Multi-Hazard Resilience Assessment of a Coastal Community Due to Offshore Earthquakes

Multi-hazard resilience assessment of a coastal community due to offshore earthquakes

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Abstract. It has been observed in different parts of the world that offshore earthquakes occurred in coastal regions were followed by tsunamis and catastrophic damages due to cascading effects. In this paper, an innovative methodology for the estimation of direct damage losses and resilience for a given community is presented. It combines two existent methodologies, including both earthquake and tsunami hazards. In detail, fragility functions related to earthquake intensity, ground failure and tsunami inundation are combined with regional hazard data to estimate damages and direct economic losses of buildings and bridges. The coastal city of Seaside in Oregon has been used as case study as one of the most vulnerable town in the Pacific North United States due to the proximity of a nearfield Cascadia Subduction Zone. The results indicate that, when the earthquake and the subsequent tsunami inundation are considered together, there is an overwhelming increase in the loss estimates in comparison to the case when the tsunami is separately considered.

Keywords: Bridge; Building; Damage; Earthquake; Tsunami.

1. INTRODUCTION

Recent catastrophic events such as the Tohoku Earthquake in Japan (2011) have raised the global awareness for the urgent need to understand the response of the built environment to multidimensional hazards. In the past years, several earthquakes such as the Indian Ocean (2004), Samoa (2009), Chile (2010) and Japan (2011) have caused catastrophic damages to coastal communities and infrastructures due to the earthquake and tsunami coupled effects. The increasing hazard on the coastal areas is also coping with an increasing exposure. Indeed, a large part of the world population reside near the coast for their livelihood [1] due to the favorable conditions for economic activities, living and trade. It increased from 0.4 billion (26% of total population) in 1900 to 1.9 billion (28%) in 2010 with a tendency of over 2.4 billion people (26%) in 2050 [2]. US faces a similar multi-hazard threat from the Cascadia Subduction Zone (CSZ), a fault that runs from Northern California to British Columbia, close to the shore (less than 160 km in most places).

Coastal Community Resilience (CCR) is defined as the capacity by which a community can adapt to and influence the environmental course, social, and economic change [3]. CCR can raise awareness and improve capabilities against coastal hazards through adaptive preparedness and mitigation measures. There are eight fundamental elements of CCR that affect its response to coastal hazards, presented in Figure 1. To develop mitigation strategies for existing structures against earthquake and tsunami coupled effects, and to activating lifesaving based strategies, a reliable performance-based engineering assessment is required [4].

This paper deals with a methodology for the estimation of community losses and resilience [6] for the city of Seaside in Oregon when multiple hazards, such as earthquakes and tsunami, are considered.

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Figure 1. Elements of coastal community resilience.

2. LITERATURE REVIEW

The conclusions of the 2005 International Convention on Disaster Reduction in Kobe revealed the key role of the Resilience terminology into the catastrophe subject and a new culture of disaster response was born. Manyena defined the resilience as the "fundamental ability of a system in which community susceptible to a shock or stress to conform and survive by way of converting its non-essential features and rebuilding itself"[5].

In the past few years, the requirement of resilient communities response when exposed to disasters has gained global recognition and, consequently, new methods have been anticipated to further quantify resilience beyond estimating losses [6,7]. Bruneau et al. [8] proposed a wide resilience definition to cover all actions that reduce losses from hazards, including of effects of mitigation and fast recovery.

A comprehensive conceptual recovery model by Miles and Chang [9] established the relationships among a community's lifeline networks, domestic business and neighborhoods. They developed some fundamental community recovery models for earthquakes as important support tools in decision-making strategies to enhance community resilience.

A model proposed by Davidson and Cagnan [10] explained the economic impact and the restoration process for post-earthquake damage to lifeline structures. This study is part of the MCEER research on Los Angeles Department of Water and Power's (LADWP's) electric and water supply systems.

Chang and Shinozuka [11] discussed a quantitative measure of resilience based on the case study of the Memphis water system. Their study proposed resilience measures that relate expected losses in future disasters to a community's seismic performance objectives. They demonstrated that the resilience framework can be valuable for guiding mitigation and preparedness efforts.

Cimellaro et al. [12], attempted to formulate the first framework to quantify resilience, however only uncertainties related to the intensity measure were considered. Whereas, in the framework described in this work, a more comprehensive approach is proposed including a variety of circumstances and conditions.

Focusing on tsunami disasters, Miyano and Lu [13] conducted one of the first attempts to estimate the human lives losses. Then, Kawata [14] proposed a relation between the death rate and the height of the tsunami wave. This study was based on historical tsunami data from Japan. Shizuoka Prefecture [15] developed a similar method as Miyano and Lu including also population data as evaluation parameter. Jaiswal et al. [16] described the development of various models and demonstrated their loss estimation capability for earthquakes that occurred since 2007.

The Central Disaster Prevention Council in Japan [17] was the first organization to cross-reference the tsunami inundation area against population data to determine the possible loss of human lives. Sugimoto et al. [18] presented a method to determine loss of life following a tsunami using numerical calculations and GIS coordinates for the Nankai tsunami in Japan.

After the 2004 tsunami, Koshimura and Takashima [19] developed a GIS-based model to estimate the number of exposed populations that were at risk from a tsunami disaster, known as the *Potential Tsunami Exposure* (PTE). This model estimated the potential tsunami exposure within the Indian Ocean. Koshimura et al. [20] have also developed a method for estimating the number of casualties that might occur while people evacuate from an inundation zone due to tsunami.

Khomarudin et al. [21] proposed an estimation of the population that is at risk due to tsunami inundation, which was based on various land-use patterns. Koshimura et al. [22] developed a fragility curve for tsunami casualties using tsunami inundation simulations and casualty reports from the 2004 tsunami in Banda Aceh, Indonesia. