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Interdisciplinary resilient spatial planning based on the reconstruction of Otsuchi, Japan

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Abstract: The 2011 Great East Japan Earthquake had a devastating impact on the town of Otsuchi in Iwate Prefecture, resulting in 1,234 immediate deaths and 59.6% of residential houses being fully damaged amongst other severe consequences. The post-disaster Reconstruction Plan (2011-2018) of this town focused on rebuilding the previously existing town with large-scale engineered interventions, resulting in a fragmented set of spatial interventions which solve problems in a single faceted way. The management of a post-tsunami reconstruction process should represent a resilient design for the future. This paper demonstrates that a modified land use design, developed and achieved through an interdisciplinary approach, represents a holistic solution to the drawbacks of the reconstruction plan. Through an iterative framework, site-specific strategies are developed at the urban and the building scale that combine safety and livability by finding synergies among disciplinary fields in an integrated manner. The result of this paper is a quantified evaluation of the reduction in flood risk achieved with a new design, making spatially evident the areas in which a refinement is required to mitigate flood damage.

Keywords: tsunami; interdisciplinary; resilience; spatial planning; strategy

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1. Introduction

On March 11, 2011, the Great East Japan Earthquake with a magnitude of 9.0 on the Richter scale occurred in the Tohoku region of Japan. This region is one of the most earthquake-prone regions on earth. The resultant tsunami caused unexpected death and damage due to the unprecedented force of the waves. After the initial rescue efforts and the relocation of 300,000 people, the Japanese government developed a reconstruction plan [1].

This paper focuses on the reconstruction of Otsuchi as a testbed for interdisciplinary urban development that both improves everyday life and provides the necessary safety in the case of a disaster. In order to achieve an integrated design, a team of students from Delft University of Technology worked together from across different disciplines from the faculties of architecture and civil engineering.

Otsuchi has an estimated population of about 12,000 residents and is situated between large mountains in a small river valley [10]. Otsuchi is located at one of Japan's most productive fishing grounds, and fishing is the major livelihood of the town, alongside the local steel industry situated in neighboring Kamaishi [3]. Like many other towns in the region, Otsuchi is experiencing severe population ageing and decline [1]. The reconstruction efforts in Otsuchi focused on rebuilding the town as it existed before and protecting it from the threat of future tsunamis. This solution oriented approach of the Japanese government led to a series of unintegrated interventions, including a seawall which reaches TP +14.5 m, significantly changing the character of the town by cutting it off from the sea.

The multidisciplinary team researched the existing situation in Otsuchi and explored potential futures first with a site-visit and workshops in Otsuchi. The goal of these activities was to analyze and synthesize the situation in order to create a interdisciplinary project strategy that can be used by all disciplines for evaluation and decision making. Within this paper, the following research question is answered:

''Considering contemporary multidisciplinary practice, how can interdisciplinary research improve the resilience of spatial strategies in a case like Otsuchi?"

The final design, the outcome of this strategy, aims to raise preparedness and resiliency in the event that a disaster of similar magnitude were to hit the Tohoku coast in the future. To do so, a proposal for a resilient design for the town of Otsuchi is developed, elaborating on the existing spatial characteristics of the town. The term '*resilience*' in this research is defined as *''the ability of a system to adjust in the face of changing conditions''* [55]. Resilience can be further interpreted and applied in different scales. For example, building flood resilience in the built environment involves reducing the risk and damages from disasters. According to Cutter et al. [5], resilience requires interdisciplinary cooperation considering flood risk as an outcome of both engineering and spatial design.

The structure of this paper is as follows. First, the methodology of the project is described. After the methodology, the context of the project is discussed. This includes the tsunami event itself, the disaster damage in Otsuchi, the reasons for the large number of casualties in Otsuchi and details about the existing reconstruction plan for Otsuchi. In the results section, the outcome of this project is presented. In this section, the project strategy and the new design is outlined. Thereafter, the existing reconstruction plan is evaluated and new reconstruction plans for the urban scale and building scale are presented. In the discussion and conclusion section, the existing and the proposed reconstruction plans are compared.

2. Context

2.1. The tsunami event

An earthquake of magnitude 9.0 on the Richter scale struck northeastern Japan on the 11th of March 2011 at 14:46. This caused a tsunami that arrived at the coast of Japan at 15:28 [39]. In Otsuchi, the wave reached a height of 10.7 meters near the town hall [7] and run-up heights of 39 meters were recorded.

The North of Japan is prone to earthquakes and tsunamis, due to the tectonic activity of the region. The Pacific and the North American tectonic plates collide in the Pacific Ocean in the East of Japan [45]. Historically, Otsuchi has been exposed to tsunamis. The most devastating ones in the record are the Keicho Sanriku Tsunami in 1611, three different tsunamis in 1703, the Meiji Tsunami in 1896, the Showa Tsunami in 1933 and the Chili Tsunami in 1960 [7]. For this reason, large breakwaters and coastal dykes have been constructed along its coast. In addition, the local government developed evacuation procedures and installed a general warning system in order to evacuate the citizens efficiently [9]. Although Japan is internationally recognized for its earthquake and tsunami resilience, the consequences of 2011 tsunami were catastrophic. The cumulative damage its causes are outlined below.

2.2. Disaster damage and casualties in Otsuchi

According to the information gathered during the site visit in Otsuchi, the following figures regarding human casualties (Table 1) and property damage (Table 2) caused by the 2011 Great Tsunami were obtained:

Table 1. Summary of the human casualties in Otsuchi due to the 2011 Great Tsunami [10].

Human losses	
Deaths	1234 people
Related deaths	47 people
Missing	437 people

Table 2. Summary of the material damage in Otsuchi due to the 2011 Great Tsunami [10].

Property damage	
Fully damaged houses	3092 houses (59.6%)
Partially damaged houses	786 houses
Missing	431 ha

In terms of percentages, 8% of the population of Otsuchi died or is still missing, 52% of the residential area and 98% of the commercial area were flooded. The population decreased from 15,994 on 11th of March 2011 to 12,892 in March 2013 [10]. Thereafter, the population continued to decrease because of displacement resulting from the long-term reconstruction plan and temporary housing situation. In June 2018, the population was 11,970 persons, translating to a population decrease of 25% [7].

2.3. Reasons for the large number of casualties in Otsuchi

Several factors aggravated the consequences of the tsunami. First, the time difference between the earthquake and the tsunami was minimal. The tsunami arrived at the shore of Otsuchi 42 minutes after the earthquake, which allowed little time to evacuate. For elderly residents especially, this caused difficulties to evacuate in time [7].

A second reason for the large number of casualties was that the meteorological agency initially announced an incorrect warning. The expected wave height in the initial warning was half of the actual wave height of the tsunami. The expected wave height would not have caused severe flooding, as it was less than the height of the seawall at that time (TP +6.4 m). This fact, combined with the power outage that affected the general warning system of Otsuchi, caused a critical delay in the evacuation of the inhabitants until they could see the actual tsunami approaching [10].

When the citizens became aware that the tsunami was much larger than expected, many evacuated by car. This reaction caused traffic jams on the main roads of the town, delaying escape. In addition, many Otsuchi inhabitants did not know what the shortest routes towards evacuation points were [10]. The combination of all these circumstances drove the population to panic and confusion in the evacuation, which led to a dramatic increase of the human losses.

2.4. Reconstruction Plan (2011-2018)

After the grave consequences of the March 11, 2011 earthquake and tsunami, the government of Japan made a new reconstruction plan (2011 to 2018) to restore the damaged urban services and to repatriate the locals to their hometowns. Their main plan consisted of a basic approach to tsunami protection, land utilization and transportation services to ensure safety while recreating the daily life and to revive the local economy. The municipality of Otsuchi had a strong vision for the future of its town; "*Seeing the ocean makes you want to go for a stroll. 'A lovely town' based on solid concepts*" [10].

The new tsunami protection strategy introduced two tsunami levels (see Figure 9 in [49]). The Level-1 tsunami is considered a frequent tsunami with a return period of one hundred years. For this level of protection, *hard* structures are used. On the other hand, the Level-2 tsunami is determined as the maximum possible tsunami and is used to design the evacuation strategy. The return period of this tsunami is approximately one thousand years [55]. For this level of protection, *soft* or non-structural measures are considered, such as spatial planning and evacuation plans.

In the event of a tsunami that exceeds the height of the Level-1 defense, flooding cannot be avoided behind the seawall. However, the new strategy guarantees the resistance of the seawall for tsunami loads that exceed those of the Level-1 tsunami. In Japan, this extra strength is known as *'nebari'*, a concept that stands for resilience or tenacity. The reinforcement of the coastal protections together with the design of evacuation plans based on a Level-2 tsunami are expected to effectively mitigate the damage caused by a potential tsunami.

The possibility of such a devastating event also requires study into other potential natural hazards. For example, flooding due to heavy precipitation is also a risk in Otsuchi [58]. Apart from being a risk by itself, heavy precipitation can trigger the occurrence of landslides due to soil instabilities because of soil saturation.

Another aspect taken into consideration in the reconstruction plan was the implementation of new policies regarding the urbanization of the town. The area behind the sea defense was purchased by the town administration and was designated as a disaster hazard area. In this zone, no residential constructions were allowed, although commercial structures and use were permitted. Land elevation works were carried out beyond the planned tsunami hazard area, where the ground height was increased from 2 to 4 meters above sea level. The residential buildings that occupied the area designated as a disaster hazard were relocated to the elevated land [7].

Despite the relocation plan of the residential areas, a tsunami of the same characteristics as the one in 2011 would still cause critical damage to most of the buildings it reached. The existing guidelines for the design of residential buildings consider earthquake loads, but no specifications that concern tsunami loads are given. Consequently, residential buildings are made of timber, which seems suitable to resist horizontal accelerations caused by earthquakes but not the water pressures caused by a tsunami (See Appendix C2). Furthermore, timber can become very dangerous floating debris when washed away by a tsunami. Concrete structures are more resistant to tsunami loads (as observed from several concrete buildings that did not collapse during the 2011 tsunami, although they needed repairs). However, this material is less resistant to earthquake loads. Henceforth, the dilemma about which material is more suitable for the buildings in Otsuchi arises, due to potential occurrence of both tsunamis and earthquakes (See Appendix C2).

Transportation services were also affected due to the tsunami. Consequently, the town remained isolated due to the lack of availability of road and rail infrastructure in the immediate aftermath. The reconstruction plan considers that the restoration of transport services is fundamental to incentivize the return of the people displaced from the town. In this line, the Japanese Government has provided funds for the reconstruction of national and prefectural roads and railways. Furthermore, the service of community buses that connect the towns of the region has also been restored [7].

Nevertheless, the transportation policies are missing a solid strategy regarding the evacuation plan. The plan aims to improve the reaction time of the population in case of a tsunami event by implementing acoustic signals, phone messages and signal panels indicating the elevation at different locations in Otsuchi. However, there is a lack of guidance on the escape routes to take according to the position of every citizen in the town, what would avoid indecision on the escape path to follow and crowding on certain routes.

Besides these implementations to recover from the tsunami event, issues during the reconstruction phase led to a gap between the plan and reality. The initial plan was not fulfilled due to several reasons, such as difficulties in building civil consensus, delays in implementation, increased costs of construction materials, and loss of local governmental representatives in the tsunami [10]. On the other hand, while designing the new reconstruction plan, some aspects were not taken into consideration, such as the residents' intentions to come back to the town, which is now leading a decline in population within the area.

Based on this analysis, in retrospect, the reconstruction plan can be 'updated' by using an interdisciplinary approach. This is done with a focus on the protection of the population of Otsuchi against an occasional event, while preserving the local identity (culture, economy and society) in day-to-day activities. Research-by design offers the opportunity to learn from Otsuchi's reconstruction for similar natural disaster prone locations for which a reconstruction plan will be necessary that effectively reduces the physical effects of a potential tsunami and anticipates the social and economical effects.

3. Methodology

In order to achieve the quality of resilience, interdisciplinary cooperation is central to the approach of this research. This cooperation goes beyond a *"conglomeration of disciplinary components"* and rather involves *"bridging and confronting the prevailing disciplinary approaches"* [14]. Through focusing on synergies and conflicts between disciplines, each spatial strategy is tested in a broadened context. This bridging and confrontation of disciplinary knowledge requires an iterative process in which methods of knowledge brokerage are applied and a design process known as "*Research by Design*". De Jonge [13] refers to this as *"the use of design as a tool to generate new knowledge, insights and possibilities"*. The analysis of the existing conditions of Otsuchi by each discipline creates an expanded context for disciplinary responses in which to test multiple aspects of the proposal. Through a process of research by design these are iteratively improved in order to create a set of integrated spatial strategies.

The research project was developed in three different phases: analysis, synthesis and design. The first phase consisted of the analyses of the information regarding the involved disciplines: Architecture, Building Technology, Geoengineering, Hydraulic Engineering, Management of the Built Environment, Transport, Infrastructure and Logistics, and Urban Water Management. Two workshops at the Technical University of Delft were dedicated to present and discuss the information of the case, other references, and involved disciplinary knowledge. This first step created the important condition of each discipline being aware of what skills and knowledge the other fields hold and how they can relate to these fields. The second step in the analysis was the fieldtrip to Otsuchi to view the site and talk to the stakeholders.

The second phase (synthesis) was done during the third workshop in Otsuchi in which students from Landscape Architecture (Tokyo University) and Civil engineering (Waseda University) joined. In this workshop the methods of scoping and charette were used. Scoping is a method to order disciplinary concepts to be able to join them with concepts of the other disciplines. This joining is done discipline by discipline via a charette. This is a conscious and controllable way to integrate the knowledge and approaches from the different disciplines involved in the project and leads to the ability to determine the most desirable and least desirable approaches. The methods and the results of the first and the third workshop are elaborated further in Appendix A.

The third phase (design) consisted of the development of the project strategy elaborated further on in the results section. This phase started during the workshop in Otsuchi and continued after returning to Delft. The initial interdisciplinary design was elaborated in depth by the cooperating disciplines individually, then brought together in an iterative process to improve the design.

Lastly, the information was documented, and the conclusions were elaborated. This interdisciplinary analysis and integrated response aims to approach the complexity of a multi-scale urban system in a way that goes beyond the traditional mono-functional solutions which have been put in place so far.

4. Proposed Strategy

In this section, the strategy developed to address the tsunami reconstruction of Otsuchi is explained (Figure 1). This strategy aims to create a transferable framework with which to build upon the reconstruction plan in other municipalities subject to devastating natural disasters.

The first step of the strategy is to establish a clear definition of the objectives and aims of the project. The objectives are fulfilled by creating a common project vision amongst all the technical disciplines involved, which is the result of a scoping process. Once the objectives are set, the design is developed separately in two different scales: the building and the urban scale. The strategy consists of an iterative evaluation of the proposed design, by which it is aimed to achieve a maximum resilience of the area of study. In this project, two iterations have been carried out with this purpose.

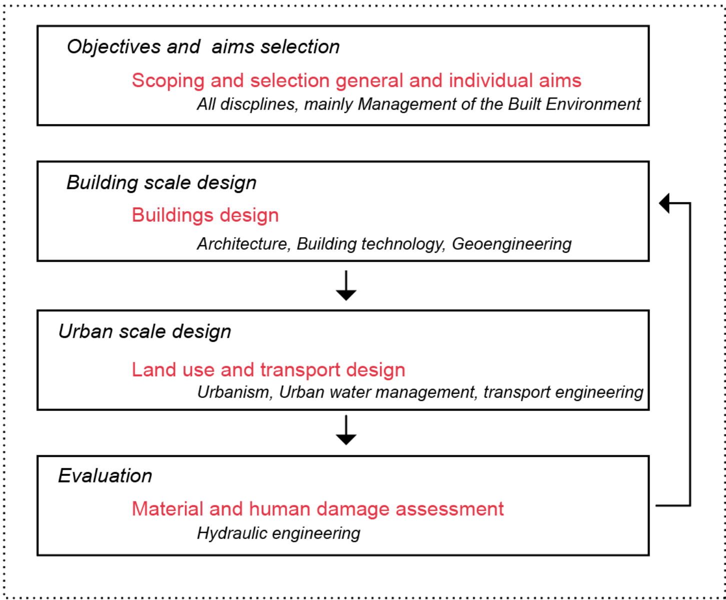


Figure 1. Proposed strategy to develop the new design.

4.1. Objectives and definition of aims

''Be proud to stay in Otsuchi'' [7] is a concept that the mayor of Otsuchi aimed to incorporate into his reconstruction project for Otsuchi. However, the project could not be realized due to blind spots in the reconstruction process (2011 to 2018). Nevertheless, the Japanese government worked extensively to recover and restore the damaged land, including the dikes to ensure future safety in the town.

From chart C.1. in ''The Resilient City: How Modern Cities Recover from Disaster'' [57], different phases of a generic post-disaster redevelopment process can been seen. Japan's existing reconstruction plan can be situated between reconstruction step I and II. This current reconstruction stage is taken as a point of departure for the improved design rather than the immediate emergency and restoration periods and therefore, the specific existing situation studied in Otuschi set the boundary conditions to develop a new set of spatial strategies. An interdisciplinary approach is particularly relevant during the overlap of the reconstruction phases, as the variety of backgrounds makes it possible to prioritise and find synergies between the multiple possible pathways and challenges presented by the complex project of reconstruction. This complexity can be understood better due to the fact it is an ongoing project with clear results. The interdisciplinary assessment thus can be steered towards improvement of these results.

Hence, a fundamental part of the process is the formulation of a clear vision. The vision was developed by means of a scoping technique that is based on the *four P's* concept [57] *'People', 'Planet', 'Prosperity'* and *'Project'*. This concept was used to find a balance and synergy between the needs of different stakeholders, economic profits and a healthy environment in the spatial interventions. The term '*project*' represents the physical outcome of the balance among the triple bottom line (PPP) and represents spatial quality, robustness, linking of scales and aesthetics.

The project vision stands for a resilient future development of Otsuchi, with the aim of improving the day-to-day quality of life and providing the necessary safety measures in the case of a disaster. The necessary objectives required for this vision are further described in the table below (Table 3).

Table 3. Main objectives of the new design.

Main objective	Description
Improve livability/attractiveness	Restore natural springs Create recreation spaces in the urban area Create mixed residential areas Restore the economy of Otsuchi Reconnect the land to the ocean Improve the quality of infrastructure
More effective natural disaster (Earthquake- tsunami - flooding) prevention measures	Create extra water storage Reduce reaction and evacuation time Provide live evacuation guidance Adapt building typologies (function, structure and materials) to local conditions and risks Adjust spatial planning based on flood risk and overall monetized material damage and human loss analysis

During this process every discipline analyses the situation according to their own technical background. Based on the overall shared vision, measures to be implemented in a new design are proposed by each discipline (Table 4).

Table 4. Measures proposed by every discipline to address the new design.

Discipline	Measures
Architecture	Combine safe construction measures and siting with living arrangements that improve the livability of the town
Building Technology	Reduce material and human losses aggravated by (a) structural failure of buildings, and (b) floating debris from building materials, during an earthquake and/or tsunami
Geo Engineering	Design safe, efficient and cost-effective structural foundations and ground stability measures
Hydraulic Engineering	Assess flood risk of the current and improved situation, based on the flood depth and the land use (material damage), and evacuation map (human loss)
Management in the Built Environment	Consider the process of the multidisciplinary team to achieve a design with long-term goals for the future of the citizens of Otsuchi
Transport	Create a safe evacuation strategy in case of a tsunami and improve daily traffic safety
Urbanism	Improve the livability of the town while ensuring the safety of the population
Water Management	Improve livability and restore natural springs in the urban area

4.2. Design

The effective implementation of the measures proposed by every discipline requires a step by step approach with shared goals and evaluation measures. As outlined above, the design phase was carried out at two different scales: the urban and the building scale.

The suitability of the proposed design is evaluated at the large scale of the project (urban scale). This aspect is analyzed by evaluating the material damage and the human losses in the existing conditions and in the proposed design. At the small scale (building scale), this analysis is carried through in the siting conditions derived from the urban scale spatial plan. This building scale proposal is further evaluated by its implications for the choice of foundation design and its structural efficiency, tested through a case study.

4.2.1. Evaluation of the Reconstruction Plan (2011-2018)

The multidisciplinary team started to be involved in the research after the first reconstruction phase. To determine the aspects that could be improved in the reconstruction plan, the evaluation of the damage in case of a Level-2 tsunami for the current stage of the Reconstruction Plan is taken as a point of departure in the research. Based on the evaluation, it is possible to assess the performance of the first phase of the reconstruction, which has been already implemented.

The existing spatial plan (Figure 2) is used to predict the monetized material damage according to land use and the predicted flood depth from a simulation of a Level-2 tsunami (similar to the 2011 Tsunami) [18].

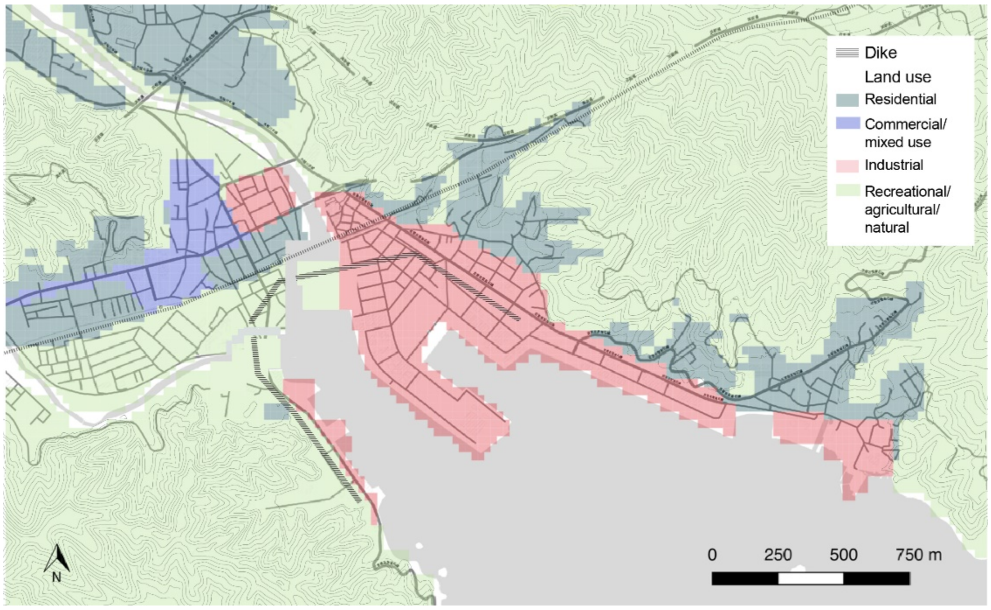


Figure 2. Land use map (current situation).

