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Procedia Structural Integrity 78 (2026) 899–904

Structural Integrity
Procedia

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XX ANIDIS Conference

Tsunami impact on coastal regions accounting for mitigation strategies

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An increasing number of coastal communities across Italy and the entire globe are exposed to tsunami hazard, also due to climate change. Tsunamis can be triggered by several events such as earthquakes, volcanic eruption and submarine landslides. Previous research conducted on tsunami risk assessment highlighted the absence of specific frameworks able to assess the economic and social loss and to quantify the potential effect of large-scale tsunami mitigation strategies on Italian coastal regions. The present paper summarizes the main objectives of the PRIN (Projects of great national interest) MITICO - MItigation of Tsunami Impact on COastal Regions project, that aims to develop a framework to perform a reliable tsunami risk and loss assessment for Italian coastal communities also accounting for the presence of large-scale mitigation strategies. A state-of-the-art on the effect of mitigation strategies on tsunami loads on structures, the vulnerability of buildings to tsunami and the direct loss analysis will be outlined thought the paper, and advancements will be presented based on the ongoing project research activities.

Keywords: tsunami risk analysis; vulnerability; loss assessment; mitigation strategies

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10.1016/j.prostr.2025.12.115

1. Introduction

Amongst coastal disasters, tsunamis are the most lethal and destructive. European countries in the Mediterranean area are exposed to tsunami hazard and have been hit by such kind of disaster (Lisbon-Portugal 1755, Messina-Italy 1909, Cyclades-Greece 1956, Turkey 2020, among many others). For instance, the Tohoku earthquake and tsunami (2011) resulted in the damage of more than 800,000 buildings, with an estimated direct damage cost of €190 billion, making it the most expensive natural disaster in documented history (Kajitani et al 2013).

Earthquake-triggered tsunamis are one of the most investigated inundation scenarios. In the case of a far-fault tsunami, the effect of the earthquake on the structural performance is almost negligible, and the coastal flooding represents the main source of damage and loss. In the Italian context, the TSUMAPS-NEAM project has estimated the probabilistic tsunami hazard triggered by earthquakes along Italian coasts in terms of maximum inundation depth on the coastline. More recently, several projects have focused on the effects of potentially triggerable offshore seismicity and tsunamis on coastal communities (Antoncecchi et al 2020), confirming the increasing awareness about tsunami risk.

In the case of a disaster, the proper management of funds by stakeholders and public administrations is possible only if an accurate tsunami risk assessment is feasible. A risk assessment process involves the quantification of the natural hazard (i.e., a probabilistic description of the size and recurrence of the event), exposure (i.e., people and assets at risk) and vulnerability (i.e., likelihood of social or economic losses if the people and assets at risk are impacted by an event). Vulnerability can be described as a function of building fragility (i.e., the probability of sustaining structural damage) and a model that converts this damage into loss (i.e., consequence functions). National research projects have also been carried out in Italy, where the Italian Ministry of Economic Development has funded the research projects SPOT and H&ERA Lacinia for estimating the impact of oil & gas platforms on the seismic and tsunami risk in selected spot areas. The research projects SIMIT and SIMIT-THARSY also looked at assessing the tsunami hazard and vulnerability for the Sicily region (Italy). These studies represent the first steps towards a tsunami risk assessment in Italy and highlight the need to define a standardized risk assessment framework specifically targeted to tsunami hazard (Behrens et al 2021).

Preventive mitigation strategies for enhancing coastal community resilience against tsunami risk can reduce economic and social loss (Oetjen et al. 2022). Nature-based (i.e., mangroves, coastal forests or reefs) and engineering-based (i.e., seawalls, tsunami gates) mitigation solutions can act as a buffer against tsunami by reducing water flow velocity and inundation depth. The effectiveness of some mitigation strategies has been observed during past tsunamis, however their effect in terms of tsunami risk and loss reduction for coastal communities has never been assessed quantitatively.

The present paper summarizes the main activities developed in the framework of the PRIN (Projects of great national interest) MITICO - MItigation of Tsunami Impact on COastal Regions project, that aims at developing a framework to perform a reliable tsunami risk and loss assessment for urban coastal communities also accounting for the presence of large-scale mitigation strategies. A state-of-the-art on the effect of mitigation strategies on tsunami loads on structures, on the vulnerability of Italian buildings and on loss analysis is outlined thought the paper, and advancements are presented based on the ongoing project research activities.

