vulnerability (not treated in this study due to lack of timely available data, but used in previous forecast studies) can be assessed quite detailed, in particular when cadastral data are available and combined with ancillary data such as information on building type from official sources, or from satellite imagery and/or photographs published in GoogleMaps and GoogleEarth. Building fragility curves as presented by among others Suppasri et al. (2011, 2013) and González-Riancho et al. (2014) should be applied. Refining building vulnerability in this way will allow for a refinement of the mortality risk calculations. Exposure can, for example, be refined by including information about the spatio-temporal whereabouts of people (cf. Freire et al., 2013), or information about the population composition (cf. González-Riancho et al., 2014). Fatality-ratio curves by Suppasri et al. (2012) or others should be used to adjust the S-curves used in the computation of the mortality risk. Additionally, the inclusion of evacuation plans (cf. González-Riancho et al., 2013; Bunpei et al., 2015) and shelter locations would help to improve the forecasting capability of the model.

Further experience can be gained e.g. from the HAZUS-MH (Hazards-United States Multi-Hazard) Flood Model (https://www.fema.gov/hazus-multi-hazard-models) that is used to assess both riverine and coastal flooding and estimates potential damage to buildings, essential facilities, transportation lifelines, utility lifelines, vehicles, and agricultural crops. HAZUS-MH also addresses building debris generation and shelter requirements. Direct losses are estimated based on physical damage to structures, contents and building interiors. The effects of flood warning are taken into account, as are flow velocity effects. HAZUS-MH can be run internationally, but without technical support or training for users/analyses outside the U.S. and Canada.

7.2.2   *Hazard and risk maps*

Hazard maps show the extent of various scenarios with corresponding probabilities (alternatively, they show the probabilities for a given threshold run-up height). Risk maps go a step further by considering also the consequences for the elements at risk. The maps are meant for land use planning, comparison with other threats, warning and handling acute situations, etc. The contents, scale, and detailing level of maps for natural hazard and risk assessment should be adapted to the intended use and the available input data. For instance:

- A *regional tsunami exposure assessment* normally combines calculated maximum water levels at the shore line for given scenarios and probabilities with simplified inundation estimates and population densities.
- A *local tsunami risk assessment* normally includes more sophisticated simulations of the inundation for the given scenarios and probabilities in combination with the elements at risk (people, economic and/or ecological values, etc.) and their vulnerability (mortality, building vulnerability, etc.).

The scale and contents of the maps can vary over the whole range from "global" to "local", depending on the intended use. Typically, maps for land use planning, handling of acute hazard situations, or various kinds of risk assessment in local communities can be presented at a scale larger than 1 : 5000 (often preferable with a scale equal to or even larger than 1 : 2500). Different scales for different users should be considered.

Contents of maps intended for land use planning with regard to tsunamis (for a given probability) are typically:

- Hazard maps: Inundation distance and inundation height (or flow depth) for various scenarios
- Wave speed or momentum (for currents) and momentum flux (for design loads), (wave energy will give a combined impression of elevation and momentum flux).
- Previous events (geological and historical records)
- Highly populated / vulnerable areas
- Exposure maps (distribution of population, distribution of values)
- Vulnerability maps
- Risk maps, risk zoning

Correspondingly, contents of maps for warning and handling of an acute tsunami situation (with a given probability or intensity) are typically:

- Inundated areas to be evacuated
- Highly populated / vulnerable areas
- Escape routes
- Elevated / safe areas
- Personnel to be warned

7.2.3   Guidelines

Vulnerability and risk analyses were performed within RAPSODI and suggest the following guidelines:

- **Numerical tools** are indispensable to simulate the tsunami-induced flow and inundation and are therfore key for any tsunami hazard and risk studies. Both these tools and the input conditions (earthquake sources and bathymetry/topography) have to be carefully selected to produce relevant inundation parameters.

- **Structural and socio-economic vulnerability studies** require a minimum of spatial data for the area of investigation which may be summarised as follows:
  o Number, size, storeys, use, and material of houses
  o Areas of private, industrial, and other uses
  o Number of people present in the area

- GIS-based tsunami **mortality risk models** allow for the estimation of casualties under tsunami attack, but results should be treated as estimates due to the large number of uncertainties which are usually involved in their applications. However, these models are capable of suggesting the right order of magnitude of casualties to be expected.

- **Risk assessment studies** can be performed linking the results from inundation simulations with occurrence probabilities of tsunami and the vulnerability results indicated before. They are usually scenario based and can be presented as risk maps which help in understanding the critical areas where mitigation measures might be specifically effective.

- **Further parameters** to be included in risk assessment studies could be ecological or societal vulnerabilities in addition to the structural ones, as well as indirect impact. Also the awareness, education level, and preparedness of the people, as well as existing warning systems, evacuation plans, tsunami breakwaters or sea walls, and the design of mitigation structures should be considered and will change the values of risk.