From the calculation of the material damage (Appendix B1), two outputs are analyzed to implement improvements in the current spatial plan. First, the geographical distribution of the material damage is displayed by means of a map that shows the monetized damage per pixel (Figure 3). The analysis of the distribution of the damage enables us to determine rationally where adaptations of the current spatial planning should be carried out. Second, the total material damage is calculated. This enables quantification of the damage reduction achieved with the new design. In case a Level-2 tsunami (similar to the 2011 Tsunami) again hits Otsuchi, the monetized material damage based on the current spatial plan is 125 million euros.

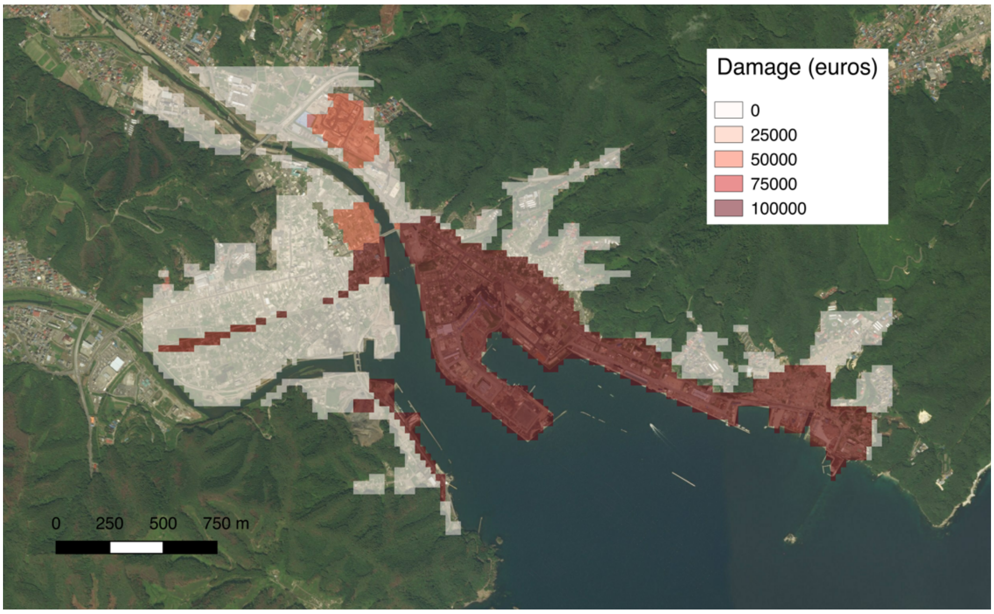


Figure 3 Geographical distribution of the damage per grid cell over the town of Otsuchi (current spatial plan).

In the evaluation of human losses, the number of casualties depends on multiple factors: the time that the tsunami takes to arrive inland, the reaction time of the population, the distance to a safe area and the evacuation velocity, which depends on the age of a person and the time of the day. In the 2011 tsunami, the time that the tsunami took to arrive at Otsuchi was 42 minutes, a value that is applied in the current analysis. In addition, it is assumed that the average reaction time of a citizen is 25 minutes in the case the tsunami occurs during the night (this scenario is considered the most critical). Finally, it an evacuation speed of 3.5 kilometers per hour is assumed.

The spatial planning of Otsuchi at the current stage of the Reconstruction Plan shows the available evacuation routes per evacuation building based on shortest paths (Figure 4). The evaluation of the human losses is carried out with the help of network analysis (Appendix B2), by which the risk is assessed at every location in Otsuchi. Points were selected within 10 meters from every road (the total number of points used was 1044). For each point, the evacuation time to a safe location is calculated, based on the distance to a safe location and the evacuation velocity. In the current situation, the safe locations are determined by the tsunami run-up spatial boundary. The results of the network analysis (Appendix B2) show that there are 144 locations in Otsuchi out of 1044 that do not guarantee an effective evacuation in case the design tsunami.

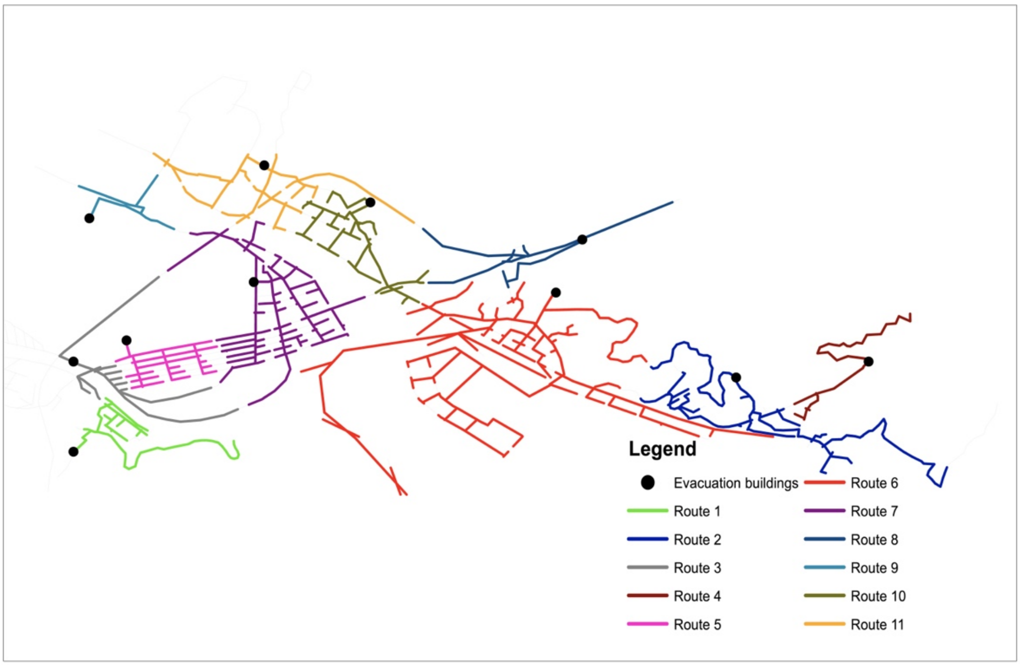


Figure 4. Analysis of the evacuation routes in Otsuchi. The safe areas are determined by the hydraulic boundaries of the tsunami inundation area (black points).

4.2.2. Design and re-evaluation of the proposed improvements of the Reconstruction Plan (urban scale)

In response to the initial evaluation, the next stage of the project addresses the reduction of the existing flood risk. Regarding the material damage, a reduction of the flood risk can be achieved by either reinforcing the current seawall or by redesigning the current spatial planning as shown in Figure 25. Due to the recent agreement between stakeholders to construct the existing concrete seawall (whose crest reaches +14.5 m MSL), it is assumed that at this stage of the reconstruction process, it is not desirable to reinforce the mentioned structure. For this reason, the elaboration of a new spatial plan is established as the strategy to reduce flood risk in Otsuchi.

In order to minimize material losses, synergies are sought among land use, safety measures, and the livability of the area. This synergy ensures that the protected urban fabric is well used and densely inhabited, reducing the likelihood of urban sprawl into areas at higher risk of future loss or damage. These principles are applied to redesign the land use zones (Figure 5).

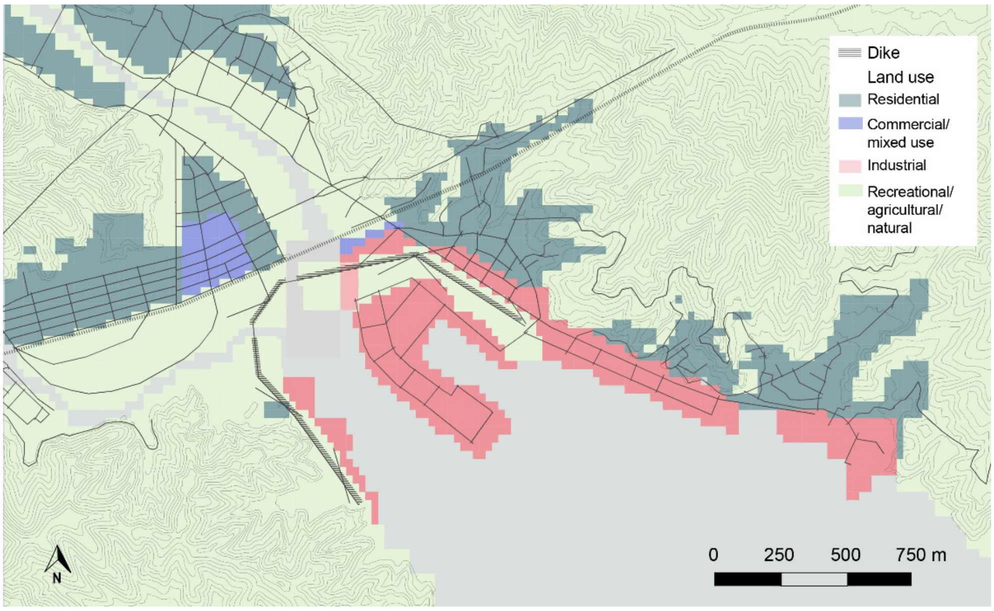


Figure 5. Land use map (proposed design).

In the mountainous zones as can be seen in Figure 5, forest management as a form of income and recreation is proposed to reduce the risk of landslides. In the urban zone, storm water storage is combined with green space and recreational parks. Next to the seawall, a retention area for tsunami water overtopping the seawall is designed as further park and recreational space. The seawall itself is proposed as a multifunctional dike where restaurants, shops, fishing industry and aquaculture industry all reconnect residents with a view of the sea. This in fact can increase safety as these commercial areas are only inhabited in the daytime, when people are alert, and gives immediate visual warning of danger approaching from the sea. In each of these zones, engineering approaches to quantify risk reduction are combined with urban quality in order to make a long-term investment into safety measures for the center of the existing urban area effective and worthwhile.

The evaluation of the proposed spatial plan leads to a new geographical distribution of the material damage (Figure 6). The overall damage in the town of Otsuchi is in this case 95 million euros. Therefore, with the new spatial plan a reduction of 24% in the material damages is achieved with respect to the current spatial plan.

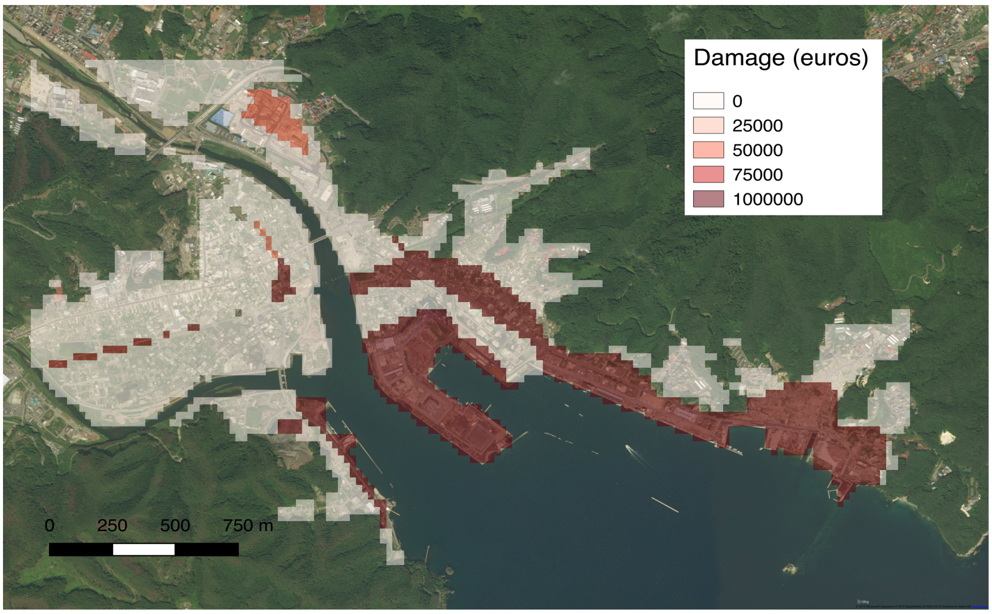


Figure 6. Material damage per grid cell (new design).

However, the direct consequence of not upgrading the flood defenses prevents reduction of flood depths in the town in case a Level-2 tsunami occurs. Consequently, solid evacuation strategies are central to achieve a resilient design. Human losses are prioritized ahead of material losses in the proposal.

Currently, the inhabitants of Otsuchi are not actively aware of the shortest route to evacuation shelters. A first step to improve the performance of the evacuation plan is to inform the population about this aspect. Furthermore, to improve the emergency measures, in the new design (vertical) evacuation buildings are located strategically to minimize the distance between every location of the town and safety locations (Figure 7). The geographical position of these buildings is based on the analysis of the current situation (section 4.2.1), by which the most critical locations for evacuation were determined.

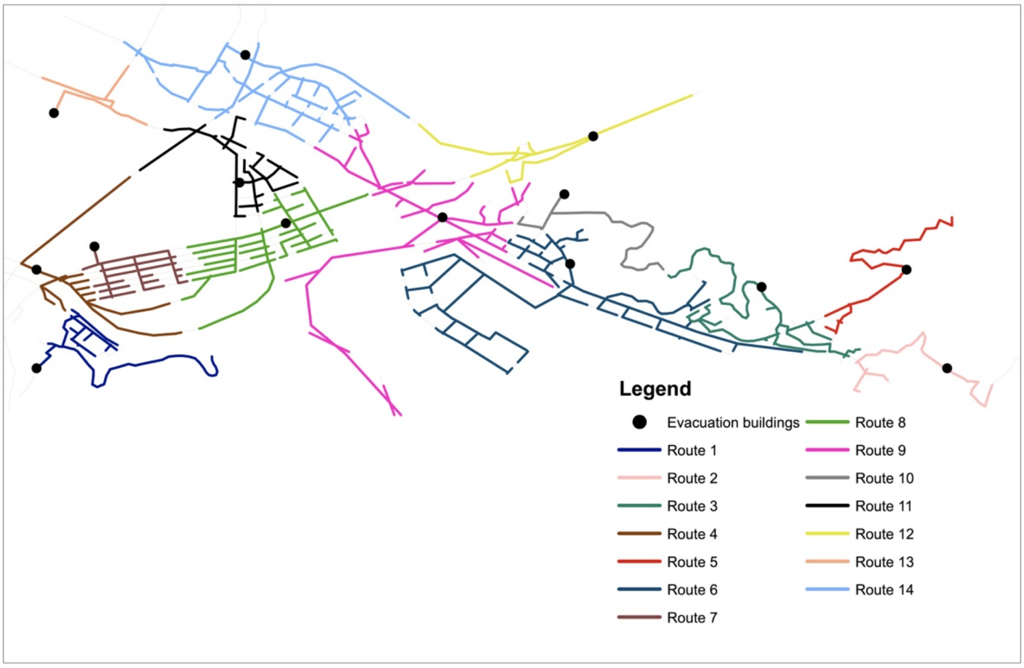


Figure 7. Evacuation routes in Otsuchi, including the vertical evacuation buildings at strategic locations.

The results of the network analysis show a relevant enhancement of the evacuation strategy performance. The number of unsafe locations in case vertical evacuation buildings are implemented in the design is reduced to 61, which represents an improvement of a 58% with respect to the current evacuation plan.

In addition to the proposed improvements in the spatial planning and the evacuation strategies, an upgrade in the channels of risk communication is recommended. A network of satellites and sensors is proposed to improve the transmission of risk alerts in the event of an earthquake or tsunami. With this strategy, the evacuation flow design can be adapted towards the needs of the changing city by making use of crowdsourced data on the evacuation path of the citizens during evacuation drills.

4.2.3. Design and re-evaluation of the proposed improvements of the Reconstruction Plan (building scale)

At the building scale, the flood depth map provides a site-specific estimation of the types and order of magnitude of loads a building would be subjected to during a tsunami. This allows for a closer understanding of the relation between human and material loss risks with structural and non-structural damage to buildings in the event of an earthquake, tsunami or resultant fire-outbreak. The mitigation of this risk is the focus of design, development and evaluation at the building scale.

As a direct outcome of the urban scale analysis and zoning proposals, four building typologies are developed in relation to each of the four urban zones and their individual risk patterns. The typologies are vertical evacuation structures, inland commercial and residential buildings, park structures and coastal commercial structures. The use and height of these buildings are informed by their location, their potential flood depth, and the resultant forces they are required to withstand. (See Appendix C1).

The safety measures incorporated into each design, especially in relation to the structural capacity of each type are synergized with the everyday utility and aesthetics of the designs to ensure their continued maintenance. Vertical evacuation structures are considered the most structurally resilient with multiple lines of defense incorporated into the design. This building typology includes an earth berm to mitigate the effects of the 1-2 meter height of predicted flood depth. The foundation of these buildings consists of deep piles, and a reinforced concrete moment frame structure is proposed. All these measures require a large initial investment from both an economic and environmental point of view. Nevertheless, a building of the mentioned characteristics creates an easy-reachable evacuation location for the population of Otsuchi. This fact implies a large social benefit, what justifies the investment.

In line with the preference on the reduction of human over material losses, the design of inland commercial and residential buildings focuses on a strong shear wall structure of reinforced concrete blocks with sacrificial infill walls made of lighter and less costly materials. This allows the building to withstand the upward lift due to inundation depths of up to 2 meters and the lateral loads of earthquakes. Additionally, the risk of damage to material is reduced by locating all living spaces above the ground floor.

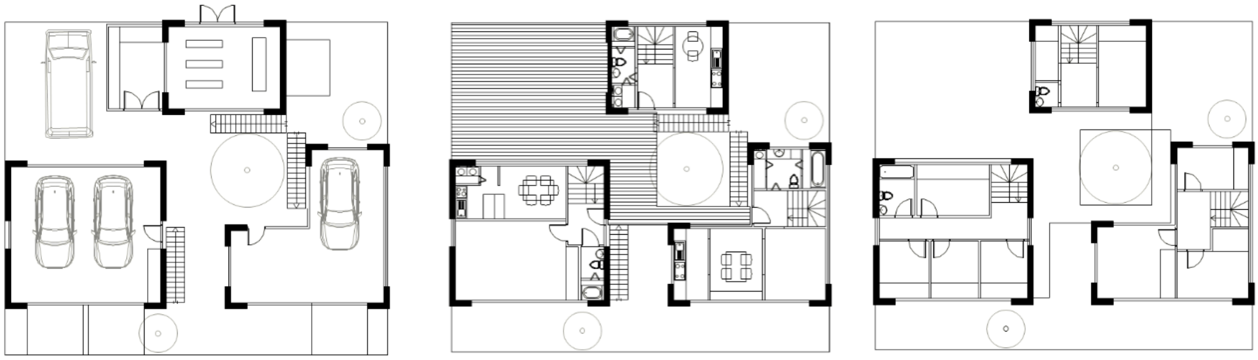
The park structures, set in the retention basin immediately inland of the seawall (see Figure 11), can withstand the massive dead loads of the construction and the weight of the raised land. This allows for a materially efficient construction while maintaining safety and providing much needed recreational spaces for Otsuchi residents.

Finally, the proposed design retains the use of the area beyond the sea wall for industrial uses and proposes the addition of commercial uses on a multifunctional dike to attract residents to reconnect with the sea. These structures would be inundated to a depth of 15m and would be unsustainable and untenable to protect. Therefore, they are proposed as largely lightweight timber structures with reinforced concrete cores which could contain appliances and machinery to prevent them from being washed away in the event of a tsunami and creating dangerous debris.

The design of the described building typologies prioritizes material efficiency for the reduction of debris creation and the protection of the most vital spaces for evacuation. This overall strategy is the basis for determining the building material, architectural layout, structural interventions and foundation types.

The residential building is chosen as a case study, since it combines the concept of material reduction through concentrated structural strength and elevated living spaces, as a combination of earthquake and tsunami resilient elements.

The chosen design is located inland on elevated land at an elevation of 2-4 meters. A three-story concrete and timber hybrid construction is proposed (Figure 8). This is connected at the first level to two other residential buildings, creating a social gathering space. To reduce the intensity of the structural and material damage, concrete block shear walls act as the load-bearing structure. These are combined with collapsible timber infill walls, which are designed to break out in the event of a tsunami. By allowing the walls to break, the additional load on the structure due to the hydrodynamic forces is relieved.



(i) (ii) (iii)

Figure 8. Proposed example floor plans, (i) ground floor storage and garage space, (ii) first floor living and communal access space (hatched) (iii) second story living and sleeping spaces.

The hybrid construction allows for the building to experience light to partial failure without complete collapse. In order to mitigate the impact of any timber wall breakaway, two main elements are incorporated into the composition of the wall. Firstly, the exterior cladding of the wall is composed of relatively small components, 100 mm x 12.5 mm timber boards that are less dangerous as floating debris during a tsunami, as opposed to the standard whole timber boards. Secondly the potential toxicity induced by floating insulation is mitigated using cellulose insulation, a green insulation material made of recycled paper. Based on the loading conditions created by this design, a foundation typology is developed.

The development of this design is conducted in an iterative manner. An initial design was proposed in relation to cost effectiveness, the local preference for single family houses and the need to densify Otsuchi and provide a mix of housing types. This led to a collection of houses joined by a shared first floor balcony where the elderly could live alongside young people and families to help each other to evacuate as efficiently as possible.

As per the structural requirements specified in the Japanese Building Code, the proposed design is categorized as a small scale building that follows design route 0 with structural specification category (a) [19]. The foundation requirements of the building is fulfilled by a combination of Japanese, European and American design codes. The Japanese codes cover tsunami loads for large buildings with deep foundation only [40]. Consequently, European and American codes are consulted to gain insight in the structural requirements for buildings of smaller dimensions [4, 22].

The structural capacity of the preliminary design is assessed in relation to the predicted flood depth and the different load types related to earthquakes and tsunamis. This leads to a refinement of the structural sizing, spacing and arrangement of the shear walls. The structural arrangement is streamlined parallel to the predicted flow if incoming water in order to reduce concrete potential debris as a result of building collapse during a tsunami (Figure 9). This improved design is used as the input for a further round of foundation design calculations.