2. Effect of large-scale mitigation strategies

Different from the seismic case, the retrofitting of buildings is not always considered as a viable tsunami countermeasure, given the large-scale potential of the coastal inundation. Oetjen et al. (2022) provides a comprehensive state of the art about the typical mitigation strategies for tsunami, identifying hard solutions (i.e., offshore breakwaters, onshore seawalls) and soft solutions (i.e., onshore vegetation belts, offshore mangrove forests). Some of them have shown to be effective during past tsunamis, such as seawalls during the Tohoku earthquake and tsunami (Nateghi et al. 2016). Such artificial structures can be constructed to protect coastal areas from coastal flooding and tsunamis, but as a drawback, they can cause significant environmental problems. On the other side, mangroves and other types of coastal forests and vegetation have increasingly been considered as possible green alternatives to be used instead of, or in conjunction with, artificial structures. Mangrove forests in the inter-tidal wetlands can provide protection against wave impact and erosion, or could be used as breakwaters (Risheharan et al. 2025).

Several hydraulic studies have been conducted so far to quantitatively assess the effects of such typical mitigation strategies on buildings in terms of force or pressure reduction (Rahman et al. 2014, Van Dang et al 2023, Khoirunnisa, et al 2024, Chen et al 2024, Van Dang et al 2025, Udarika et al. 2025). However, such findings have never been incorporated into generalised methods to be included in tsunami risk assessment frameworks.

In the framework of the MITICO project, a different tsunami mitigation strategy is considered, consisting of artificial offshore buffers placed in the tidal zone to amplify the roughness of the bathymetry. Such kind of solution has proven to reduce the run-up of waves (Goseberg et al 2013). To provide further knowledge on the effectiveness of such mitigation strategies, original experimental data are produced in MITICO on the effects of such solution of forces and pressures measured on buildings. Such findings will feed analytical models to account for mitigation strategies in the hazard reduction on coastal areas.

3. Vulnerability of buildings to tsunami

Vulnerability models for buildings are of paramount importance for risk and loss analysis at urban scale. Several studies so far have investigated the vulnerability of structures to tsunami, both based on empirical observations after major events or on numerical simulations. After past tsunamis (Indian Ocean 2004, Great East Japan 2011), sets of empirical tsunami fragility functions have been developed based on observed damage on buildings (Reese et al. 2011, Charvet et al. 2014, Suppasri et al. 2015, Mas et al. 2020, among others). Analytical fragility functions for single buildings such as reinforced concrete (RC) frames (Petrone et al. 2016, Medina et al. 2019, Del Zoppo et al. 2023, Waenpracha et al. 2023, Harati and van de Lindt 2024) or steel warehouses (Karafagka et al. 2018) have been proposed so far.

In the Italian context, large-scale tsunami fragility functions for Italian masonry buildings are proposed in Belliazzi et al. 2021 and Ferrotto and Cavaleri 2021, while Del Zoppo et al. 2025 have proposed time-dependent fragility functions for Italian RC building classes, as shown in Figure 1a. In particular, six building classes are identified, based on the construction period (before or after 1980), design concept (gravity loads or seismic) and number of stories (low-rise and mid-rise), considering the actual distribution of existing residential buildings according to ISTAT data. In accordance with the EMS-98 damage scale, five dagame levels are identified, out of which two (DS1 and DS2) mainly focus on damage to non-structural components and three (DS3 to DS5) to structural damage up to collapse. Such fragility models specifically account for the characteristics and properties of Italian constructions and can represent a valuable tool for the tsunami risk assessment at urban scale.

However, a limitation of such analytical vulnerability models with respect to empirical models is represented by the lack of proper validation on experimental results. To fill this gap, component-level fragility functions subject to tsunami loading are derived in the context of the MITICO project and validated over original experimental data and advanced numerical modelling. Such improved fragility functions provide more reliable estimations of the damage to buildings during a coastal inundation and will serve to the loss assessment methodology described in the next section.

4. Direct loss analysis

Evaluating economic losses provides a quantitative basis for emergency planning and policy-making in tsunami hazard zone. Direct loss estimation models rely on the evaluation of repair costs - absolute or relative to reconstruction costs – based on empirical data from previous events or on simulated cost analyses. In the case of tsunami economic consequences estimation, only the FEMA has developed a loss model so far for the US context. In the FEMA HAZUS 5.1 model, tsunami damage is categorized either as flood damage, based solely on inundation depth, or as flow damage, which includes also lateral hydrodynamic forces. The model defines a set of damage states (i.e., moderate, extensive, and complete), with associated economic loss ratios ranging from 5% to 100% of the replacement cost. These include structural and non-structural repair costs, as well as losses to building contents. Loss ratios are expressed as percentages of the building or contents replacement value and vary by occupancy type, such as residential, commercial, or industrial. The HAZUS loss model identifies 36 building types, many of them most commonly used in the US, along with their respective height ranges and typical heights. For example, for residential single-family dwelling, structural repair costs range from 0.5% to 23.4%, while non-structural repairs span from 1.5% to 76.6%. Contents losses reach up to 100% in the most severe damage states.