8 Guidelines for risk assessment studies and safety of coastal structures

This chapter is essentially based on three parts which are i) a summary of guidance provided by this report; ii) the guidance provided by ASCE on tsunami loads and effects (ASCE, 2015); and iii) the guidance provided by the Japanese Ministry of Land, Infrastructure, Transport, and Tourism (MLIT, 2015) on safe tsunami breakwater design. However, the chapter is structured following the guidance on vulnerability and risk studies first (section 8.1) and then the guidance for the safety of coastal structures and buildings next (section 8.2).

8.1 Vulnerability and risk assessment studies

RAPSODI has looked into vulnerability and risk analyses approaches for tsunami prone areas, especially for the 2011 Tohoku tsunami (chapter 7). This has revealed a couple of findings and guidance which are repeated here

- **Numerical tools** are indispensable to simulate the tsunami-induced flow and inundation and are therfore key for any tsunami hazard and risk studies. Both these tools and the input conditions (earthquake sources and bathymetry/topography) have to be carefully selected to produce relevant inundation parameters.
- **Structural and socio-economic vulnerability studies** require a minimum of spatial data for the area of investigation which comprise – amongst others - the number, size, storeys, use, and material of houses; areas of private, industrial, and other uses; and the number of people present in the area.
- GIS-based tsunami **mortality risk models** allow for the estimation of casualties under tsunami attack but results should be treated as estimates due to the large number of uncertainties which are usually involved in their applications. However, these models are capable of suggesting the right order of magnitude of casualties to be expected.
- **Risk assessment studies** can be performed linking the results from inundation simulations with occurrence probabilities of tsunami and the vulnerability results indicated before. They are usually scenario based and can be presented as risk maps which help in understanding the critical areas where mitigation measures might be specifically effective.
- **Further parameters** to be included in risk assessment studies could be ecological or societal vulnerabilities in addition to the structural ones, as well as indirect impacts. Also the awareness, education level, and preparedness of the people, as well as existing warning systems, evacuation plans, tsunami breakwaters or sea walls, and the design of mitigation structures should be considered and will change the values of risk.

Furthermore, for a better communication of hazards and risk and to improve the visualisation opportunities for tsunami risks, tsunami hazard and risk maps can be produced based on:

- A **regional tsunami exposure assessment** normally combining calculated maximum water levels at the shore line for given scenarios and probabilities with simplified inundation estimates and population densities.
- A **local tsunami risk assessment** normally including more sophisticated simulations of the inundation for the given scenarios and probabilities in combination with the elements at risk (people, economic and/or ecological values, etc.) and their vulnerability (mortality, building vulnerability, etc.).

8.2   Safety of coastal structures and buildings

8.2.1   RAPSODI guidance

Within RAPSODI several investigations have been performed to better assess the safety of coastal structures and buildings, amongst which was an extensive literature review and further data analysis of the 2011 Tohoku tsunami. The key lessons learned and guidance from these studies (cf. chapters 3 and 4) are repeated here below:

- **Damages of coastal structures** occurred considerably often during the 2011 event and were mostly due to sliding when the relative wave height exceeded 3 m. However, this cannot be easily generalised and some failure mechanisms are still not fully understood.
- **Damages to buildings** mostly depend on the construction type and material and appeared to be full damages when the inundation height exceeded 2 m. Very often, scour due to the strong flow patterns around buildings has caused additional damages .
- **Strategies (hard measures)** for protection against tsunami and storm surges are often based on a multiple-step approach and not based on single measures. It is generally advisable to build on such a 'stepwise' defence strategy rather than relying on single hard structures.

RAPSODI has more specifically investigated the stability of rubble mound breakwaters under tsunami loads by means of hydraulic model tests. Some of the guidance provided in chapter 6 is repeated here:

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- **Hydraulic model tests** are valuable tools to investigate the behaviour of structures and buildings under tsunami attack since they allow insight in the performance and failure modes of these structures.
- Model tests of **rubble mound breakwaters** under tsunami load need to be performed under the most similar conditions to prototype investigating the type of incoming tsunami wave (e.g. broken or not) and the water level at the location (submerged or emerged). Results seem to indicate that the breakwaters crown wall is crucial for stability and so is the armour layer on the harbour side of the breakwater. Both parts of the breakwater could be potentially reinforced to increase the stability against tsunami attack.
- The **analysis of model test results** needs to be done carefully taking into consideration different tsunami scenarios as indicated before, the possible failure modes of the structure, and model and scale effects.

8.2.2 *ASCE standard on tsunami loads and effects*

The American Society of Civil Engineers (ASCE) is planning to publish a new standard on the 'Minimum Design Loads and Associated Requirements for Buildings and Other Structures', chapter 6 of which is on 'Tsunami Loads and Effects' (ASCE, 2015).