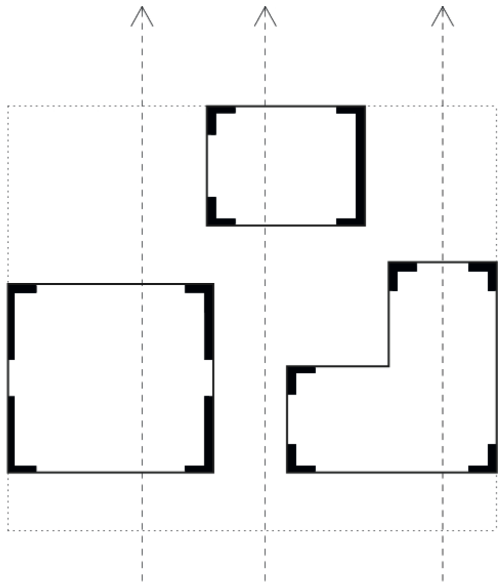


Figure 9. Design of the structural arrangement of three houses, based on the concept of shear walls oriented parallel to the flow. Flow direction is indicated by arrows, and shear walls in bold.

The housing typology proposed can be applied to single, two and three-story buildings. The foundations of these buildings should be feasible and able to resist loads from severe earthquakes, tsunamis up to a certain inundation depth and potentially aftershocks during the tsunami. The bearing and horizontal capacity are evaluated for three types of shallow foundations. Based on the cost and the relationship between load and capacity, a foundation typology is selected for the one, two and three-story buildings.

The three types of foundation are a regular raft foundation, a raft foundation with shear keys and a micro-pilled foundation (Figure 10). The simple raft foundation is the most economic and simple foundation. It has the lowest horizontal and vertical bearing capacities. Both the horizontal and vertical bearing capacities can be increased with the addition of shear keys perpendicular to the direction of lateral loading. Micro-piles are short piles grouted in-situ with steel reinforcement. The length of micro-piles exceeds the length of shear keys and therefore has the effect of increasing the bearing capacity of the foundation. The density of piles further increases the foundation capacity.

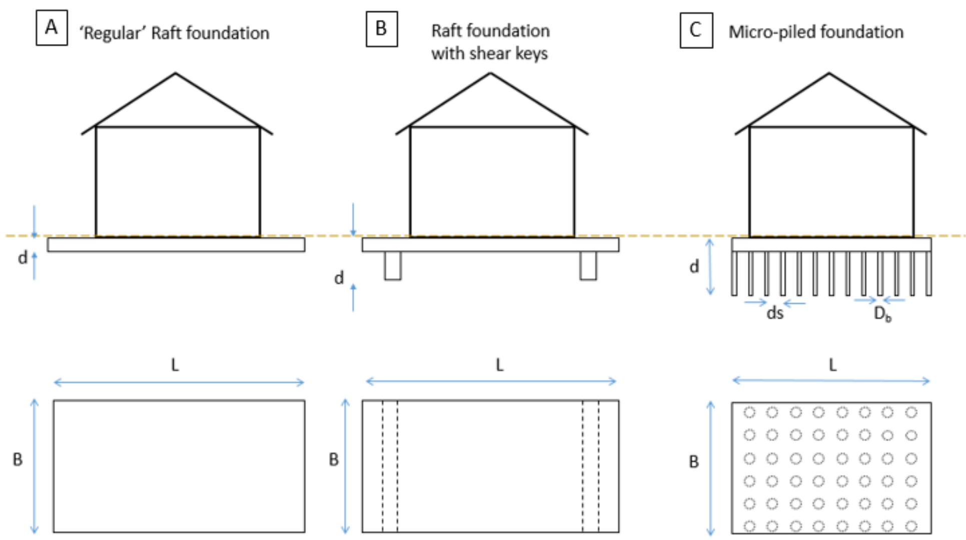


Figure 10. Types of foundations for residential buildings.

For the three cases, the dimensions and embedment of the foundations are taken as input such that the dimensions and the embedment are within reasonable measures and for standardized sizes (Appendix C3). Based on the results, for combined tsunami and aftershock conditions, the three-story house typology requires a micro-piled foundation. A shear key foundation cannot resist this load combination when it supports a three-story building, but is sufficiently resistant when supporting a two-story building.

The shear key foundation is sufficient for a three-story building in case of tsunami loading or severe earthquake loading, but not when both loads act simultaneously. The results show that a raft foundation is suitable under earthquake loading or tsunami flooding for a single-story house. The micro-piled foundation can be designed in a suitable way for all loading cases. However, the use of micro-piles lead to over dimensioning of the foundation in case they are used in single-story buildings.

The question which arises from the analysis is whether houses near the inundation limits (i.e. with a short flood duration) should be designed to be resilient for simultaneous tsunami and aftershock conditions, since the probability of this phenomenon occurring is much lower. In this case, micro-piled foundations are proposed for three-story buildings, raft foundations are suggested for two-story buildings and regular raft foundations are recommended for single-story buildings. This conclusion feeds back into the urban scale design by providing another layer of specificity to the locally generated zoning guidelines, meaning they are locally specific in function, typology and height, going beyond the existing nation-wide guidelines.

4.2.4. Summary of the interventions

To conclude the results section, Figure 11 shows a general overview of the interventions implemented in the new design. At the shoreline, a Level-1 multifunctional flood defense is located. At the mouth of the Otsuchigawa and Kozuchigawa rivers, flood gates are present to stop the tsunami from progressing in the upstream direction. The spatial plan has been modified to reduce the material damages in case a Level-2 tsunami occurs. Furthermore, a more effective evacuation plan has been developed, by creating awareness among the population about the horizontal evacuation routes and by identifying strategically optimal locations for new vertical evacuation buildings. Finally, the new spatial plan includes space for growth, in order to facilitate the return of previously tsunami-displaced citizens.

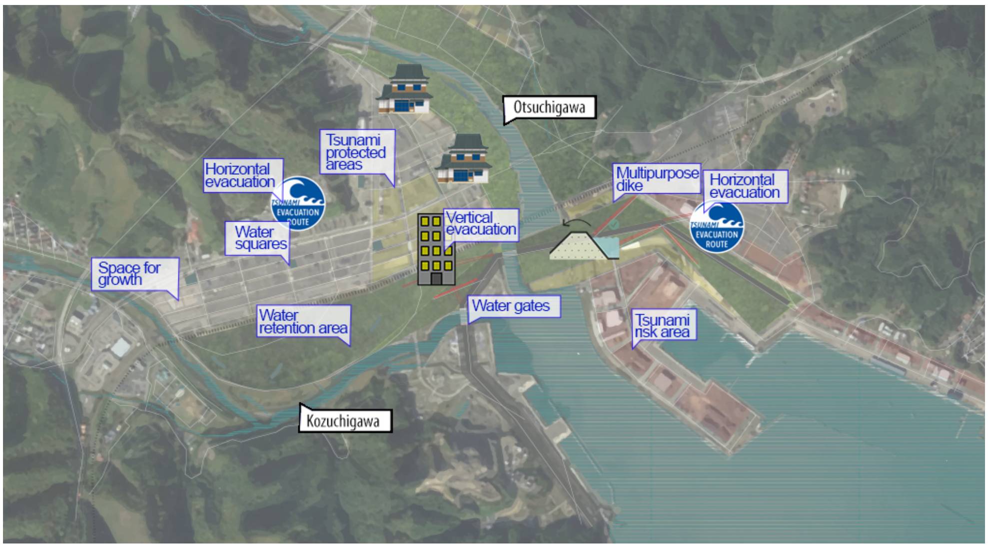


Figure 11. Overview of the interventions implemented in the new design.

5. Discussion

The proposal developed takes as a starting point the current stage of the reconstruction plan. Initially, the existing reconstruction efforts were considered a limitation to a new proposal. However, through site-specific analysis of the existing situation in Otsuchi the complexity of such a project can be understood better and enabled synergies to be found among the cooperating disciplines. In the initial design phase this led to key spatial proposals for ways which livability could be incorporated into safety measures, for example in the recreational water retention area and the proposal for a multifunctional dike, bringing back industry and commerce to the shorefront.

In the second stage of design, at the urban and building scales, the site specificity of the analysis gave clear parameters for making efficient use of scarce resources by prioritizing human safety over material risk at the urban scale, and partial structural stability and decreased debris creation over total structural and non-structural resilience at the urban scale. In both of these cases, the level of safety provided by new structures is balanced with economic practicalities and everyday livability over the long term.

In the third stage, where the detailed proposals are recombined in an improved iteration, the process of analysis from each of the different disciplinary fields enables the prioritization and synthesis of the site-specific constraints into a solid tsunami-resilient design. In this way the project strategy developed, from objectives and aims selection, through urban and building scale design to an integrated design and its evaluation in terms of material and human losses. This was successful in that it provided a method for applying disciplinary knowledge in an improved way that goes beyond the application of broad national standards or the a priori assumption of reconstruction to a previous state as the goal for reconstruction efforts.

Specific spatial proposals which emerged out of this process could be adapted to other towns subject to extreme natural hazards. One key example is that by incorporating evacuation strategies into the early stages of spatial planning, the strategic siting of vertical evacuation centres siginificantly improves existing evacuation times. In order to elaborate on this conclusion, further research should be done into the actual dimensions and the structural characteristics of this building typology. Furthermore, the limited capacity of these buildings must be acknowledged.

A second example is the elaboration of existing zoning policies, such as the retention area and the land elevation measures, to improve the daily lives of citizens by catering to their current needs for recreational space and a greater cultural connection to the sea. These measures were not prioritized in the existing reconstruction plan, but are in line with a future oriented approach which aims to attract residents back to Otsuchi, and thereby make the investment in safety infrastructure worthwhile. This approach to spatial synergies could be adopted in other disaster reconstruction efforts.

A final example, the design of a case study housing typology, prioritized environmental and economic sustainability through the strategic use of breakout non-structural elements. This allows for designs which are both more livable in that they allow for larger houses as the construction costs are mitigated, and allow for more traditional timber architecture, a benefit to both local cultural traditions and craftsmanship. This prioritization, enabled by site-specific foundation design, has the added benefit of reducing the risk of dangerous debris in the event of a tsunami, highlighting further possible synergies between hydraulic urban analysis and other disciplinary knowledge for long-term resilience.

6. Conclusions

The goal of this paper is to use the experience of Otsuchi to develop a set of integrated spatial strategies for the future development of similar towns subject to extreme natural hazards. Through a process of research by design, scoping and an integrated response, a final proposal is achieved by means of an iterative design process. As a result, the final proposal consists of set of integrated spatial strategies that aim to improve livability and provide effective natural disaster prevention measures.

To approach the complexity of the urban system, an *interdisciplinary* and *integrated* response is used to find solutions that go beyond the traditional mono-functional way of working, which have been put in place so far. The strategy proposed aims to be applicable in similar contexts, such as the coastal towns of Oregon, Washington, and British Columbia that are gradually preparing for the next Cascadia tsunami.

By addressing the flood risk from an urban and a building scale in an integrated and interdisciplinary manner, it is seen that the problem can be tackled effectively. For instance, by demarcating zones based on the expected flood risk, the structural provisions of buildings can be designed (to be completely resistant, partially resistant or sacrificial), and evaluated accordingly, therefore providing data on the expected damage in the area and creating the opportunity to incorporate appropriate evacuation strategies.

Similarly, by anticipating the expected flood risk in the residential area, the foundation typology of semi-sacrificial buildings was designed for specific loading conditions, which impacted the structural composition of the building, resulting in a hybrid construction designed for partial collapse.

The final evaluation of the proposed urban scale design is achieved by the analysis of damage costs, while at the building scale the interest lays in adding value to the urban scale design.

Long term benefits could be obtained by introducing short term interventions. In this line, synergies are sought among land use, safety measures and the livability and attractiveness of the area. These synergies ensure that the protected urban fabric has an adequate use and is densely inhabited, reducing the likelihood of urban sprawl into areas with higher exposure to tsunami damage. Based on these principles, an effective resilient strategy to enhance livelihoods while protecting against tsunamis is proposed.

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Appendix A. Scoping exercises

The project was developed in different phases. The first one consisted of the analyses and synthesis of the information regarding the setting of the project. The second phase of the project consisted in the development of the project strategy elaborated further on in the results section. Lastly in the third phase, the information was documented, and the conclusions were elaborated.

For the analyses and the synthesis phase, three workshops were held. The first two workshops were held in the Technical University of Delft and the third one was held during the site visit to the town of Otsuchi. Students from the disciplines of Architecture, Building Technology, Geoengineering, Hydraulic Engineering, Management of the Built Environment, Transport, Infrastructure and Logistics, Urban Water Management, and Urbanism attended the first, second, and third workshop, while students from Landscape Architecture and Civil engineering joined the third workshop.

During the first workshop a charette method was used to integrate the knowledge and approaches from the different disciplines involved in the project. During the charette, each student brought questions to ask the other disciplines and a statement of what they could offer to them as well. In the workshop, five rounds of discussions took place. During the first round, the students elaborated on the knowledge of the problem and their ideas on how to tackle it. During the next rounds, the disciplines were confronted on a one-to one basis in order to understand shared knowledge and identify the trade-offs amongst them.

Figure A1 shows a summary of the measures proposed by each of the disciplines. Targeting the speed of the recovery, enhancing the vertical and horizontal evacuation, modifying the land uses and the density of the tissue, creating space for water storage, improving the distribution of the evacuation centers, and developing new and improved building typologies with construction principles for disaster mitigation such as better foundations were the approaches found as a common ground for the interdisciplinary work. Figure A2 shows in more detail the relations according to such measures.

During the second workshop, the project group presented the research question for the project.

Lastly, the third workshop took place during the site visit to Otsuchi. In the workshop, the students determined the most desirable and least desirable approaches using the charette method. During the workshop the students were divided in five different groups, as follows:

-Architecture and Building Technology
-Landscape Architecture, Management of the Built Environment and Urbanism
- Geoengineering
-Hydraulic Engineering and Civil Engineering
-Transport Infrastructure and Logistics
-Urban Water Management

Each of the groups then had to present a set of measures or approaches to answer the research question previously agreed on. Following, a set of scoping exercises were held in order to categorize the approaches proposed by the each of the groups according to their desirability. In order to determine the previous, seven rounds of exercises were held. During the first one, individually the groups categorized the measures on the scales of:

-People: Top down to bottom up approaches
-Profit: Approaches with the largest and least expenditure
-Planet: More to least sustainable approaches

During the next six rounds, the groups were confronted on a one to one basis to develop categorization of the integrated measures on the same scales as in the previous round. Finally, on the last round, the groups, individually determined the desirability of the initial or modified proposed measures according to the knowledge gained in the charette.

The results of the first and the last rounds are presented in Figures A3 to A7.

Scoping excercise 1

Management of the Built Environment	-Land ownership -Community engagement **-Recovery speed** -Bottom up/Top down **-Vertical and horizontal evacuation**
Hydraulic Engineering	-Boundary conditions **-Land use maps** **-Foundations**
Transport, infrastructure and logistics	**-Vertical and horizontal evacuation** **-Water storage** **-Distribution of the facilities/evacuation centers**
Urban water management	-Distribution of water due to overtopping and rainfall **-Water storage** -Management of salt/fresh water
Urbanism	**-Land use** **-Distribution of the facilities/evacuation centers** **-Water storage** **-Building typologies** **-Vertical and horizontal evacuation** **-Density of the tissue**
Architecture	**-Density of the tissue** **-Building typologies** **-Foundations** **-Vertical and horizontal evacuation**
Building Technology	**-Construction principles for disaster mitigation** **-Recovery speed in relation to the construction principles** **-Vertical and horizontal evacuation** **-Foundations** **-Water storage**
Geoengineering	**-Construction principles for disaster mitigation** -Stability of the dike and other structures -Soil type **-Foundations**

Figure A1. Measures proposed by each discipline to tackle the project. The approaches that were mentioned by more than one discipline are highlighted in bold letters.

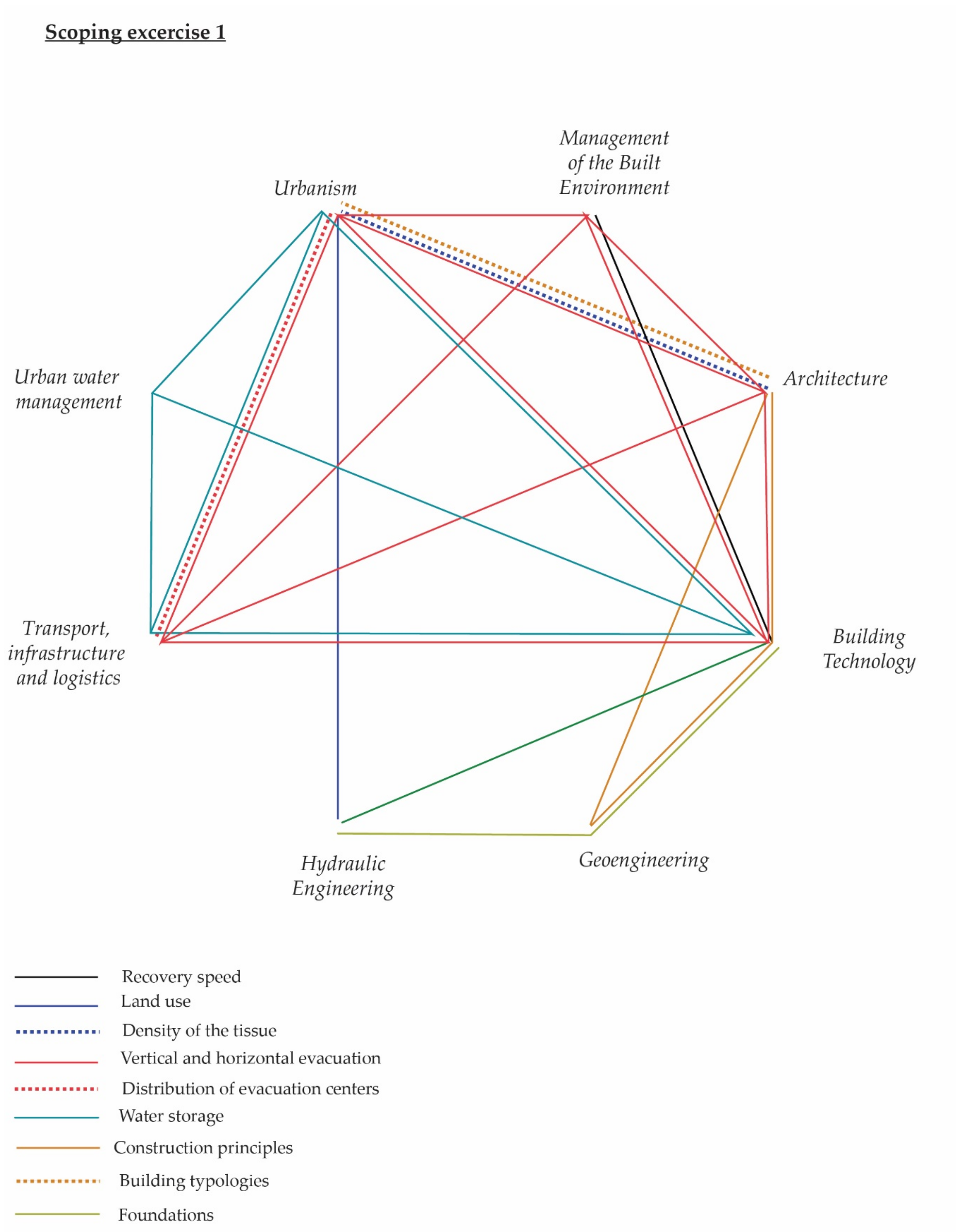


Figure A2. The diagrams shows the connections amongst the disciplines in relation to the potential collaboration that they could have according to the approaches proposed.

During the second workshop, the project group presented the research question for the project. Lastly, the third workshop took place during the site visit to Otsuchi.