Given the lack of specific data for the Italian context, a new method for tsunami loss estimation has been developed (Zucconi et al. 2025). The method takes advantage of the extensive literature on repair costs for seismic damage available for Italian building stock, that has been collected over years (Del Vecchio et al. 2020). By associating the tsunami damage classification recently proposed by Del Zoppo et al. (2025) to the seismic damage states defined in EMS-98 and derived from AeDES (Level 1 Form for Post-Earthquake Damage and Usability Assessment and Emergency Countermeasures in Ordinary Buildings) observations, new consequence functions can be derived for tsunami damage on Italian buildings based on a reliable cost quantification. An application of the method is reported in Figure 1b, where statistics of repair costs ratios have been derived for the collapse of masonry infill walls (DS2 according to Del Zoppo et al. 2025) as a function of the building height. Such kind of analysis, conducted for all tsunami damage levels, can lead to a first proposal of consequence functions for tsunami loss estimation in Italy.

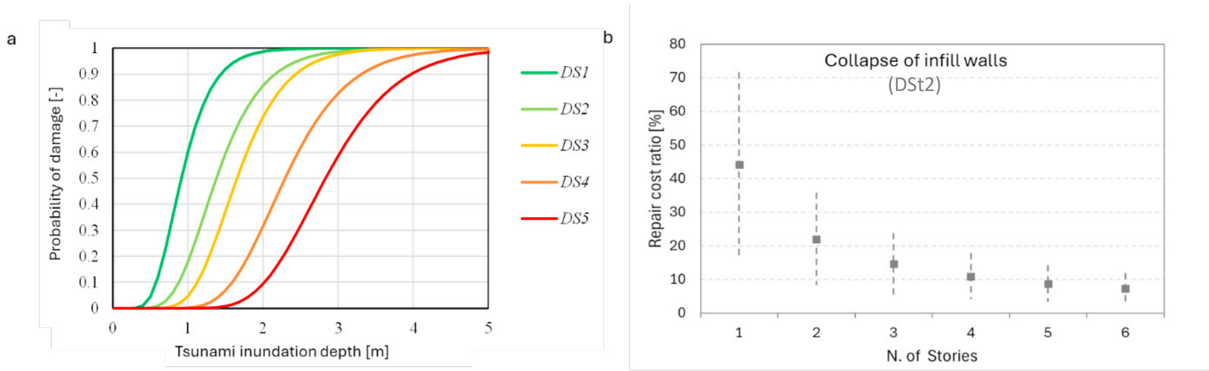

Fig. 1. (a) fragility functions for a class of RC buildings; (b) statistics of repair cost ratio (Cr%) for the collapse of masonry infill walls.

5. Conclusions

Given the rising awareness about tsunami and coastal flooding risk on Italian coasts, several efforts have been put over the last years to develop tsunami risk assessment frameworks. In the Italian context, where empirical data from past events are not available, analytical tools are needed to quantify tsunami risk and loss associated to a coastal inundation. Furthermore, the effects of large mitigation strategies such as the enhancement of bathymetry roughness have never been properly incorporated into tsunami hazard and risk assessment framework.

In this context, the MITICO project promotes advances in the field aiming at the following results:

- Develop a model for the estimation of tsunami hazard maps in presence of large-scale mitigation strategies, in the form of reduced inundation depths and flow velocities;
- Derive component-level fragility function, validated over original experimental results on large-scale structural and non-structural components;
- Produce economic consequence functions validated over Italian empirical data from seismic reconstruction costs to compute the expected direct losses in the aftermath of a tsunami.

Future works will present in detail the results of the project, along with future perspective to improve the tsunami risk assessment for Italian coastal communities.

Acknowledgements

The authors acknowledge the financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title 2022YBAXTY - MITICO, MItigation of Tsunami Impact on COastal Regions – CUP MASTER: E53D23003910006, CUP E53D23003910006, CUP: F53D23002050008 - Grant Assignment Decree No. PE8 prot.961. adopted on 30-06-2023 by the Italian Ministry of Ministry of University and Research (MUR).

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