The standard deals with, amongst other issues, the loads asserted on buildings and structures subject to tsunamis and includes a) hydrostatic loads; b) hydrodynamic loads; c) debris impact loads; and d) foundation design. In these sections the standard provides detailed guidance on how to assess forces and under which boundary conditions to apply them. Most of these loads and further parts in the standard are linked to buildings, not necessarily to coastal defence structures. It is therefore an excellent guidance in addition to what can be found from the RAPSODI work and to what will be described in the next section for Japanese tsunami breakwaters.

8.2.3 *Tsunami-resistant design of breakwaters in Japan*

Following MLIT (2015), the basic principle of tsunami-resistant design of a breakwater shall be to aim at providing the breakwater with a "tough construction" highly resistant to tsunami damage so that the functions required of the breakwater against the "design tsunami" can be maintained and that the functions required of the breakwater even if the harbour is hit by tsunamis greater in scale than the "design tsunamis" can be maintained as much as possible.

When breakwater performance is checked, comprehensive verification shall be conducted for the overall stability of the breakwater against the expected tsunamis and the seismic motions preceding the tsunami based on a full understanding of the failure mode of the breakwater by tsunami and a full consideration of the topography of the harbour and various characteristics of the harbour including facility layout.

For the overall stability of the breakwater, the stability performance shall be checked for sliding and overturning of the upright part against the wave force of the tsunami, the stability of the foundation with respect to the load bearing capacity, and the stability of the foundation mound and seabed ground (original ground) against the flow of tsunami waters. It shall then be verified that the resultant expected damage be less than the upper limit for each performance requirement posed to the breakwater.

An example procedure for comprehensive verification on overall stability of breakwater is shown in Figure 8.
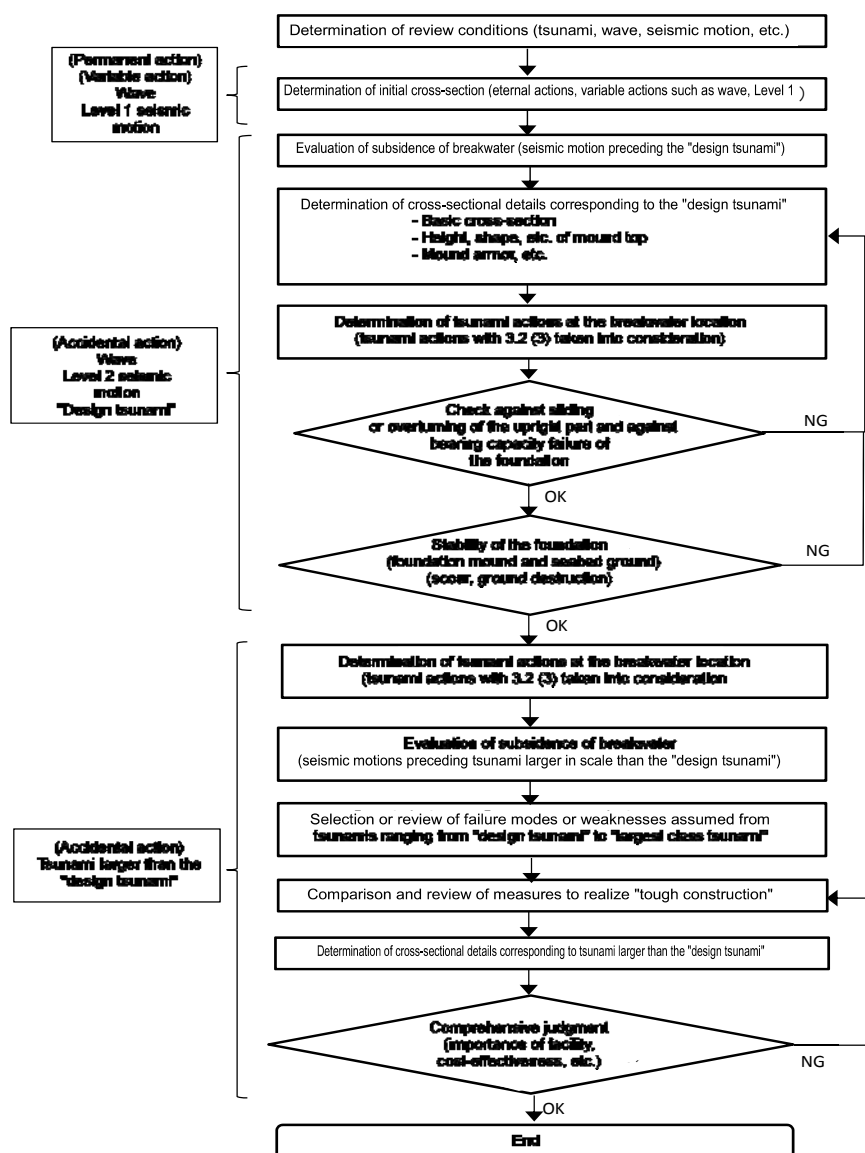
Figure 8 Example procedure for comprehensive verification on overall stability of breakwater

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