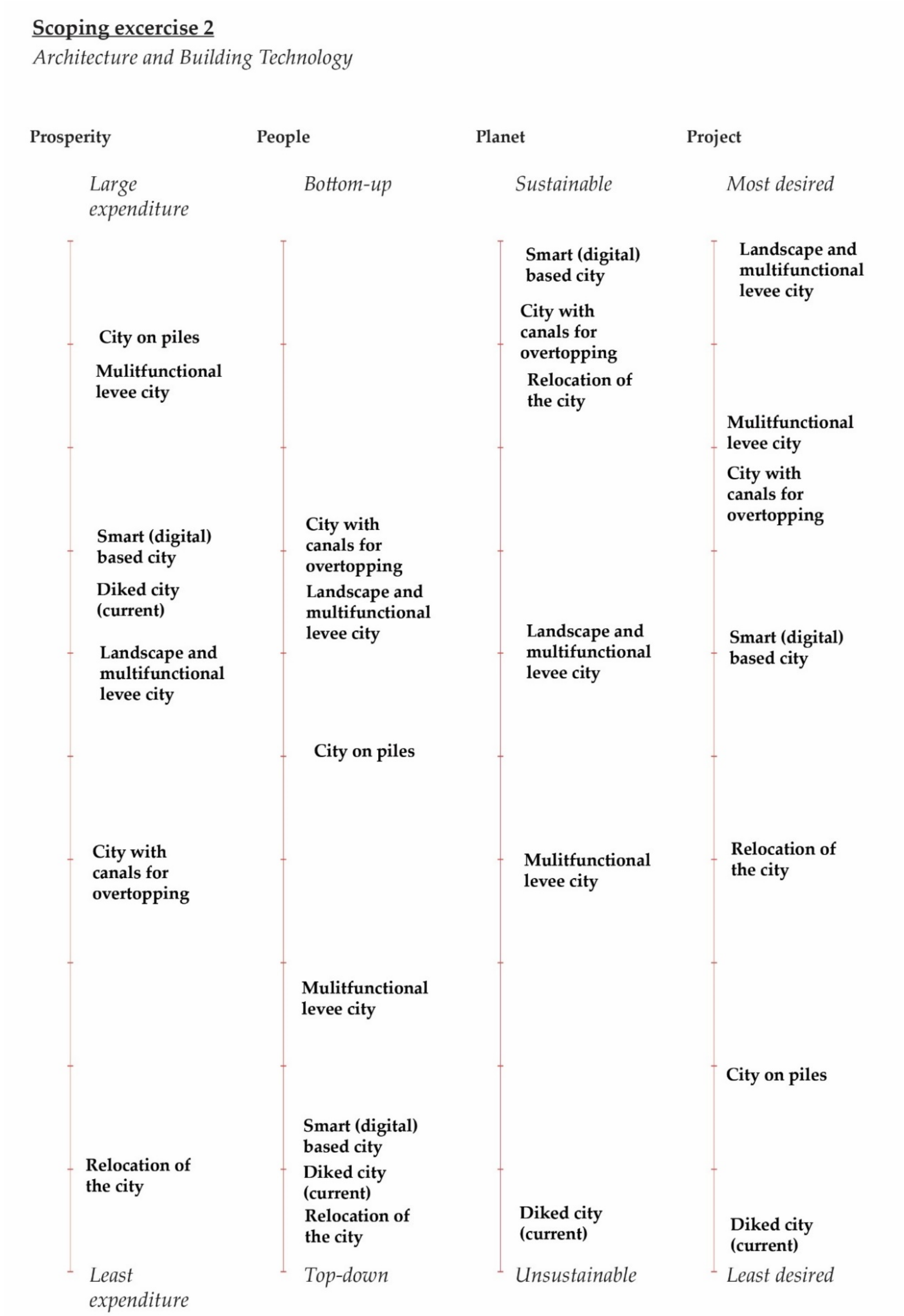


Figure A3. Scoping of the approaches of the discplines of Architecture and Building Technology

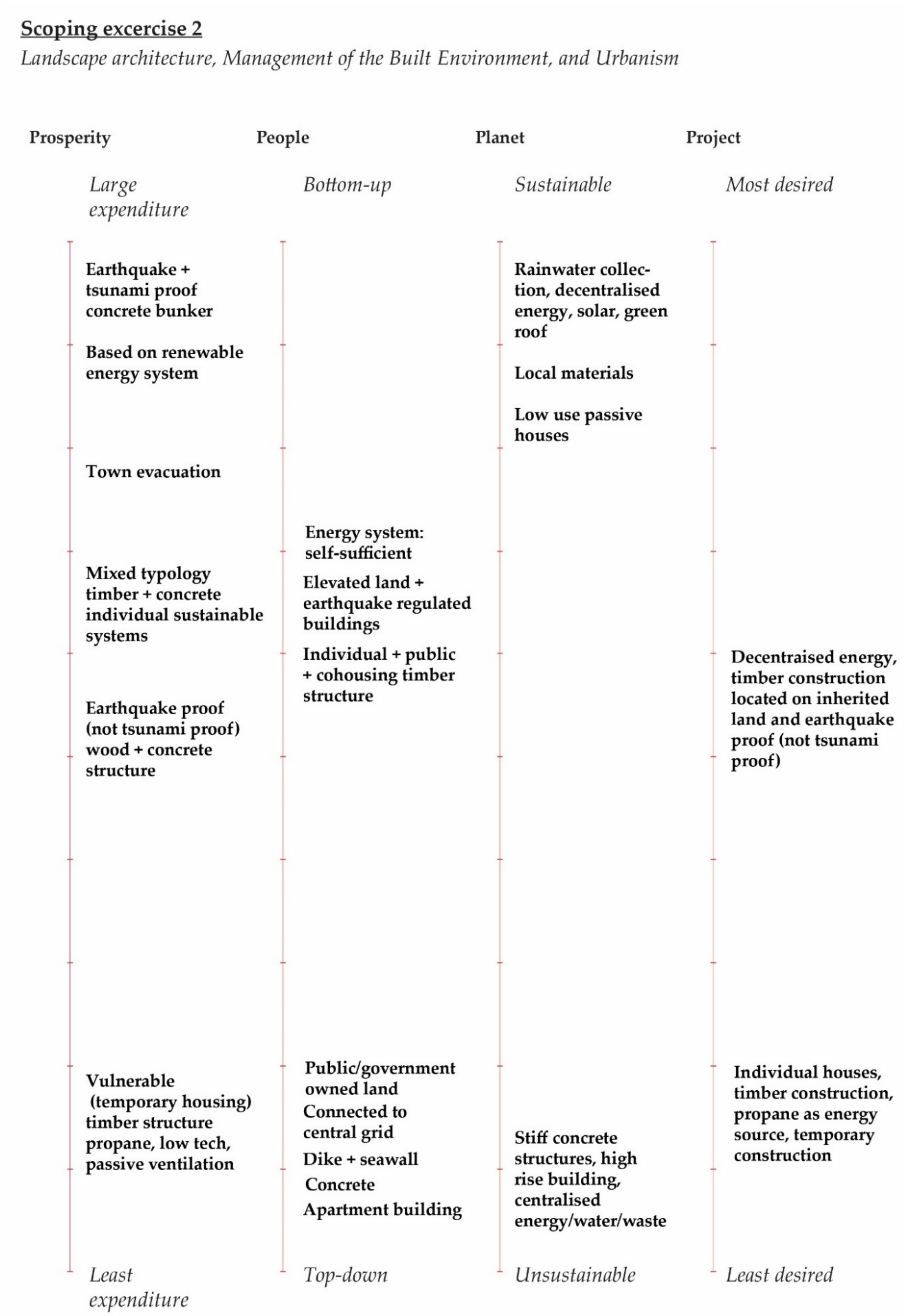


Figure A4. Scoping of the approaches of the disciplines of Landscape Architecture, Management of the Built Environment, and Urbanism

Scoping excercise 2

Geoengineering

Sea Wall

Feature	Method	People	Costs	Planet	Project
Soil Dike	Super levee	-	-	-	-
	Soil reinforcement	+	+	+/-	+
Concrete strucutre	Pile foundation	-	+/-	+/-	+/-
	Anchoring	+/-	+/-	+/-	+
	Scour protection	+	+	+/-	+

Land elevation/terrasses

Feature	Method	People	Costs	Planet	Project
Consolidation	Vibro-compaction	+/-	+/-	-	+/-
	Stone columns	+/-	+/-	+	+
	Pre-loading	-	+	+/-	+/-
	Roller compaction	+	+/-	-	+/-
Slope stability	Slope reinforcement	+	+	+/-	+
	Retaining wall	+/-	-	+/-	+/-
	Gravity based wall	-	-	-	-
	Anchoring	+	+/-	+	+
	Grouting	+	+/-	+/-	+/-
	Shotcrete	+/-	+	+/-	+/-
Liquifaction mitigation	Drainage	+	+	+	+
	Block caging	-	+/-	+/-	+/-
	Deep foundation	-	-	+/-	-

Landreclamation

Feature	Method	People	Costs	Planet	Project
Land reclamation	Caisson	+/-	-	+/-	-
	Keywall	+/-	+/-	+/-	+/-
	Material dumping	+/-	+	+/-	+

Breakwater

Feature	Method	People	Costs	Planet	Project
Breakwater	Anchoring	+/-	+/-	+/-	+/-
	Suction caissons	+/-	-	+/-	-
	Pile foundation	+/-	-	+/-	-

Figure A5. Scoping of the approached of the discipline of Geoengineering

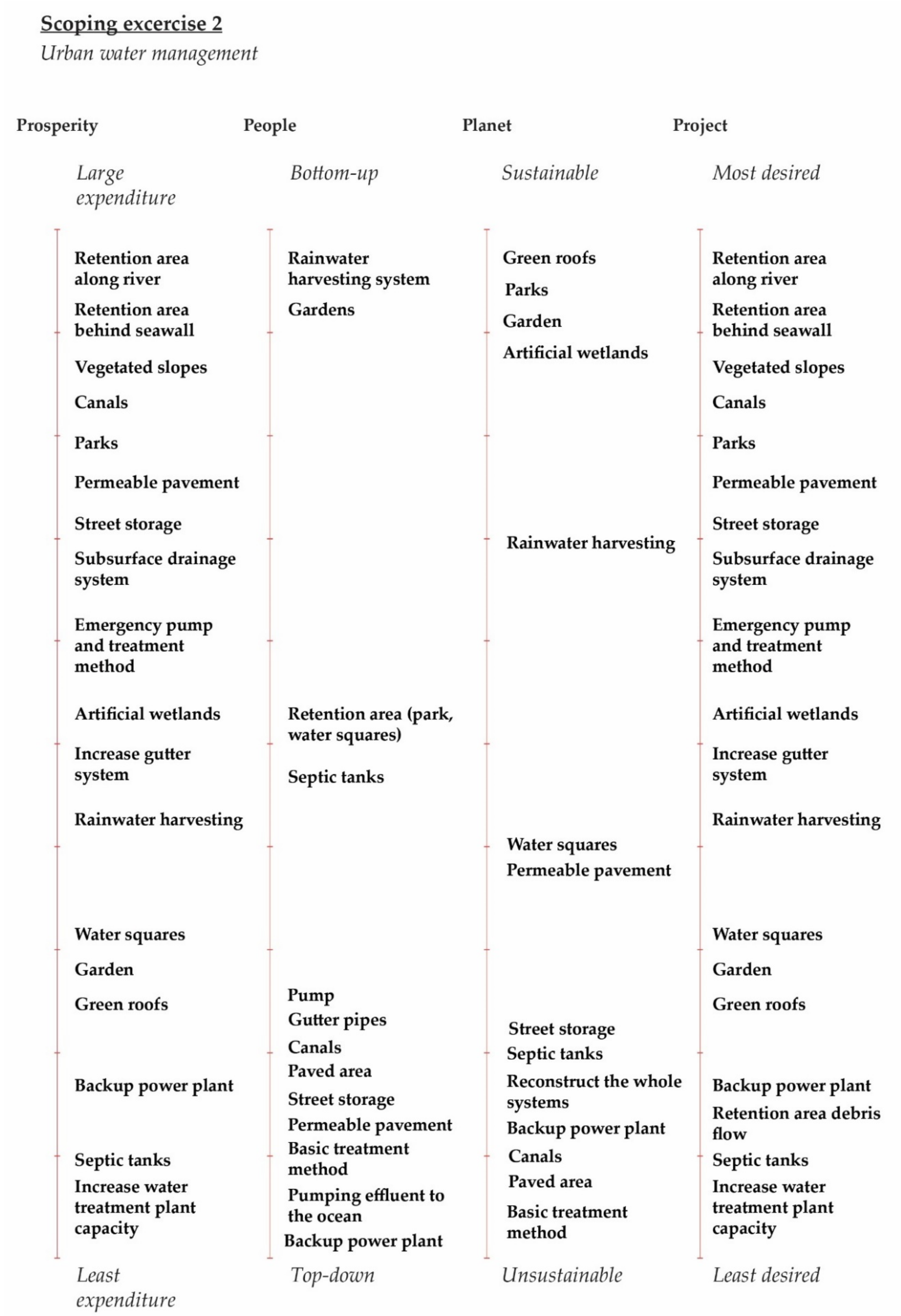


Figure A6. Scoping of the approached proposed by the Urban Water Management discipline

Figure A7. Scoping of the approaches proposed by Transport, Infrastructure and Logistics

Appendix B. Urban Scale

Appendix B1. Material risk assessment

1. Introduction

On March 11 of 2011, an earthquake of magnitude 9.0 hit the northeast coast of Japan (38.1035N, 142.861E), originating a devastating tsunami. This is most likely the largest tsunami event in the last one thousand years in Japan [49]. The damage in the coastal cities of the North of Japan was tremendous, with more than 18,000 fatalities including missing.

The tsunami was originated 130 km to the East of the shore of Sendai (Miyagi Prefecture), at a depth of 32 km. Surveys reported that the tsunami run-up heights exceeded 30 m in some locations [56].

The 2011 Great Tsunami was characterized by large heights, as the tsunami that affected the Sanriku coast in 1896 [49]. This type of tsunami has a frequency of occurrence of one in a hundred years [1]. On the other hand, the tsunami affected a large area and had a relatively large source zone, as in the 869 Jogan Tsunami [25]. The Jogan tsunami type has a return period of a thousand years [1]. Therefore, the 2011 Great Tsunami is characterized by a low frequency of occurrence and the huge scale of the tsunami source [49].

One of the cities that suffered the worse consequences of the tsunami was Otsuchi, a town with a population of 15,994 citizens before the tsunami [16]. In this town, 1,234 people lost their lives (including missing and related deaths, as of March 2018), what represented the 8% of the population. The massive destruction of the tsunami led to a decrease of the population of a 25.2%, from 15,994 citizens before the tsunami to 11,970 citizens after the tsunami (as of June 2018).

Furthermore, 3,092 buildings were destroyed (59.6% of the buildings of the town) and 786 buildings suffered major damage or partial destruction [29]. Moreover, the inundation area ascended to 431 ha. The 52% of the residential land and the 98% of the commercial areas were flooded, respectively. The maximum run-up height in Otsuchi was 24.5 m above the Tokyo Peil, the standard datum of Japan topography. The tsunami arrived to Otsuchi 42 minutes after the earthquake [17].

Surveys were carried out immediately after the tsunami to evaluate the damage at the affected locations [49]. The observations demonstrated that at the locations at which the seawalls resisted the tsunami, the inland inundation levels were notably lower, leading to a less severe damage. Accordingly, a strong dependence between the seawall height and the damage level was noted. A last conclusion extracted from the examination of the coastal defenses was the enhancement of their tenacity when a gravel fill or partitioning walls were present at the landside slope of the seawalls.

After the scale of tsunami destruction suffered by the North of Japan, Japanese government institutions and academia elaborated conjointly a new strategy for tsunami flood protection. The traditional strategy for tsunami protection stablished design guidelines to avoid overflow up to a certain design wave height. In case this tsunami height is exceeded, non-structure-based countermeasures become fundamental, such as the quality of the evacuation routes and a resilient city planning. However, no tsunami height was specified to start applying the *soft* measures, leading to lack of efficiency in the reduction of damage [49].

The new tsunami protection strategy introduced two tsunami levels. The Level-1 tsunami is considered a frequent tsunami with a return period of one hundred years. For this level of protection, *hard* structures are used. On the other hand, the Level-2 tsunami is determined as the maximum possible tsunami and is used to design the evacuation strategy. The return period of this tsunami is approximately one thousand years [54]. For this level of protection, *soft* or non-structural measures are considered, such as spatial planning and evacuation plans.

In case of occurrence of a tsunami that exceeds the height of the Level-1 defense, flooding cannot be avoided behind the seawall. However, the new strategy guarantees the resistance of the seawall for tsunami loads that exceed those of the Level-1 tsunami [49]. In Japan, this extra strength is known as *nebari*, a concept that stands for resilience or tenacity. The reinforcement of the coastal protections together with the design of evacuation plans based on a Level-2 tsunami are expected to mitigate effectively the damage caused by a potential tsunami.

According to the new tsunami protection strategy, the authorities of Otsuchi started the reconstruction of the town. The tragic event had proved that hard structures were not reliable for a large magnitude tsunami [49]. Furthermore, the construction of a seawall capable to withstand a Level-2 tsunami was not feasible. In this context, the local authorities decided to construct a Level-1 defense and put more emphasis in the soft measures to reduce damage in case of a Level-2 event.

A Level-1 line of defense was built in the shoreline, substituting the collapsed seawall (Figure 19). The construction of the new seawall supposed an upgrade of 8.1 meters of the height of the crest of the seawall (before the tsunami the crest was at TP +6.4 m and after the reconstruction it was at TP +14.5 m). The new design of the seawall was expected to protect Otsuchi from a tsunami with a frequency of one in one hundred years, which a height of TP +13.5 m. The width of the dike is four times larger than in the previous structure, in order to reduce the run-up height in the defense. The seawall consisted of a soil core covered by an external concrete layer of 50 cm. Additionally, scour protection was placed at the toes of the structure, to reduce the soil erosion during a tsunami.

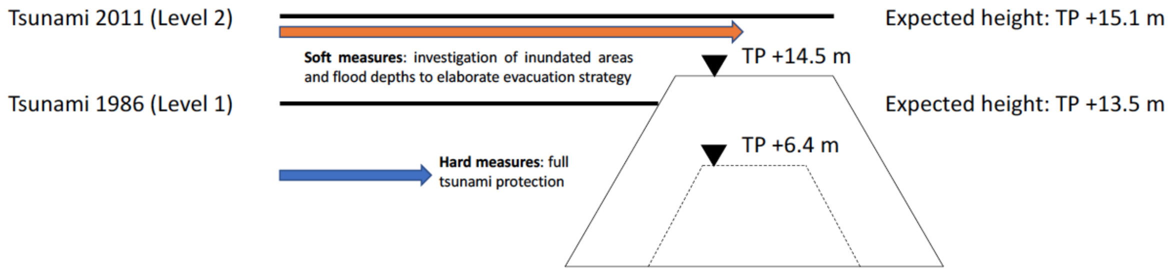


Figure B1. Schematization of the Level-1 and the Level-2 strategy in Otsuchi.

2. Flood Risk Assessment according to the current spatial planning

The goal of this project is the evaluation of the performance of the reconstruction plan applied in Otsuchi. To do so, it is assessed the damage that a tsunami with similar characteristics to the Great Tsunami of 2011 would produce in the reconstructed town. Based on the results of the evaluation, improvements in the reconstruction design will be proposed to enhance the effectivity of the reconstruction plan.

2.1. Evaluation of the material damage

The material damage produced by a tsunami is a function of the inundation depth and the land use of every location. The relationship between these two variables and the damage is commonly assessed by damage curves [18], from which the monetized damage can be estimated (Figure B2). The procedure is explained step by step in the following subsections.

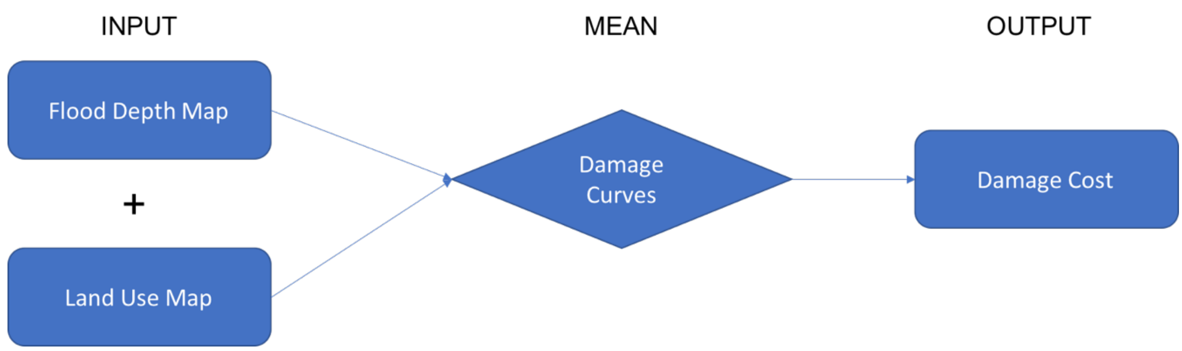


Figure B2. Procedure to estimate the material damage cost.

2.2. Flood depth map

For the flood risk assessment, the engineer focus on the inundation map of the area of interest, which in this case is Otsuchi. The inundation map is generally a raster, showing the inundation depth in every cell of the spatial domain. This map has been provided by the Iwate Prefecture, in jpeg format (Figure B3).

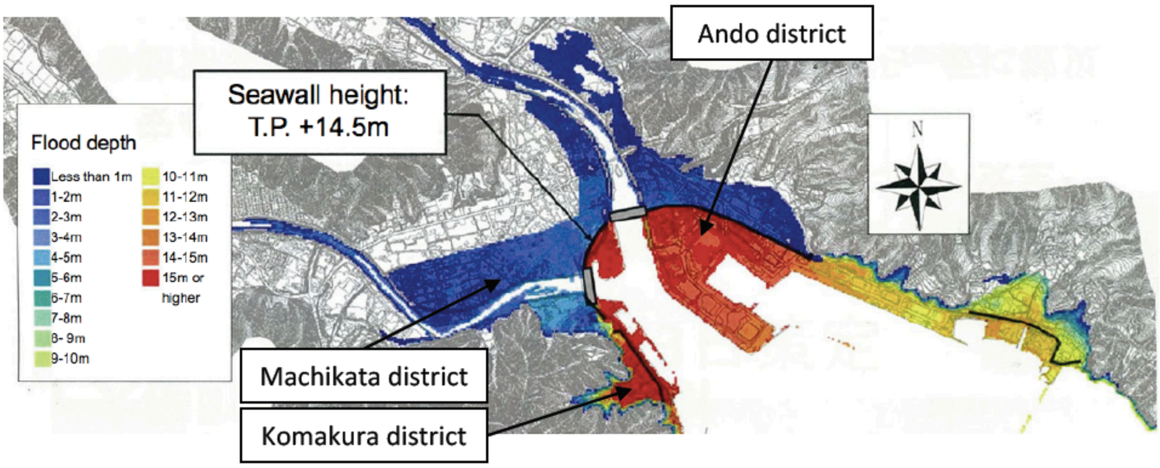


Figure B3. Inundation map of Otsuchi, as a result of a Level-2 tsunami (Disaster Recovery Bureau, 2018).

The image archive (Figure B3) has been processed by means of QGIS to obtain a raster of resolution 1 arc second (pixels of 30.82 m x 30.82 m).

2.3. Spatial planning: land use map

The spatial planning of Otsuchi has a large relevance on the resilience of the town against tsunamis. Apart from depending on the flood depth, the material damages depend on the land use. The land use map (raster) of the current context of Otsuchi is shown in Figure 2. In this map, the following land uses have been included:

- Residential
- Commercial
- Industrial
- Agricultural

The monetized damage for each land use increases with the inundation depth, up to a certain maximum that considers the complete degradation of the asset. The maximum damage for each land use ($d_{i,max}$) is shown in Table. The land use and the flood depth maps should be aligned, to develop an accurate evaluation of the costs.

Table B4. Maximum monetized damage for every land use, in euros per square meter (European Commission, 2017).

Land use	Maximum damage (euro/m²)
Agricultural	0.02
Residential	111.00
Commercial	138.00
Industrial	114.00

2.4. Damage curves

The relationship between the flood depths and the land uses is found by means of damage curves. These mathematical functions have been developed by the European Commission (2017) and relate the inundation depth to a damage factor (f), whose value is comprised between 0 (no damage) and 1 (maximum damage). The functions are based on normalized damage curves obtained from an extensive literature study in which damage values in every continent were analyzed. The study assumes that over an inundation depth of 6 m, the damage is maximum ($f = 1$). The continental curves are obtained by calculating the average value of the curves of the countries for which information was available. In this case, the curves for Asia have been used.

In order to calculate the damage for every pixel in an efficient way, the symbolic expression of the curves is used. This expression is obtained by curve fitting techniques. The mentioned curves for every land use are shown below:

- Residential

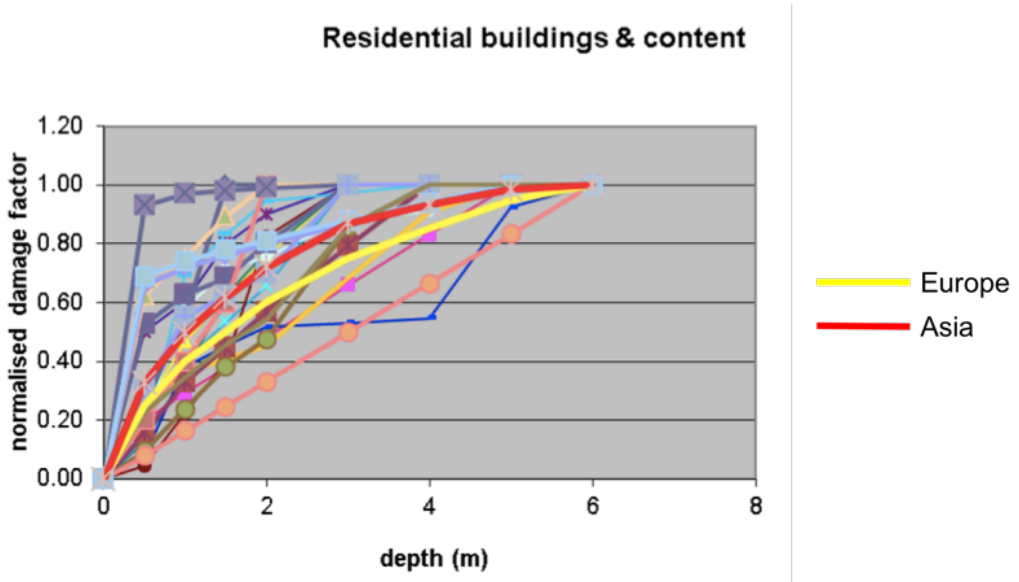


Figure B5. In red, the curve relating the flood depth and the damage factor for residential land use.

Table B6. Values of the damage curve for residential land use, in function of the flood depth.

Water depth (m)	Damage factor
0	0
0.5	0.33
1	0.49
1.5	0.62
2	0.72
3	0.87
4	0.93
5	0.98
6	1.00

The mathematical function of the damage curve for the residential land use is:

$$f_{residential} = \frac{1.276d + 0.00295}{d + 1.532} \quad (4)$$

The R-square coefficient of the fitted curve is 0.9983.

- Agricultural

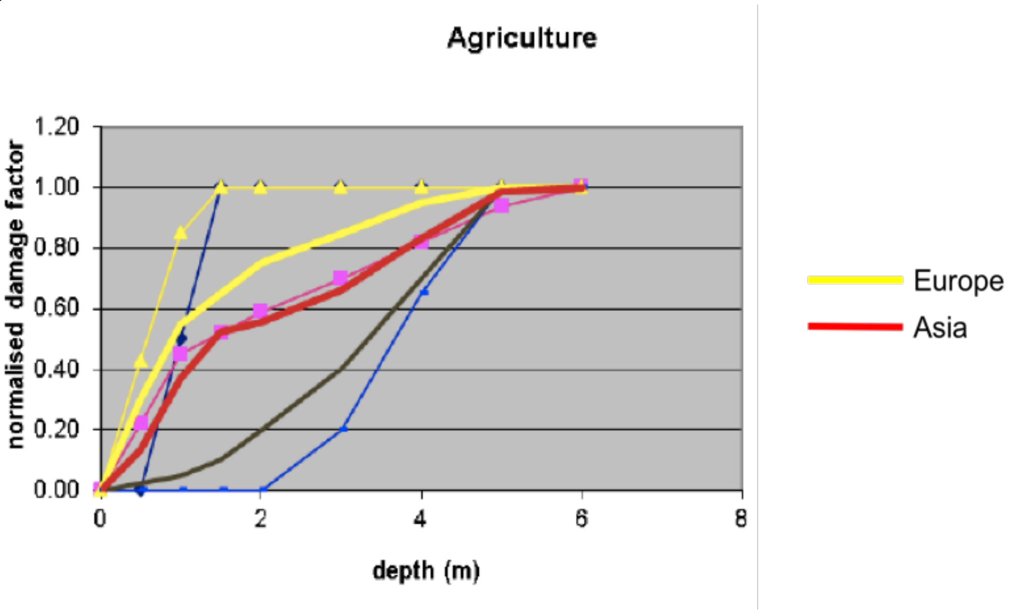


Figure B7. In red, the curve relating the flood depth and the damage factor for agricultural land use.

Table B8. Values of the damage curve for agricultural land use, in function of the flood depth

Water depth (m)	Damage factor
0	0
0.5	0.17
1	0.37
1.5	0.51
2	0.56
3	0.69
4	0.83
5	0.97
6	1

The mathematical function of the damage curve for agricultural land use is:

$$f_{agricultural} = \frac{1.612d - 0.004277}{d + 3.621} \quad (5)$$

The R-square coefficient of the fitted curve is 0.9939.

- Commercial

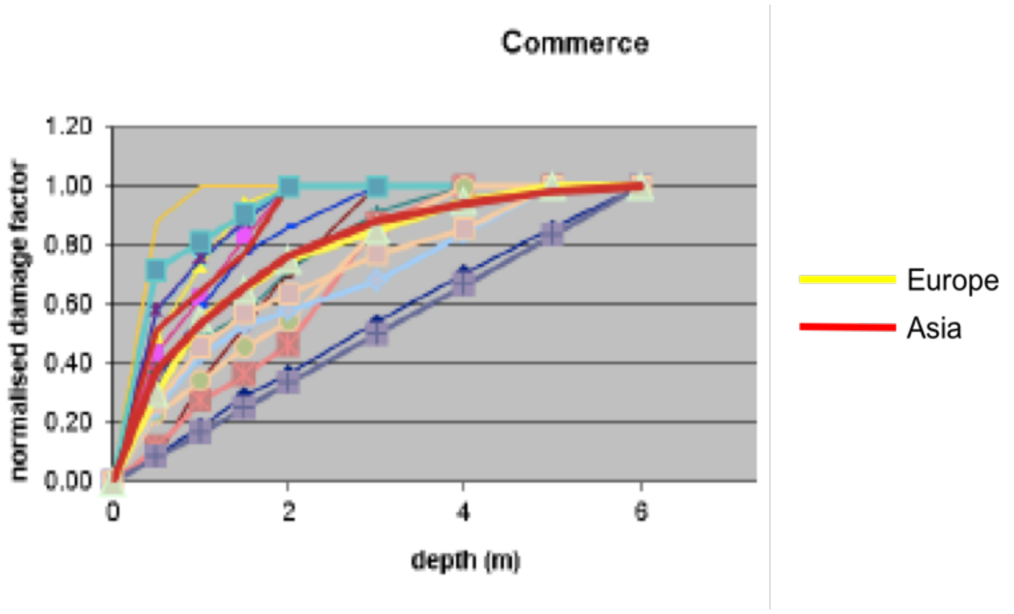


Figure B9. In red, the curve relating the flood depth and the damage factor for commercial land use.

Table B10. Values of the damage curve for commercial land use, in function of the flood depth.

Water depth (m)	Damage factor
0	0
0.5	0.38
1	0.54
1.5	0.66
2	0.76
3	0.88
4	0.94
5	0.98
6	1

The mathematical function of the damage curve for the commercial land use is:

$$f_{commercial} = \frac{1.21d + 0.004899}{d + 1.194} \quad (6)$$

The R-square coefficient of the fitted curve is 0.9987.

- Industrial

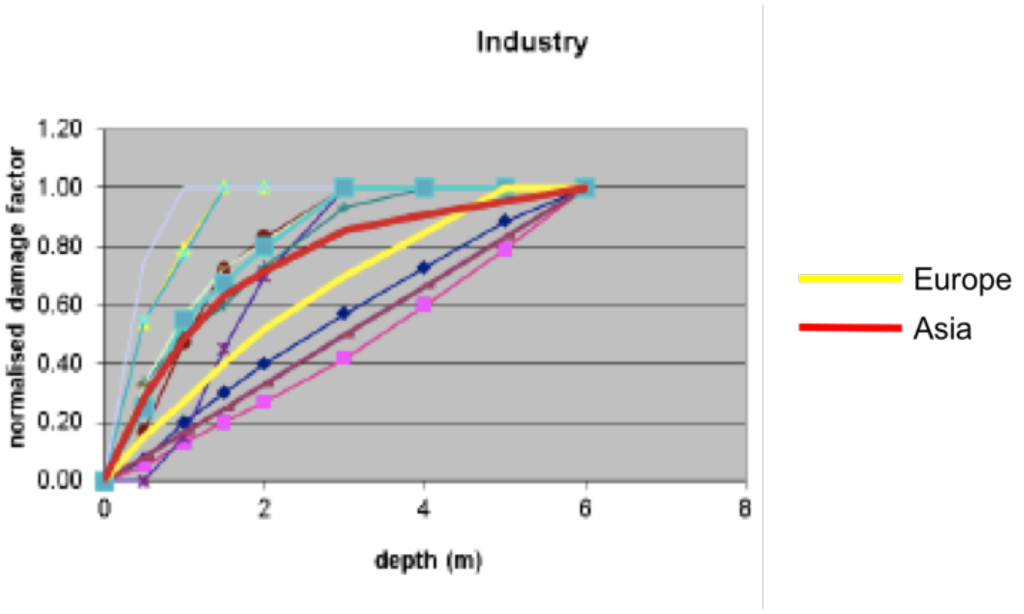


Figure B11. Values of the damage curve for industrial land use, in function of the flood depth.

Table B12. Values of the damage curve for industrial land use, in function of the flood depth.

Water depth (m)	Damage factor
0	0
0.5	0.28
1	0.48
1.5	0.63
2	0.72
3	0.86
4	0.91
5	0.96
6	1

The mathematical function of the damage curve for the industrial land use is:

$$f_{industrial} = \frac{1.275d - 0.01579}{d + 1.565} \quad (7)$$

The R-square coefficient of the fitted curve is 0.9982.

2.5. Calculation of the material damage

Given the inundation depths, the land uses and the damage curves, it is possible to calculate the material damage in Otsuchi. The material damage map is a raster, whose associated value is the monetized cost of the damage in euros. The raster can be treated mathematically as a matrix of size $m \times n$, where m is the number of rows and n is the number of columns. This matrix is called *material damage matrix*:

$$D_{m\times n} = \begin{bmatrix} D_{11} & \cdots & D_{1n} \\ \vdots & \ddots & \vdots \\ D_{m1} & \cdots & D_{mn} \end{bmatrix} \quad (8)$$

The components of the material damage matrix (D_{ij}) are:

$$D_{ij} = D_{lu,max} f_{lu}(d_{ij}) A_{pixel}, \qquad with\ i = 1, \dots, m\ and\ j = 1, \dots, n \tag{9}$$

where $D_{lu,max}$ is the maximum damage according to the land use (Table), $f_{lu}(d_{ij})$ is the damage factor depending on the land use (see $f_{residential}, f_{agricultural}, f_{commercial}$ and $f_{industrial}$ in section 0) and A_{pixel} is the area of every pixel, which is 956.18 m^2. It is assumed that the density of development of a certain land use is the same in all the pixels.

From the calculation of the damage, two outputs are evaluated to assess improvement in the current spatial planning:

- Geographical distribution of the material damage: this damage map shows the monetized damage per pixel (Figure 3). The analysis of the distribution of the damage enables to determine rationally where the adaptations of the current spatial planning should be carried out.
  Due to the implementation of sacrificial land in the Machikata district (see the 'water retention area' in Figure 11), because of the Reconstruction Plan, the damage in this district has been reduced notoriously. However, the Ando district (East of Otsuchi) is still under high flood risk. Consequently, a review of the spatial planning in that area is developed.

- Total material damage: by calculating the total material damage for the current situation, it is possible to quantify the damage reduction achieved with the new design. The total material damage is the sum of the damage at every pixel:

$$d_{total} = \sum_{i=1}^{n} \sum_{j=1}^{n} D_{ij} \tag{10}$$

The total damage for the current situation in Otsuchi ascends to 125,170,274 euros.

3. Flood Risk Assessment according to the new design

3.1. Spatial planning: new land use map

Based on the geographical distribution of the material damage for the current spatial planning, a new land use map has been elaborated (Figure 55).

In the Ando district, a green area has been implemented between the industrial area at the port and the residential area to the North-East. Moreover, in the Machikata district the industrial and residential areas close to the Otsuchi river have been transformed to green areas.

3.2. Calculation of the material damage

Using the new land use map and the damage curves previously proposed, the material damage for the new design is calculated. Again, the two outputs of this calculation are:

- Geographical distribution of the material damage: according to the changes in land use in the Ando and the Machikata district, the damage in those areas has been reduced (Figure 6).

- Total material damage: the overall damage in the municipality of Otsuchi for the new design is 94,899,947 euros. Therefore, the new design reduces the material damages in a 24%.

Appendix B2. Human risk assessment

This part is an elaboration of the information given in the paper regarding transportation. The tsunami of 2011 caused a lot of damage to the infrastructure; roads were not accessible anymore and the train line was destroyed. People were also not able to get to a safe location in time. Many inhabitants used cars to evacuate which caused large traffic jams on the main roads. Furthermore, there was not much awareness for possible tsunamis and what the quickest ways towards safe locations are [29]. Because of these reasons, there were a lot of casualties and damage in Otsuchi. The paper aimed to raise the preparedness in case a disaster of similar magnitude may hit Japan in the future. According to Shuto [51], evacuation is the most important and effective method to save human lives during a tsunami. Therefore, there is a focus on reducing the human losses by improving evacuation locations and the awareness of citizens for these locations.

In order to locate evacuation buildings at strategic positions the distance between any given point in Otsuchi and an evacuation building needs to be minimized. This is done with the help of a network analysis. There are different types of network analysis, but given the fact that the closest facility need to be found in case of a tsunami, there is chosen for the closest facility analysis. This analysis allows to perform multiple analyses simultaneously [29].

In order to carry out this analysis, several assumptions have been made. First, data points located in a proximity of 10 meters of any road are selected. These data points are extracted from the raster dataset which already have been used while setting the hydraulic boundaries for the area. The total number of data points that have been used for this analysis is 1044. From this amount, 11 data points are appointed as evacuation building.

After calculating what the shortest path to which evacuation building is from each data point, the distances can be obtained. With the help of the following formula, the total time needed for evacuation can be calculated:

$$t_{evac} = t_{reac} + \frac{l}{v_{esc}} \quad (11)$$

Where l is the distance towards an evacuation centre and v_{esc} the escape velocity. The outcome of the first iteration is shown in Figure **4.** in the main text of this paper. For each data point, there is calculated which evacuation building is the closest nearby and what the distance is in meters.

There is assumed that evacuation will be done by foot with a speed of 3.5 kilometers per hour. There is chosen to not use cars for this analysis, because of the uncertainty of this type of transportation. Not everyone is owning a car which can make modelling difficult. Furthermore, public transportation is also included, because the frequency if very low in this area which makes it too unreliable. In 2011, there were 42 minutes between the earthquake and the tsunami. This amount of time will also be used for this analysis. Because an earthquake can happen day or night, the response time of people will differ. Therefore, three different scenarios are developed in order to increase the certainty of this analysis. These scenarios are shown in Table.

Table B13. Scenarios used for analysis of the evacuation in case of Level-2 tsunami.

Scenario	Response time	Evacuation time
1	15 minutes	< 27 minutes
2	20 minutes	< 22 minutes
3	25 minutes	< 17 minutes

Using the formula which is shown above, the number of points which can reach an evacuation building in a given amount of time can be calculated. The results are graphically shown in Figure 4 in the main text and in Table below.

Table B14. Results of the first iteration. At the bottom of the table, the number of unsafe points in Otsuchi in case of Level-2 tsunami are shown.

Evacuation Center	Total number of data points	Data points <27 minutes	Data points <22 minutes	Data points <17 minutes
1	57	57	57	51
2	118	115	109	100
3	64	64	64	64
4	39	39	39	39
5	63	63	63	63
6	287	256	204	167
7	165	165	165	165
8	60	60	60	60
9	24	24	24	24
10	78	78	78	78
11	89	89	89	89
Total unsafe points		**34**	**92**	**144**

From the table can be concluded that the amount of data points which cannot reach an evacuation building in a certain time is too big. Number 1, 2 and 6 are not reachable of people. Also, the distribution of data points per facility is uneven. Therefore, a new iteration is needed. In this iteration, new locations are added. Because areas which are mainly located on lower grounds are having difficulties reaching an evacuation building within the given time frame, these new proposed locations are vertical evacuation buildings. While choosing for certain locations, the flood depth map is used as a basis, so no buildings are located in high risk areas. In this second iteration, 14 locations are used. The outcome of the closest facility analysis is shown in Figure B15.

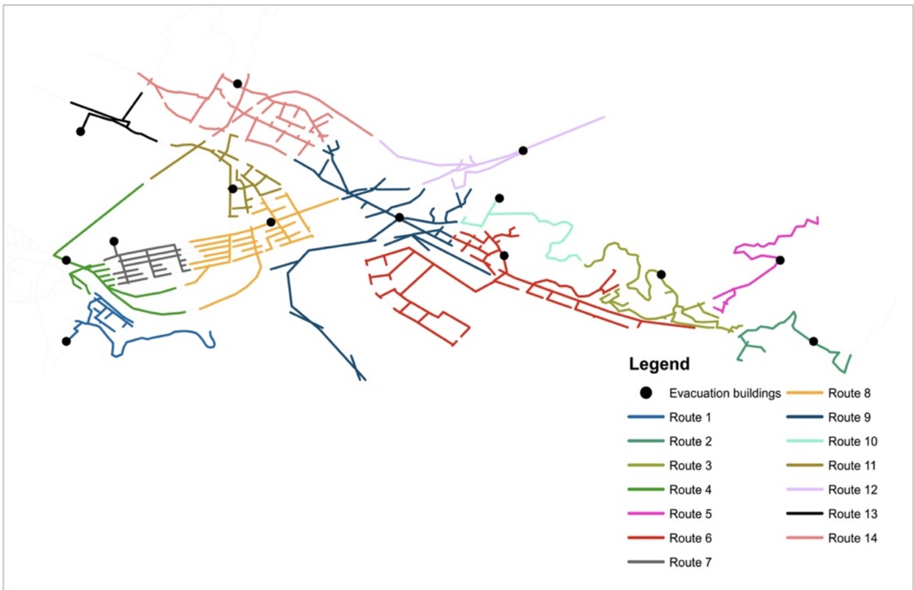


Figure B15. Evacuation routes in case additional evacuation routes are available

The time needed for evacuation is calculated in the same way as in iteration 1. The results are shown in Table B16. Results of the second iteration, in which vertical evacuation buildings are included.

Table B16. Results of the second iteration, in which vertical evacuation buildings are included.

Evacuation Center	Total number of data points	Data points <27 minutes	Data points <22 minutes	Data points <17 minutes
1	57	57	57	51
2	34	34	34	34
3	72	72	72	70
4	59	59	59	59
5	39	39	39	39
6	162	162	156	130
7	59	59	59	59
8	112	112	112	112
9	151	151	140	132
10	31	31	31	29
11	63	63	63	63
12	53	53	53	53
13	24	24	24	24
14	128	128	128	128
Total unsafe points		**0**	**17**	**61**

From this table, there can be concluded that there are still data points which cannot reach an evacuation building when there are maximum 22 or 17 minutes available to evacuate, but the amount is significantly reduced compared to iteration 1. If there are 27 minutes available, every data point can reach a facility safely. Furthermore, there are still differences in amount of data points per building; building 6 has for example 162 data points, while location number 13 has only 24. The locations with the highest amount of data points are mainly located in the residential area. In order to offer everyone a safe place to stay, the capacity here can be increased by increasing the number or the size of (vertical) evacuation buildings.

Looking at the possibility to reduce the number of not reachable data points, two aspects are important. First, the option of increasing the number of evacuation buildings may be not the most feasible solution. The data points which cannot reach the evacuation center are mostly located close to the water. An evacuation building at that location may be not able to resist the force of the water. Secondly, this analysis is based on the use of roads. Because pedestrians can walk over dry land as well, there are maybe paths which are shorter than stated in the analysis. In order to include both these aspects, a third iteration is necessary. Here, additional connections will be made with areas which are difficult to reach in order to reduce evacuation times. The results of this iteration are shown in Figure 7 in the main text of this paper.

The time needed for evacuation is calculated in the same way as in the previous iterations. The results are shown in Table B17.

Table B17. Results of the third iteration, in which additional evacuation routes are included.

Evacuation Center	Total number of data points	Data points <27 minutes	Data points <22 minutes	Data points <17 minutes
1	57	57	57	51
2	34	34	34	34
3	71	71	71	69
4	59	59	59	59
5	39	39	39	39
6	163	163	157	131
7	59	59	59	59
8	112	112	112	112
9	151	151	140	132
10	31	31	31	31
11	63	63	63	63
12	53	53	53	53
13	24	24	24	24
14	128	128	128	128
Total not reachable		**0**	**17**	**59**

The difference between the results of iteration 2 and iteration 3 is small. The last iteration has reduced the result of the data points which cannot reach an evacuation building within 17 minutes with just a reduction of two data points. It should be noted that these areas are not located in the urban areas, but mostly at the edges of the area. When response times are high, at night for example, it is highly unlikely that there are people in these 'unsafe' areas. Furthermore, enough attention must be paid towards improving the warrant system, so response times will be reduced and everyone can reach a safe location within the given time.

As already mentioned at the beginning of this appendix, a reason why it was not possible for people to quickly evacuate was due to crowding. Because of the unawareness of the locations of evacuation buildings, the most people chose to use the main roads out of town [29]. Increasing the awareness is thus an important part in raising the preparedness in case a disaster may hit the area in the future. This can be done by providing information at schools and during town meetings. Another way is adapting the current infrastructure, like roads, in such a way that they are changing the travel behavior of people. This concept is called *'Sustainable Safety'* and is based on three design principles: functional use, homogenous use and predictable use. The road network has to be adapted in such a way that road users understand the road's course, the behavior is required on the various road types and what they can expect from other road users. Optimizing the physical characteristics is a way to realize this ambition [61]. In time sensitive situations, people are often panicking which can influence road safety in a negative way [29]. Guiding people towards safe locations with the help of a design according to Sustainable Safety can help here.

Appendix B3. Urban design

Following the evaluation of the urban design proposed in Phase 1 of the reconstruction plan developed by the authorities of Otsuchi, it was determined that most of the damage is caused due to the exposed industrial zone that is not within the area protected by the dike, on the areas adjacent to the river, and on patches of land south of the elevated blocks. The evaluation also determined that the evacuation times to the current evacuation centers are not sufficient.

A new design proposal was done with three main aims:

-the improvement of the evacuation times as well

-the reduction of the potential damage that the mentioned areas would suffer

- the enhancement of the livability

As a first step to developing such, a new street layout was designed, shown in Figure B18, taking into account the location of the new dike, proposed locations of new evacuation centers, and green areas that would serve as water retention areas in case of overtopping. It was also considered that the town would potentially need more space to grow in the future. Even though Otsuchi has a declining population, it is foreseen that this might change. For such purpose within the original water retention areas, space was also considered to allocate future growth.

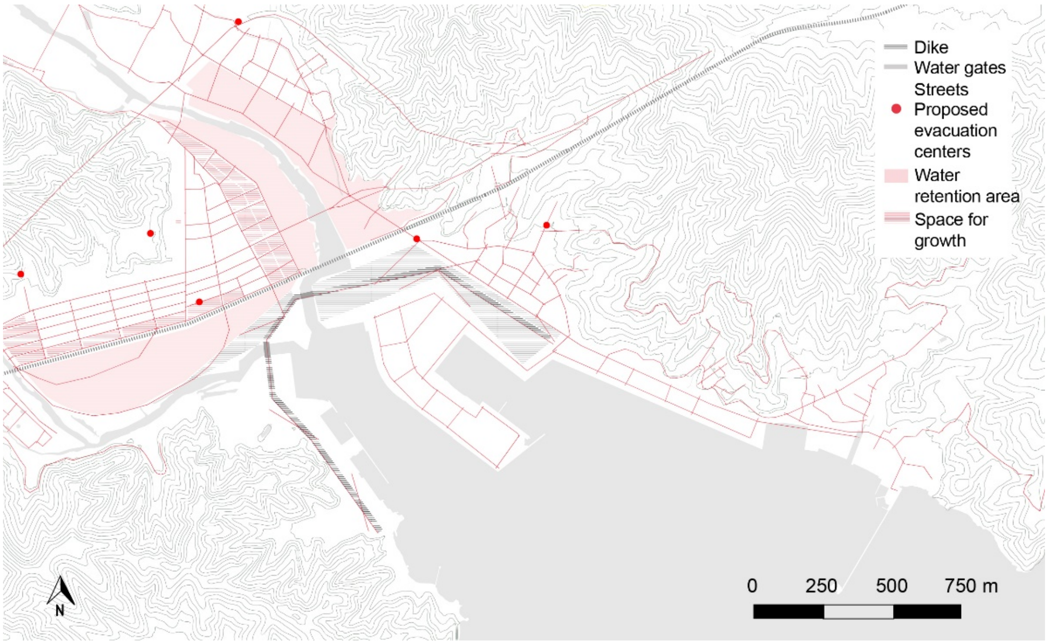


Figure B18. Proposed street layout in relation to the proposed evacuation centers, routes, and water retention areas

Following, an analysis of the street network was realised. The Place Syntax Tool (PST), developed by the Chalmers University of Technology [9] was used. The PST is an open source tool for Geographical Information Systems software. Within some of its features, street network analyses can be run to measure the accessibility and the integration of such network. Figure 28 shows how reachable each segment of the network is from each other segment within the boundary conditions. The results of the analysis helped to determined which areas have the potential to become more frequented and therefore to be better suited to have commercial, recreational or mixed uses. Areas with regular reach were determined to be suitable for residential purposes. Lastly, the low integrated areas were destined for industrial purpose mainly.

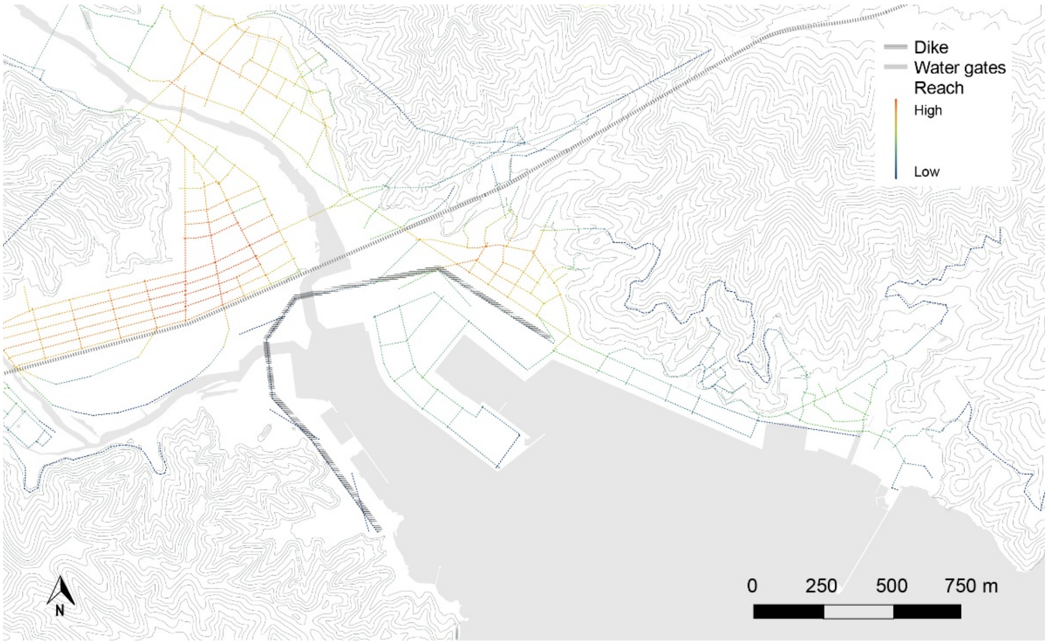


Figure B19. Reach analysis of the proposed street layout

Figure 5 in the main text shows the new urban design proposed. The commercial and mixed use is proposed to be concentrated in the areas with high reach within the urban fabric and next to the multifunctional dike, promoting the use of the multifunctional dike as a commercial and recreational corridor. Housing is to be allocated in areas closer to the hills, leaving more space for water retention. The water retention are, as mentioned before is proposed to be use as a green recreational space with light structures. Lastly, the industrial area is set to remain mainly in the same location as in the previous design, meaning that it would suffer from the same amount of damage in case of a tsunami. This risk is therefore minimized on an architectural scale and shown in the appendix C.

Appendix C. Building Scale

Appendix C1. Building design

In this appendix the bridging role of architectural design between risk management and liveability is elaborated and a set of site-specific guidelines are drawn as conclusions. In response to the urban scale zoning, four key building typologies were developed based on the risks and characteristics associated with each zone. These consisted of industrial and commercial buildings on and before the multifunctional dike, recreational structures in the water retention area, residential buildings in the urban centre and vertical evacuation buildings distributed throughout the town.

In order to develop a coherent set of building typologies the predicted flood height and its associated risks, of soil liquefaction, uplift forces and foundation scour are considered alongside liveability factors such as the integration of functions, sustainable levels of material and monetary resource investment and the local methods of construction.

Beyond this, one key typology was chosen to develop in terms of structural and material detail. The residential building in the urban centre was chosen as it is the most commonly needed building type and one in which a new approach to risk was employed. In most literature on disaster resilience emphasis is placed on total structural robustness, requiring sizing and investment which go far beyond sustainable limits for individual houses. While total structural robustness led the design of the vertical evacuation centres, the residential typology composes the most necessary elements required for safety, while balancing the monetary and material costs of construction, and the potential for debris creation.

Building Typologies:

Type 1: Industrial and commercial structures, Multifunctional dike

Possible functions: restaurants, music venues, industrial warehouses, fishing industry warehouses and shipyards
Requirements: medium sized enclosed spaces, structural
Structural strategy: concentrate appliances and machinery within structurally resilient cores or shear walls to minimise the potential for large, dangerous debris, allow open spaces to be washed away in the event of a tsunami using breakout wall connections
Characteristics: reinforced concrete structural cores or shear walls, lightweight timber construction surrounding, two story buildings with appliances and machinery elevated on the second floor to prevent damage in the event of abnormally high tides

Precedents and sources:

Berrios, L. et al. Tsunami Safe® House: A design for the Prajnopaya Foundation. Masters Thesis. Massachusetts Institute of Technology, USA, 2005. Available online: http://senseable.mit.edu/tsunami-prajnopaya/ (accessed on 29th May 2019).

Ardekani, A.; Hosseini, M. Urban and Architectural Approaches To Design against Tsunami, In 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 2012. Sociedade Portuguesa de Engenharia Sismica, Lisbon, Portugal, 2012. Volume 38, 30465-30473.

FEMA, Guidelines for Design of Structures for Vertical Evacuation from Tsunamis: Second Edition, 2012.

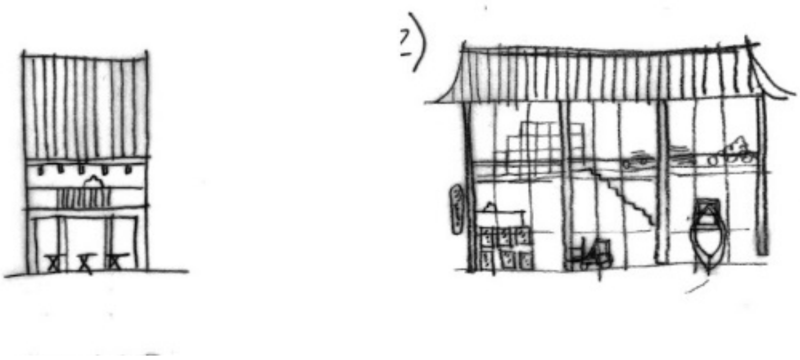


Figure C1. Possible configuration of industrial and commercial builidng guidelines

Type 2: Recreational structures, Water retention area

Possible functions: dance halls, sports seating
Requirements: large open spaces, shielded from weather but not enclosed, structural integrity in tsunami event but not a location for refuge
Structural strategy: heavy weight earth berm and reinforced concrete construction, allow flows to move through structure with open arrangement
Characteristics: Earth berm base protecting foundations, hydrodynamically shaped structures perpendicular to predicted inflow of water

Precedents:
Okushiri-Island, Aonae Prefecture, Japan.
Tsunami Refuge at Shirahama Beach Resort, Shiramhama Prefecture, Japan.

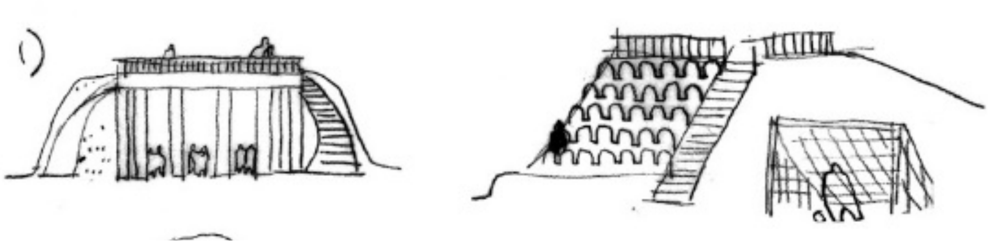


Figure C2. Possible configuration of recreational structure guidelines

Type 3: Residential and commercial buildings, Tsunami protected areas

Possible functions: housing and small commercial units
Requirements: preference for individual houses, a design aim to encourage co-living environments with multiple generations for ease of evacuation, the ability to withstand flooding to a height of 2m, sustainable material and monetary investment in construction while maintaining core structural integrity in a tsunami event, minimise debris creation
Structural strategy: elevate living spaces above the ground floor, employ reinforced concrete shear walls to create a strong core with lightweight breakaway timber panels infill construction to reduce material and monetary costs

Characteristics: multiple houses grouped together in the same plot, commercial functions enabled at the ground floor along with storage and garages, living spaces elevated to the first floor, communal space provided alongside single-family units with external access for ease of evacuation

Precedents and sources:

Ardekani, A.; Hosseini, M. Urban and Architectural Approaches To Design against Tsunami, In 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 2012. Sociedade Portuguesa de Engenharia Sismica, Lisbon, Portugal, 2012. Volume 38, 30465-30473.

FEMA, Guidelines for Design of Structures for Vertical Evacuation from Tsunamis: Second Edition, 2012.

Figure C3. Possible configuration of residential and commercial building guidelines

Type 4: Vertical evacuation centres, Distributed

Possible functions: offices, hospitals, government buildings, larger scale retail
Requirements: Minimum height of 5 storys, structurally able to maintain integrity in the event of both tsunamis and earthquakes, storage for supplies and backup generator in case of emergency, memorable and recognisable public façade
Structural strategy: Reinforced concrete moment frame on deep piles, breakaway lightweight infill construction at ground floor
Characteristics: Earth berm base protecting foundations to height of expected flood depth, circular columns to reduce impact of potential tsunami related debris, open structural configuration at ground floor perpendicular to predicted flow of water to allow flow of water, elevated back up generator and supplies, integrated services to avoid suspended ceilings or floors.

Precedents and Sources:

Nishiki Evacuation Tower, Taiki Town, Mie Prefecture, Japan.

Bowe, J. et al. Architecture of Recovery: A Framework for an Alternative Future. Masters thesis. University of Queensland, Australia, 2014.

FEMA, Erosion, Scour, and Foundation Design, 2009.

Nishiyama, I. et al., Building Damage by the 2011 off the Pacific Coast of Tohoku Earthquake and Coping Activities by NILIM and BRI Collaborated with the Administration, UJNR Wind and Seismic Effects, PWRI, Japan, 2011.

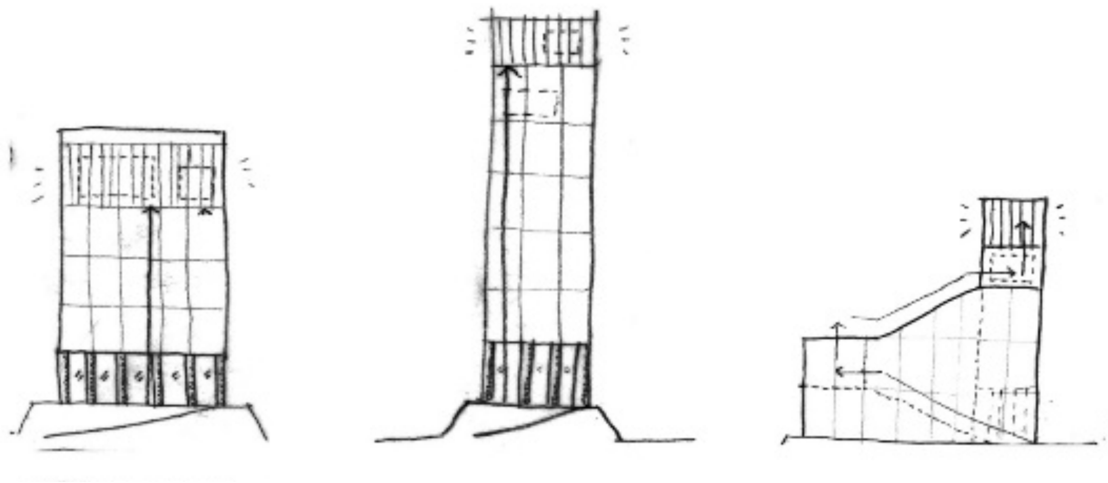


Figure C4. Possible configuration of vertical evacuation centre guidelines

Case Study: Residential and commercial buildings, Tsunami protected areas

Following on from the establishment of the key architectural characteristics of the different urban zones, the single-family house is taken as a case study for further development. It is chosen for further study because it is the most common type, and therefore small changes made to the existing norms could have a large impact.

The key architectural aims for the residential typology was an arrangement which satisfies the local demand for single-family houses but also caters for traditional intergenerational living arrangements. The site visit to Otsuchi highlighted that a major shortcoming of the reconstruction plan was the construction of residential towers which both separated residents from the ground which they maintain a deep cultural connection to, and generations from each other, with some towers catering to young families which others cater to the elderly. This developed into a proposal for houses of different sizes, untied by the same construction systems and components.

A second aim was the integration of commercial uses into the residential typology to create more mixed use neighbourhoods. Currently, Otsuchi is very monofunctional, with large inherited land parcels inhabited by single houses, leading to a very dispersed urban character and a tendency towards urban sprawl. This has the secondary effect of providing a lack of amenities in the city centre, especially in comparison to the town centre prior to the 2011 tsunami. Synergy is found here with the need to elevate the living spaces above the ground floor to minimise material losses in the event of 1-2m flooding as far as possible – the ground floor is proposed as space for storage and garages as well as commercial uses which can enliven the streetscape. This separation of storage from living spaces runs in line with traditional Japanese residential separation of house from kura where much of the furniture is stored while in not use. This arrangement feedback into the initial aim of more closely-knit residential units with the design of a first-floor communal deck from which multiple houses are accessed.

Finally, the central requirement of tsunami resilience is provided for through the arrangement of reinforced concrete shear walls. These are arranged perpendicular to the predicted flow of water to reduce additional loading as far as possible. Breakaway structurally insulated panels are specified to further allow for the passage of water without allowing force to be transferred to the shear walls. Fixed appliances and services are grouped in the lee created by shear wall corners in order to reduce as far as possible their being washed away as dangerous debris.

This arrangement (see Figure 8) was a point of collaboration between Architecture, Building Technology and Geoengineering and is further elaborated in Appendices C2 and C3.

Appendix C2. Building material specification

This chapter elaborates the measures incorporated into the building design to reduce the material and human losses aggravated by (a) Structural failure of buildings (b) Floating debris from building materials, during an earthquake and/or tsunami

After the 2011 Great earthquake, multiple surveys and assessments were conducted in regions affected by the earthquake and tsunami to investigate the degree of structural damage incurred by buildings and therefore assess the permissible design loads for structures. From the survey conducted by Ishiyama [30], the following is concluded :

Wooden structures: The damages to wooden structures is divided into three zones as per the inundation depth in the area. In general, structures covered by the Tsunami waves to a height of 2m and more experienced complete structural collapse due to the lateral force of the water "but also due to the water pressure on the ceiling of the first floor causing floating of the upper floors"[30].

Steel Structures: Steel structures such as industrial and commercial buildings mainly remained upright with damages restricted to non-structural members such as finishing walls, ceilings and other such elements. In some cases, the immediate water pressure of the tsunami and consequent failure of multiple non-structural members lead to the ultimate collapse of the load-bearing structure.

Reinforced concrete structures: Reinforced concrete buildings in general resisted the tsunami without collapse however when constructions present shallow or weak foundation and in some cases the building shapes induced the floating force resulting in overturning of the building. In other cases where buildings did not completely collapse, severe damages to non-structural elements like panels and ceilings were observed.

The level of damage in buildings due to an earthquake is determined by the strength and ductility of the structure. "The degree of ductility indicates the extent to which earthquake energy is absorbed by the structure that would otherwise cause it to continue to resonate"[22]. Although reinforced concrete is the most suitable material for heavy construction, the force of an earthquake is directly related to the weight of the building and therefore the heavy weight of the concrete construction aggravates the forces between the ground acceleration and the upper construction. Therefore lightweight materials such as timber are preferred over heavy materials to combat earthquake forces.

The following conclusion was drawn by Ishiyama [30] based on the conducted survey:

Table C5. Damage levels as per material and disaster type

Type of structure	Level of Earthquake damage	Level of Tsunami damage
Wooden structure	Low	High
Steel structure	Medium	Medium
Reinforced structure	High	Low

Bonnevie [6] observed the following damage patterns in particular structural elements without protection (such as residential buildings) in the Tohuku region after the 2011 Great earthquake and Tsunami:

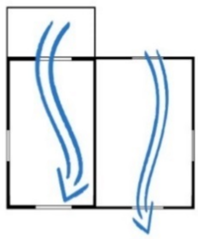
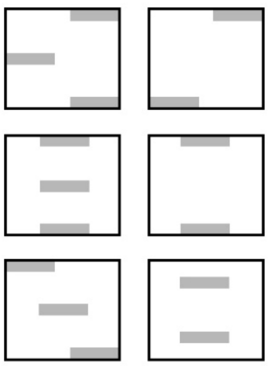
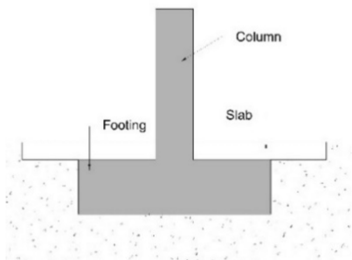
Table C6. Failure modes in building elements under impulsive and stationary tsunami forces

Building component	Failure mode
Wooden wall	Complete collapse caused by debris impact under impulsive Tsunami loading
Concrete wall/block wall	In stationary or standing Tsunami pressure, scour and rebar fracture caused failure of the structure, while bending,

	shear failure and/or overturning were the reasons for collapse under impulsive tsunami loading
Circular buildings	Collapse caused by debris impact under impulsive Tsunami loading
Rectangular/Square shape building	Failures caused by sliding and debris impact under impulsive Tsunami loading and scour under stationary Tsunami pressure

Based on the thus explained literature review of building damages occurred due to the 2011 Earthquake and Tsunami, the following structural strategies are developed:

Table C7. Structural strategies to tackle Tsunami and Earthquake damage in buildings

Measure	Description	Effect on Failure mode	Reference
	Aligning structural members in the direction of water flow and incorporating collapsible infill walls to break away under strong water pressure	By blocking the flow of water, there is an increase in load on structural members leading to bending/shear failure and/ or overturning.	[43] House Reconstruction Aceh ~ Indonesia Technical Advice Reinforced Concrete Tsunami House Reconstruction Aceh ~ Indonesia, (July).
	Symmetrical or regular layout with parallel shear wall arrangement.	Shear walls resist forces parallel to their length. Considerable size of lever arm mitigates reduced resistance against in-plan torsion.	[22]. Seismic Design for Architects Ou Tw Ittin G Th E Qu a K E.
	Shallow or strip footing connected to the structural slab	Control over relative horizontal movement during an earthquake.	

The structural strategies and material specifications are incorporated into one of four building typologies, as elaborated in section 4.2.3 and Appendix C1. The two main decisions made in the design are:

1. Incorporating redundancies: By including redundancies in the design such as sacrificial infill walls, the structural integrity of the building can be saved.
2. Concrete construction: As seen from the literature review of surveys conducted after the 2011 Great earthquake, wooden constructions underwent explosive failure under tsunami forces. However, the extent of destruction and failure in concrete constructions depended on the thickness and the strength of the structure.

The following materials are specified for the semi-sacrificial building:

Table C8. Material specification for flooring [14]

Building Component	Description	Specific weight (kN/m²)	Elaboration
Slab	Reinforced concrete (150mm thickness)	3,5	Withstands tsunami forces better than the typical wood construction
Insulation	Cellulose insulation (80mm thickness)	0,03	A green insulation material mitigating toxicity as a floating debris.
Finish	Vinyl floor covering (3mm thickness)	0,06	Minimal waste as a debris (compared to traditional floor covering such as tiles)

Table C9. Material specification for load-bearing walls [14]

Building Component	Description	Specific weight (kN/m²)	Elaboration
Structure	Reinforced Concrete block (390x190x290mm)	4,3	Blocks: 1. Facilitates easy and efficient construction. 2. Optimized material use due to prefabrication of the element.
Internal Finish	Stucco (20mm thickness)	0,4	-
External Finish	Plaster (25mm thickness)	0,38	-

Table C10. Material specification for collapsible infill and interior walls [14]

Building Component	Description	Specific weight (kN/m²)	Elaboration
Structure	89mm x 38mm timber studs (@500mm centres)	0,51	Collapsible lightweight frame
Insulation	Cellulose insulation (40mm thickness)		1. Green insulation material with thermal resistivity

			similar to fiberglass without cons such as formaldehyde and potentially harmful fire retardants. 2. Provides tougher protection against air leaks.
Finish	Plywood board (10mm thickness)		Single layer of plywood board.
External cladding	Timber boards (12,5mm thickness)		Planks of 100mm x 1200mm fixed in tongue and groove joint. Advantages: 1. Ease of construction 2. Size of planks reduces damage risk as a floating debris

Table C11. Material specification for roof [14]

Building Component	Description	Specific weight (kN/m²)	Elaboration
Structure (Battens & Rafters)	Timber	0,83	Typical lightweight timber roof construction, is advantageous in an earthquake as it does not lend to the stiffness of the structure.
Sheeting	Plywood		
Tiles	Concrete		

Miscellaneous:

Table C12. Material specification for miscellaneous elements in the building [14]

Building Component	Description	Specific weight (kN/m²)
Services	-	0,1
Ceiling	Plasterboard (12mm thickness)	0,13
	Joists (25mm thickness)	0,06
Live load	-	2

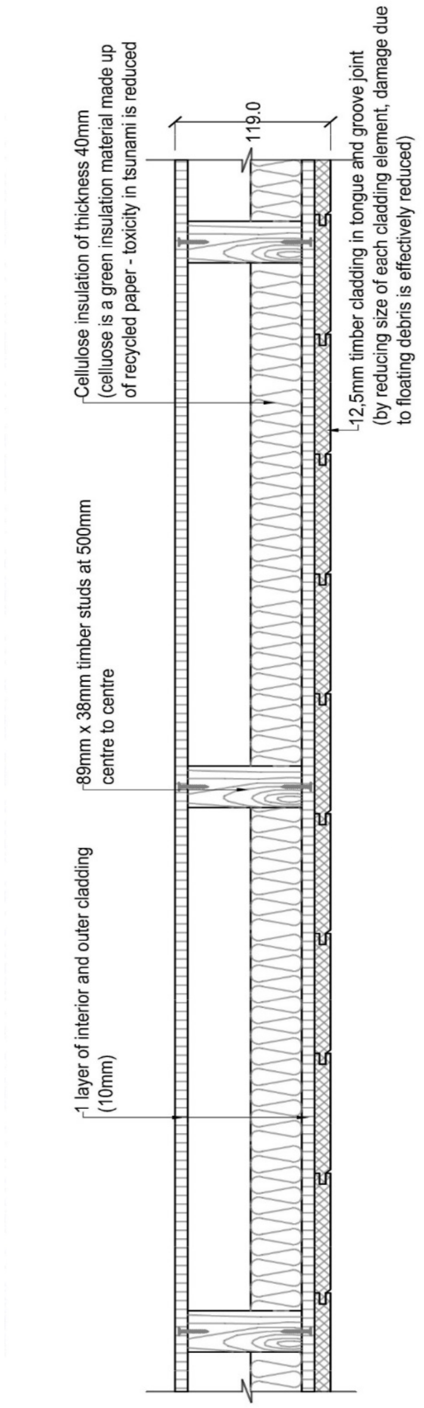
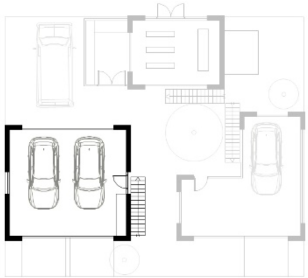


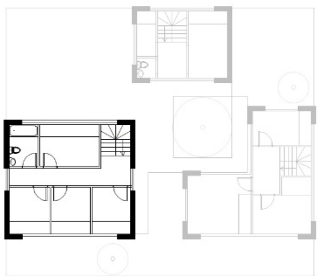
Figure C13. Collapsible timber wall detail: Scale – 1:5

Table C14. Load calculations per floor for one of three clustered buildings

Load calculation per floor:

	Ground floor: Total load : 604,1 kN

	First floor: Total load : 627,0 kN

	Second floor: Total load : 637,0 kN Total Roof load: 49 kN

These vertical loads per floor have been used in the calculation of foundation typologies, elaborated in Appendix C3.

Appendix C3.1. Lab results of a soil sample from Otsuchi of the section of elevated land

In this appendix, the grain size distribution as well as advised parameter values of the soil used for ground elevate elevation in the downtown area of Otsuchi are determined. A small sample of 170 grams was taken of the fill material originating from 'completely weathered granite'. Note that care should be taken with regards to the actual outcomes of the lab testing as the sample might not be representative for the fill material and due to the inaccuracies and uncertainties originating from a limited lab testing. The advised parameter values are therefore literature based according to the soil classification obtained from the grain size distribution.

1. Grain size distribution

1.1. Wet sieving results

The wet sieving results of the sample are given in Table C15 and Figure C16. The results show that the soil would classify as a silty gravel to a silty sand according to the USCS soil classification ASTM D 2487.

Table C15. Sieving results.

Sieve size	Retained weight (g)	Percentage retained
6.3 mm	55.14	38.5 %
2.0 mm	29.54	20.6 %
1.18 mm	6.31	4.4 %
600 μm	11.48	8.0 %
300 μm	8.71	6.1 %
150 μm	7.04	4.9 %
63 μm	7.36	5.2 %
Tray	17.67	12.3 %
Total	**143.25**	**100 %**

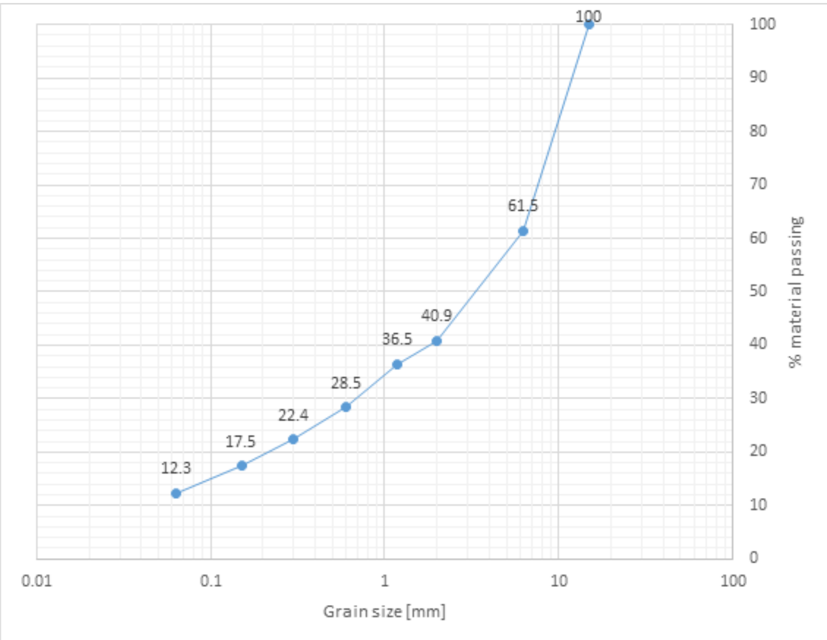


Figure C16. Grain size distribution of the Otsuchi sample.

1.2. Hydrometer results

The fill material originating from weathered granite, therefore the particle density was considered 2.75 Mg/m^3 for the processing of hydrometer data. The grain size distribution of the fine fraction is given in Figure C17. Although at site it was determined that clay particles could be present in the sample, the clay fraction in the sample was too small to be observed from the hydrometer test. Note that a fraction of grain sizes is larger than the actual largest fine grain size. This suggests some coagulation occurred.

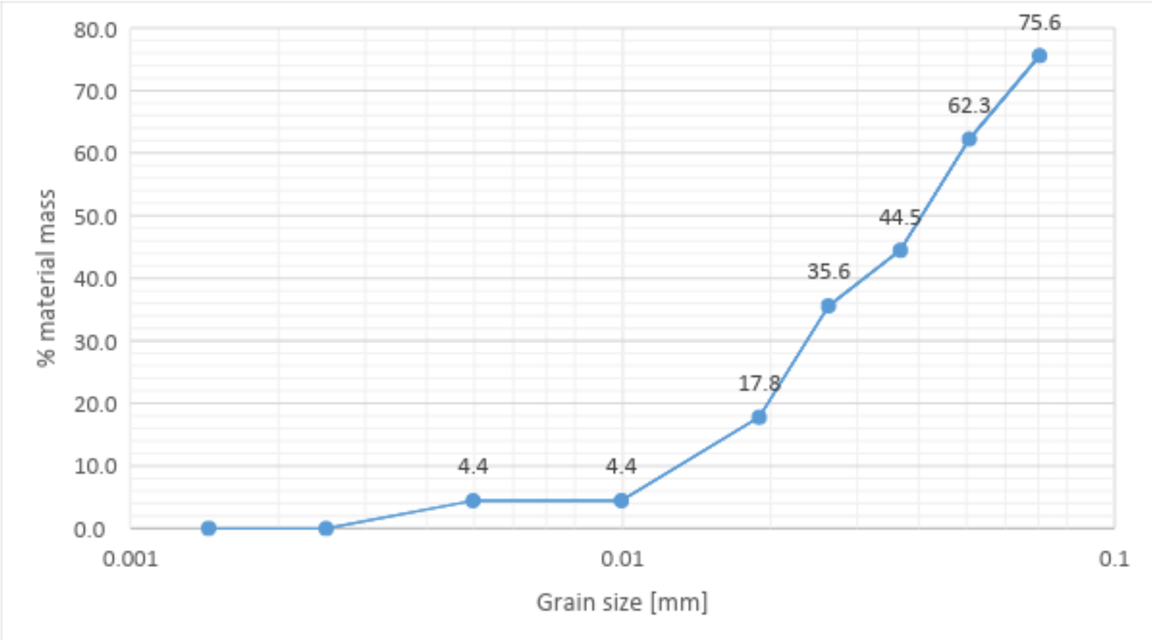


Figure C17. Grain size distribution of fines of the Otsuchi sample.

2. Advised properties of the soil

The soil was consolidated to 87 % degree of compaction [26], which is defined as given in equation 12 [53], where d,max is the dry density of the soil at its densest state. The relative density Dr of the soil can then be determined using equation 13. d,max and d,min were taken for a silty sand as 2275 and 1410 kg/m3 [15].
The elasticity modulus at 50% strain E_{50} can be determined using equation 14 [40]. The specific storage Ss is determined according to equation 15 [21] where w is the density of water and g the gravitational acceleration and where the compressibility α is given by equation 16.
The permeability K of a silty sand is expected to be $10^{-5} < K < 10^{-2}$ cm/s [21]. Based on the grain size distribution, the permeability can be determined from equation 17 (Hazen correlation) where D10 is the grain size diameter at 10 % passing weight. Constant C was taken as 1. The results of the specific storage and permeability including intermediate steps are given in Table C18.

Table C18. Advised properties of the soil.

D_r	E_{50}^{ref}	α	S_s	K (Fitts)	K (Hazen)
73 %	43.8 GPa	2.3 10^{-8} m^2/N	2.2 10^{-4} [-]	10^{-5} - 10^{-2} cm/s	10^{-4} cm/s

$$D_c = \frac{\gamma_d}{\gamma_{d,max}} \tag{12}$$

$$D_r = \frac{\gamma_{d,max}}{\gamma_d}\left(\frac{\gamma_d - \gamma_{d,min}}{\gamma_{d,max} - \gamma_{d,min}}\right) \tag{13}$$

$$E_{50}^{ref} = 60\,000\,\frac{D_r}{100} \qquad [\frac{kN}{m^2}] \tag{14}$$

$$S_s \approx \rho_w g \alpha \tag{15}$$

$$\alpha = \frac{1}{E_{50}^{ref}} \tag{16}$$

$$K = C.D_{10}^2 \tag{17}$$

Appendix C3.2. Design of the foundation of the housing units

The devastation of the coastal city of Otsuchi during the 2011 Tohoku earthquake calls for not only flood protection but also resilience of buildings and their foundation. In this chapter, a foundation typology is chosen for different housing typologies based on the failure mechanisms of the foundation during the events of a severe earthquake, flooding by tsunami and the scenario of tsunami flooding combined with a severe aftershock. Effects such as scour, debris loads and fracture of the foundation elements were not considered.

The housing typologies consist of a single to three floored house whilst the considered foundation typologies were composed of a simple raft foundation, a raft foundation with shear keys and a micro-piled foundation. During the loading scenarios, the foundation is exposed to additional vertical and horizontal loads combined with moments. The horizontal and vertical bearing capacity were therefore determined by using limit equilibrium methods for the raft and shear key typology, whilst for the micro-piled solution a limit equilibrium method was used to determine the vertical bearing capacity only and the horizontal capacity was determined with limit states methods.

1. List of symbols

B: Width [m]
B': Effective width [m]
L: Length [m]
d: Foundation embedment [m]
W: Weight of the structure [kN]
V_s: Seismic vertical force additional to normal conditions [kN]
V: Total Vertical forces [kN]
H_s: Seismic horizontal force additional to normal conditions[kN]
H: Total Horizontal forces [kN]
k_v: Vertical seismic coefficient [-]
k_h: Vertical seismic coefficient [-]
$q_{h,tsunami}$: Horizontal pressure caused by incoming tsunami [kPa]
$H_{tsunami}$: Horizontal force caused by incoming tsunami [kN]
$F_{buoyant}$: Buoyant force of inundated section [kN]
$V_{tsunami}$: Vertical force during tsunami inundation [kN]
ρ_w: density of saline water [kg.m^{-1}]
ρ_c: density of concrete [kg.m^{-1}]
g: gravitational acceleration [m.s^{-2}]
a: water depth coefficient [-]
h: inundation depth [m]
z: elevation [m]
W_z: weight of the tsunami inundated section [kN]
N_c, N_q, N_γ: Brinch Hansen Static capacity factors [-]
$N_{c,E}$, $N_{q,E}$, $N_{\gamma,E}$: Pseudo-static capacity factors [-]

$i_c,\ i_q,\ i_\gamma$: inclination factors [-]
$s_c,\ s_q,\ s_\gamma$: shape factors [-]
M: moments [kN.m^{-1}]
β: load inclinations [-]
$d_c,\ d_q,\ d_\gamma$: depth factors [-]
ϕ: soil friction angle [-]
c: soil cohesion [kPa]
C_u: Undrained shear strength [kPa]
$\underline{C_u}$: mean Undrained shear strength [kPa]
γ': effective soil volumetric weight [kPa.m^{-1}]
σ_v': vertical effective stress [kPa]
$k_{h,lim}$: limiting value of the pseudo-static coefficients [-]
q_v: Static bearing capacity [kPa]
$q_{v,E}$: Pseudo-static bearing capacity [kPa]
q_h^{wedge}: passive wedge pressure [kPa]
$q_{h,d}$: drained horizontal capacity (horizontal) [kPa]
$q_{h,u}$: undrained horizontal capacity (horizontal) [kPa]
$q_{h,d}^{slab}$: drained sliding capacity for a slab (horizontal) [kPa]
$q_{h,u}^{slab}$: undrained sliding capacity for a slab (horizontal) [kPa]
δ: interface friction angle [-]
α: soil-foundation adhesion [-]
K_p: passive earth pressure coefficient [-]
$Q_{g,b}$: Ultimate capacity of pile group acting as a block [kN]
Q_g: Ultimate capacity of pile group [kN]
D: pile diameter [m]
α_{bond}: Micro-pile Grout to Ground bond [kPa]
$N_{c,g}$: Pile group bearing capacity factor [-]
E: Soil Young modulus [kPa]
υ: Soil Poisson ratio [-]
E_u: Undrained soil Young modulus [kPa]
υ_u: Soil Poisson ratio [-]

2. Foundation typologies

The foundation should be affordable and should be able to resist loads from severe earthquakes, tsunamis up to a certain inundation depth and potentially aftershocks during the event of the tsunami. The choice was therefore made to select three types of shallow foundations for which the bearing and horizontal capacities are determined. Based on the results, a foundation typology is selected for the housing typology. The three types of foundation consist of: a 'regular' raft foundation, a raft foundation with shear keys and thirdly a micro-pilled foundation. The simple raft foundation is the cheapest and easiest foundation types of the ones proposed here, however it has the lowest horizontal and vertical bearing capacities. Both the horizontal and vertical bearing capacities can be increased with the addition of shear keys perpendicular to the direction of lateral loading. The increase in bearing capacity is achieved by mobilizing passive earth pressures, triggering a deeper bearing failure mechanism and by mobilizing soil at a higher confining pressure. As the name suggests, micro-piles are short piles grouted in-situ with steel reinforcement. The length of micro-piles exceeds the length of shear keys and therefore has the effect of increasing the bearing capacity of the foundation. The density of piles further increases the foundation capacity. For the three cases, the dimensions and embedment of the foundations are taken as input such that the dimensions and the embedment are within reasonable measures and for standardized sizes. The foundation typologies and foundation dimensions are shown in Figure **10**10 in the main text.

3. Load calculations

During its lifetime, foundation of the tsunami resilient house will have to have a sufficient bearing and lateral capacity to resist different loads. During a seismic event, the seismic ground acceleration causes both the vertical loads and vertical loads to increase. During a tsunami, additional side loads are applied to the structure which also increases the lateral loads, however, the tsunami also causes a reduction in vertical load are a result of buoyancy of the structure. In the following sections, the loads during these events are calculated.

3.1. Loads normal conditions

During normal conditions, the horizontal loads are negligible. The vertical loads can be separated in two categories: the dead loads and live loads. The details of these loads can be found in Appendix C2.

3.2. Loads during earthquake

As mentioned before, the seismic event causes additional vertical and lateral loads V_s and H_s. These can be determined according to equation 18 and 19 respectively, where W is the weight of the structure (both live and dead loads) and k_h and k_v the horizontal and vertical seismic coefficient. For severe earthquakes, and an importance factor Z of 1.0, the horizontal seismic coefficient can be taken as 0.4g for a short story building (i.e. high resonance frequency) at ground floor [31]. The seismic importance zoning can be found in Ishiyama [31]. The vertical seismic coefficient is then given by equation 20 [32].

$$V_s = k_v W \tag{18}$$

$$H_s = k_h W \tag{19}$$

$$k_v = \frac{2}{3} k_h \tag{20}$$

3.3. Loads during tsunami according to Japanese codes

For the tsunami case, inundation heights were based on figure 3 for the downtown where inundation depths h up to 3 meters are expected. During the event of a tsunami, the water causes additional lateral loads whereas the vertical loads are reduced due to buoyancy.

The horizontal pressure $q_{h,tsunami}$ on the structure caused by the tsunami can be determined according to equation 21 [8] following the simplified scheme in Figure C19 for pseudo-hydrostatic conditions. ρ_w is the density of sea water (in this case sea water), g the gravitational acceleration, a the water depth coefficient, h the inundation depth and z the location of the acting pressure. The water depth coefficient a was taken as 1.5. An important remark is the fact that this parameter will change according to where the building is positioned with respect to the sea dike [40]. The resulting force $H_{tsunami}$ can then be determined following equation 21, where B is the exposed surface area of the structure perpendicular to the wave direction, and $z1$ amd $z2$ the minimum and maximum height of pressure-exposed surface.

The buoyant force $F_{buoyant}$ resulting from a certain inundation height can be calculated according to equation 22, where W_z is the weight of the inundated section of the building, ρ_w and ρ_c the density of water and concrete respectively. For simplifications, the density of concrete was taken to represent the average density of the inundated ground floor. The resulting vertical load is then given by equation 23.

$$q_{h,tsunami} = \rho_w g(ah - z) \quad (21)$$

$$H_{tsunami} = \int_{z1}^{z2} q_{h,tsunami} B dz \quad (21)$$

$$F_{buoyant} = W_z \frac{\rho_w}{\rho_c} \quad (22)$$

$$V_{tsunami} = W - F_{buoyant} \quad (23)$$

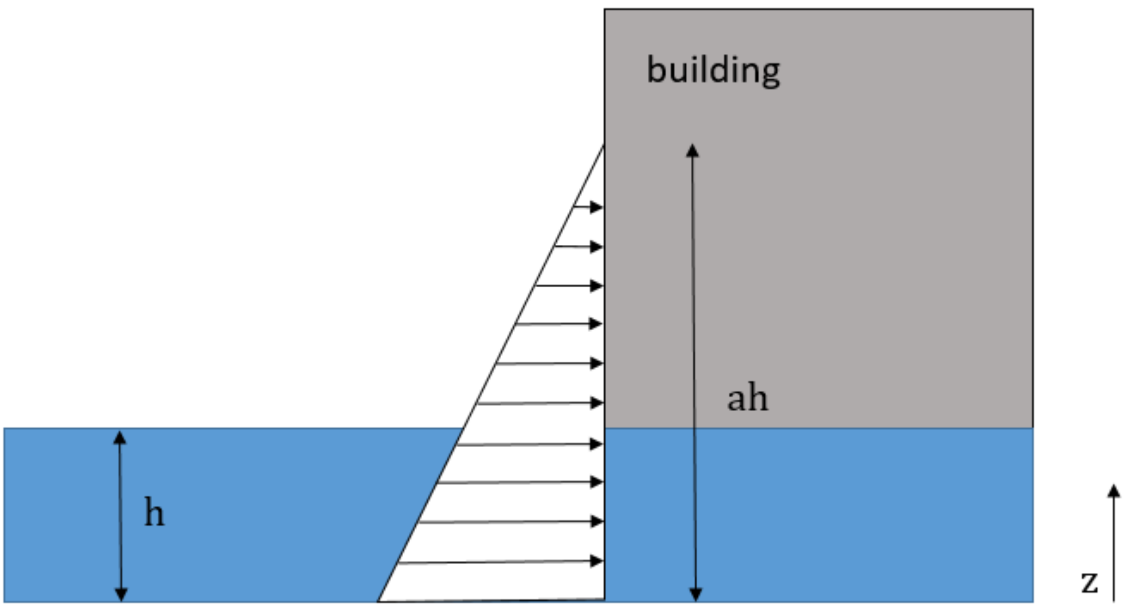


Figure C19. Design tsunami pressure distribution (Nakano, 2017).

3.4. Loads during tsunami and aftershocks

After the main shock of the 2011 Tohoku Earthquake, several aftershocks of severe amplitude (above 7 on the Richter scale) occurred within the same hour of the main shock, which is also within the timespan of the Tsunami flooding in Otsuchi [27]. In this case, both the effects of the tsunami and the seismic event have to be considered in the design which is: an increase in lateral loads due to the water pressure and the horizontal seismic acceleration, as well as the increase of the vertical loads due to vertical seismic acceleration combined with the reduction of vertical load occurring due to the buoyancy effects of the flooding. Macabuag [35] states that the combined loading to tsunami and earthquake is yet to be fully quantified as the combined effects of cyclical degradation of structural materials and the bearing soil loaded in the ductile range are yet to be fully understood. These effects are therefore neglected in this analysis.

3.5. Overview of the loads during different scenarios of loading

In Table C20, Table C21 and Table C22, the vertical and horizontal loads as well as the moments are given for the different loading scenarios and house typologies.

Table C20. Loads for a single-story house.

Loads	Normal conditions	Earthquake	Tsunami	Tsunami + aftershock
Vertical [kN]	981	1242	721	914
Horizontal [kN]	-	392	450	842
Moments [kN.m^{-1}]	-	378	1350	2062

Table C21. Loads for a two-story house.

Loads	Normal conditions	Earthquake	Tsunami	Tsunami + aftershock
Vertical [kN]	1921	2434	1662	2105
Horizontal [kN]	-	769	450	1219
Moments [kN.m-1]	-	754	1350	2438

Table C22. Loads for a three-story house.

Loads	Normal conditions	Earthquake	Tsunami	Tsunami + aftershock
Vertical [kN]	2880	3646	2619	3317
Horizontal [kN]	-	1152	450	1602
Moments [kN.m-1]	-	1137	1350	2821

4. Bearing and lateral capacity

In this section, the bearing and lateral capacity of the foundation typologies are determined by using limit equilibrium methods for the raft and shear key foundations and limit states for the micro-piled foundation. The soil sample gathered at the project location in Otsuchi showed that the soil on which the shallow foundation is built is a silty sand to a silty gravel with a medium to high relative density. The soil's permeability (10^{-4} cm/s) sits in between permeabilities, which would imply fully drained or undrained conditions. It is therefore not clear if the conditions during the event of a tsunami flooding are drained or undrained. The calculations for both behaviors was therefore performed. For the severe seismic and combined flooding and aftershock, undrained conditions were considered.

4.1. Bearing capacity calculation method

The governing bearing capacity equation under static conditions for shallow foundation from Brinch Hansen is given in equation 24. Static capacity factors N_c, N_q and N_γ are given in equations 25 to 27. Factors $i_c,\ i_q$ and i_γ are inclination factors, given by equations 28 to 30, which occur because of both horizontal and vertical loads. $s_c,\ s_q$ and s_γ are shape factors defined by equations 31 to 33. The parameters $d_c,\ d_q,\ d_\gamma$ are depth factors given by equations 34 to 36 and k is given in equation 37. For these equations ϕ is the friction angle, c the cohesion and γ the volumetric weight of the soil. For the drained analysis, the cohesion was set as zero and for the undrained analysis the friction angle was set to zero whilst the cohesion was set as the undrained shear strength. The effective volumetric weight γ' was taken for saturated conditions. V represents the vertical loads, H the horizontal loads, D the depth of the foundation, L its length, B the width of the foundation and B' the effective width. Conti [11], proposed a pseudo-static approach in order to take the seismic effects into account by introducing seismic bearing capacity factors $N_{c,E},\ N_{q,E}$ and $N_{\gamma,E}$ which replace the static capacity factors from Brinch Hansen bearing capacity formula (equation 38). In this case, the inclination factors are already taken in the seismic bearing capacity factors. The formulas to determine the seismic bearing capacity factors for cohesive frictional soils (i.e. drained conditions) are given in equations 39 to 50 and for purely cohesive soils (i.e. undrained conditions) in equations 51 to 66. $k_{h,lim}$ is given in equation 67 and the remaining factors in equation 68 and 69.

The vertical capacity for a group of micro-piles can be estimated for undrained conditions by taking the minimum capacity between the pile-group failing as a whole with equation 70, and the capacity of the pile-group acting as distinct piles equation 71 [48]. D is the pile diameter, $\underline{C_u}$ the average undrained shear strength over the pile length, $N_{c,g}$ the bearing capacity factor for pile groups given in equation 72, α_{bond} the grout to ground bond, n_p the number of micro-piles and η the efficiency factor. The grout to ground bond and the efficiency factor were chosen as 145 kPa (medium dense silty sand for gravity grout) and 0.7 (3 pile diameters spacing between piles) respectively. For drained conditions, the efficiency factor was set as 1.

$$q_v = i_c s_c d_c c N_c + i_q s_q d_q q N_q + \frac{1}{2} i_\gamma s_\gamma d_\gamma \gamma' B' N_\gamma \tag{24}$$

$$N_q = \frac{1+sin\phi}{1-sin\phi} exp\ (\pi\ tan\phi) \tag{25}$$

$$N_c = \left(N_q - 1\right)cot\phi \tag{26}$$

$$N_\gamma = 2\left(N_q - 1\right)tan\phi \tag{27}$$

$$i_c = 1 - \frac{H}{c + tan\phi} \tag{28}$$

$$i_q = {i_c}^2 \tag{29}$$

$$i_\gamma = {i_c}^3 \tag{30}$$

$$s_c = 1 + 0.2\frac{B}{L} \tag{31}$$

$$s_q = 1 + \frac{B}{L} sin\phi \tag{32}$$

$$s_\gamma = 1 - 0.3\frac{B}{L} \tag{33}$$

$$d_c = \begin{cases} 0.4k, & (undrained) \\ 1 + 0.4k, & (drained) \end{cases} \tag{34}$$

$$d_q = 1 + 2tan\phi(1 - sin\phi)^2 k \quad (35)$$

$$d_\gamma = 1 \quad (36)$$

$$k = \begin{cases} D/B, & for\ D/B \leq 1 \\ \tan^{-1}(D/B), & for\ D/B \geq 1 \end{cases} \quad (37)$$

$$q_{v,E} = s_c d_c c N_{c,E} + s_q d_q q N_{q,E} + \frac{1}{2} s_\gamma d_\gamma \gamma' B' N_{\gamma,E} \quad (38)$$

$$N_{qE} = e_q^k e_q^\beta N_{qS} \quad (39)$$

$$N_{cE} = e_c^k e_c^\beta N_{cS} \quad (40)$$

$$N_{\gamma E} = e_\gamma^k e_\gamma^\beta N_{\gamma S} \quad (41)$$

$$N_{qS} = \frac{1 + \sin\ \phi}{1 - \sin\ \phi}\ e^{\pi \tan\ \phi} \quad (42)$$

$$N_{cS} = \left(N_{qS} - 1\right)\cot\ \phi \quad (43)$$

$$N_{\gamma S} = 1.5\left(N_{qS} - 1\right)\tan\phi \quad (44)$$

$$e_q^\beta = (1 - 0.5\tan\beta)^5 \quad (45)$$

$$e_c^\beta = e_q^\beta \quad (46)$$

$$e_\gamma^\beta = (1 - \frac{\tan\beta}{\tan\phi})^{4.1\tan\phi^{1.4}} \quad (47)$$

$$e_q^k = \left(1 - \frac{k_h}{\tan\phi}\right)^{0.37\tan\phi^{0.5}} \quad (48)$$

$$e_c^k = 1 \quad (49)$$

$$e_\gamma^k = \left(1 - \frac{k_h}{\tan\phi}\right)^{0.47} \quad (50)$$

$$N_{qE} = e_q^k e_q^\beta N_{qS} \quad (51)$$

$$N_{cE} = e_c^k e_c^\beta N_{cS} \quad (52)$$

$$N_{\gamma E} = e_\gamma^k \quad (53)$$

$$N_{qS} = 1 \quad (54)$$

$$N_{cS} = 2 + \pi \quad (55)$$

$$N_{\gamma S} = 0 \tag{56}$$

$$e_q^{\beta} = 1 \tag{57}$$

$$e_c^{\beta} = 0.5 + 0.5\sqrt{1 + \frac{\tau}{c_u}} \tag{58}$$

$$e_{\gamma}^{\beta} = 0 \tag{59}$$

$$e_q^k = 1 - a_q \frac{k_h}{k_{h.lim}} - b_q (\frac{k_h}{k_{h.lim}})^2 \tag{60}$$

$$e_c^k = 1 \tag{61}$$

$$e_{\gamma}^k = -a_q \frac{k_h}{k_{h.lim}} - b_q (\frac{k_h}{k_{h.lim}})^2 \tag{62}$$

$$a_q = 0.75\ k_{h.lim} \tag{63}$$

$$b_q = 1.4\ \ k_{h.lim} \tag{64}$$

$$a_{\gamma} = 1.75\ k_{h.lim} \tag{65}$$

$$b_{\gamma} = 1.4\ \ k_{h.lim} \tag{66}$$

$$k_{h,lim} = \frac{C_u}{\gamma(D + \frac{B}{2})} \tag{67}$$

$$\tau = \frac{H}{B'} \tag{68}$$

$$\tan\beta = \frac{H}{V} \tag{69}$$

$$Q_g = (2B + 2d)D\underline{C_u} + BLN_{c,g}C_u \tag{70}$$

$$Q_g = (2B + 2d)D\underline{C_u} + BLN_{c,g}C_u$$

$$Q_g = (\alpha_{bond}\pi DL)n_p\eta \tag{71}$$

$$N_{c,g} = \begin{cases} 5\left(1 + \frac{0.2B}{L}\right)\left(1 + \frac{0.2D}{B}\right) \ for \ \frac{D}{B} \leq 2.5 \\ 7.5\left(1 + \frac{0.2B}{L}\right) \qquad for \ \frac{D}{B} > 2.5 \end{cases} \tag{72}$$

4.2. Horizontal capacity calculation method

The horizontal capacity of the raft and raft with shear key was determined by calculating the sliding and lateral earth pressures of the foundation. The sliding capacity of the concrete slab under drained conditions $q_{h,d}^{slab}$ was determined according to equation 73, where c is the cohesion, σ_v' the vertical effective stress at the sliding plane and δ the interface friction angle between the concrete slab and the soil. In the case of larger embedment d, passive wedges develop whilst shearing. The increase in capacity q_h^{wedge} due to passive wedges is shown in equation 74, where K_p is the passive earth pressure coefficient. Under normal conditions, the horizontal capacity in drained conditions is then given in equation 75. Under drained conditions, the sliding capacity $q_{h,u}^{slab}$ from the slab is given by equation 76, where c_u is the undrained shear strength at the representative depth of the failure mechanism and α the soil-foundation adhesion. α was taken as 0.8 for a medium stiff soil [42]. The horizontal capacity under undrained conditions can then be determined with equation 77. The vertical acceleration is generally out of phase with the horizontal acceleration and have different frequency contents [11]. The horizontal and vertical factors of safety were therefore determined considering the contribution of one axial component at the time i.e. by calculating the horizontal resistance with $k_v = 0$ and bearing resistance with $k_h = 0$.

$$q_{h,d}^{slab} = c + \sigma_v' tan\ (\delta) \tag{73}$$

$$q_h^{wedge} = \frac{1}{2} K_p \gamma'_{sat} d^2 \tag{74}$$

$$q_{h,d} = q_{h,d}^{slab} + \frac{q_h^{wedge}}{L} \tag{75}$$

$$q_{h,u}^{slab} = \alpha S_u \tag{76}$$

$$q_{h,u} = q_{h,u}^{slab} + \frac{q_h^{wedge}}{L} \tag{77}$$

For the pile-group foundation, a limit state approach is taken by using Deltares software D-pile Group in order to determine the displacements of the foundation under the different loading cases. The elastic limit state of piles for horizontal displacements was taken as 4% of the pile diameter [50]. For both the drained and undrained analysis, the Poulos model was used as it gives a rapid estimation of the displacements by assuming elastic behavior. A Poisson ratio υ of 0.3 [52] and a Young's modulus E of 20MPa were used [16] as the drained parameters. For the undrained analysis, the undrained Poisson ratio υ_u was taken as 0.5 and the undrained Young's modulus E_u was determined using equation 48 [24]. The pile diameter D was chosen as 0.25 meters and the pile spacing is three diameters. The piled foundation therefore consists of a ten by eight pile grid resulting in 80 micro-piles. The calculations were performed for three-meter long piles. As the piles remain within the linear elastic regime, the factors of safety were back-calculated.

$$E_u = \frac{3E}{2(1+\upsilon)} \tag{78}$$

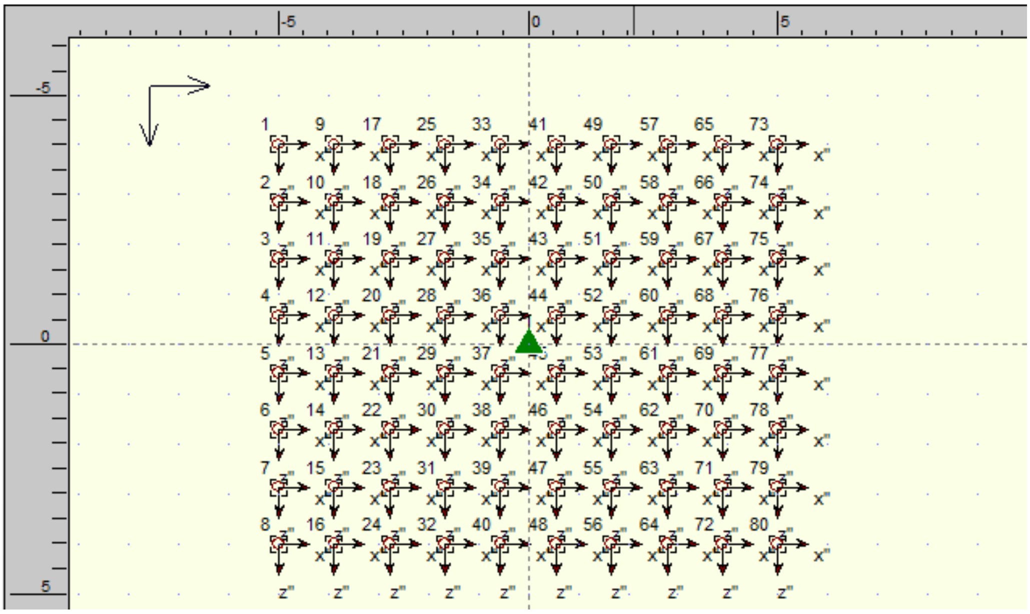


Figure C23. Top view of the micro-piled foundation as modeled in D-pile Group Software.

4.3 Soil parameters and partial factors

For the analysis, the ground water table was taken at ground elevation and the saturated volumetric weight at 19.6 kN/m^3 [23]. As mentioned in section 2.2, the horizontal ground acceleration k_h was taken as 0.4g. For the undrained analysis, the undrained shear strength C_u was taken at the relevant depth of the failure mechanism [36]. The friction angle of the soil was taken as 30 degrees whilst the silty-sand to concrete interface friction angle was taken as 20 degrees and the adhesion factor as 0.8. The partial factors for the soil parameters, failure mechanisms and loads were taken from Eurocode 7 and are shown in Table C24. Note that Eurocode 7 provides ranges of partial factors. Due to the uncertainties in data and assumptions, the most conservative partial factors within these ranges were chosen. The partial factors were used as reduction factors for the cases in which the contribution of the loads, failure mechanism and soil parameters are contributing to the stability and as increasing factors in the opposite case.

Table C24. Partial factors for the loads, failure mechanisms and soil parameters [4].

Parameter	Loads	Bearing capacity	Horizontal capacity	Friction angle ϕ'	Undrained shear strength C_u
Partial factor	1.5	1.4	1.1	1.25	1.4

5. Results and foundation typology recommendations

In this chapter, the outcomes of the calculations are discussed and foundation typologies are advised according to the loading conditions and housing typology.

5.1. Results of the calculations

The results are expressed as factors of safety, i.e. the ratio of the resisting forces to the applied forces, of the horizontal and vertical components for drained versus undrained conditions. A factor of safety below unity means the foundation is unsuited for the considered loading conditions. This analysis was performed considering different number of floors in the house. The considered dimensions for the foundations are the following: a length of 10 meters, a width of 8 meters, a raft thickness of 0.5 meters, a shear-key length of 1 meter, a pile length of 4 meters with 0.25-meter pile diameter and a total of 80 piles using a pile spacing of three diameters.

In Table, the results for normal conditions are given. Note that there is no horizontal factor of safety under normal conditions as the lateral loads during normal conditions (wind) were neglected. The results for severe seismic conditions, tsunami flooding and combined tsunami flooding with a severe aftershock are presented in Table C26, Table C27 and Table C28, respectively.

Under normal conditions, all foundation typologies exceed a factor of safety of unity which is also the case for the undrained conditions although not realistic (instantaneously applying the loads on the soil). Also, the vertical factors of safety decrease as the loads increase, which is to be expected. The results during seismic conditions show that both the lateral and vertical safety factors decrease with increasing vertical load for both drained and undrained conditions, expect for the horizontal capacity of the raft foundation. This is to be expected since the lateral capacity scales with the vertical loads for drained conditions and the horizontal loads scale with k_h (both drained and undrained conditions) for the same vertical bearing capacity. The results however show that a simple raft foundation is not advisable for multiple floored housing.
The factors of safety during the event of a tsunami all exceed unity regardless of the drainage conditions. Also, all factors of safety exceed unity and exceed those during severe seismic conditions which implies that the undrained conditions are to be considered for the project. The tsunami case was considered under several assumptions however, namely that the most critical case is at a maximum flooding depth of 3 meters without any contribution of the remaining cladding and without the contribution of scour or debris loads. The horizontal factors of safety increase with increasing vertical load as this increases the horizontal capacity. On the contrary, the vertical factors of safety decrease with increasing vertical loading as mentioned before, however the vertical factors of safety during a tsunami exceed those during normal conditions because of buoyancy.
During the combined tsunami flooding and seismic loading, several mechanisms take place at the same time such as vertical unloading because of buoyancy, lateral loading due to the water pressure, lateral and vertical seismic loading of the foundation. As a result, there appears to be an optimal housing typology of two floors for the drained conditions for a raft and shear key foundation. This however is not the case considering undrained conditions.

Table C25. Factors of safety in the vertical and horizontal direction for different number of floors during normal conditions.

		Drained Conditions			Undrained conditions		
Direction	**# stories**	**Raft**	**Shear key**	**Micro-piles**	**Raft**	**Shear key**	**Micro-piles**
Vertical	1	13.3	21	26.5	4.3	5.9	5.6
Horizontal	1	-	-	-	-	-	-
Vertical	2	6.8	10.7	13.5	2.2	3	2.9
Horizontal	2	-	-		-	-	-
Vertical	3	4.5	7.1	9.0	1.4	2	1.9
Horizontal	3	-	-		-	-	-

Table C26. Factors of safety in the vertical and horizontal direction for different number of floors during severe seismic conditions.

		Drained Conditions			Undrained conditions		
Direction	**# stories**	**Raft**	**Shear key**	**Micro-piles**	**Raft**	**Shear key**	**Micro-piles**
Vertical	1	4.2	7.7	20.9	3.2	4.0	4.4
Horizontal	1	37	53	5.5	1.7	9.2	6.2
Vertical	2	2.1	3.9	10.7	1.6	2.0	2.2
Horizontal	2	37	45	2.8	0.9	4.6	3.2
Vertical	3	1.4	2.6	7.13	1.1	1.3	1.9

Horizontal	3	37	42	1.9	0.6	3.1	2.1

Table C27. Factors of safety in the vertical and horizontal direction for different number of floors during the event of a tsunami with 3-meter inundation depth.

		Drained Conditions			**Undrained conditions**		
Direction	**# stories**	**Raft**	**Shear key**	**Micro-piles**	**Raft**	**Shear key**	**Micro-piles**
Vertical	1	12.4	21.4	36	5.5	7.6	7.6
Horizontal	1	18.8	33	4.7	1.5	8	5.2
Vertical	2	6.9	11.2	15	2.5	3.4	3.3
Horizontal	2	43	57	4.7	1.5	8	5
Vertical	3	4.6	7.4	9.9	1.6	2.2	2.1
Horizontal	3	68	82	4.7	1.5	8	5.3

Table C28. Factors of safety in the vertical and horizontal direction for different number of floors during the event of a tsunami with 3-meter inundation depth and a severe earthquake aftershock.

		Drained Conditions			**Undrained conditions**		
Direction	**# stories**	**Raft**	**Shear key**	**Micro-piles**	**Raft**	**Shear key**	**Micro-piles**
Vertical	1	0.5	1.6	19.9	2.1	2.6	6.0
Horizontal	1	10	18	2.56	0.8	4.2	2.8
Vertical	2	1.1	2.3	8.6	0.9	1.1	2.6
Horizontal	2	16	21.5	1.7	0.5	2.9	2
Vertical	3	1.0	1.9	5.5	0.6	0.7	1.65
Horizontal	3	19	23.4	1.3	0.4	2.25	1.5

5.2. Foundation typology recommendations

The results show that the drainage conditions for the tsunami flooding scenario are not governing for the design. Since undrained conditions are to be expected during a severe seismic event and combined tsunami and aftershock, undrained the undrained conditions are governing for the outcomes.

Concerning the foundation typology, the results show that a simple raft foundation is only suitable for normal conditions and seismic conditions for a single floored house. This solution is therefore not conceivable in the flooding zone. The raft with additional shear keys is an adequate solution for severe seismic conditions and flooding up to 3 meters for all three housing typologies. It is however not sufficient to resist the combined tsunami and severe aftershock scenario if the house has more than two floors. The use of micro-piles is a suitable solution in all loading cases and for all housing typologies. It is however not an optimized solution for single floored houses.

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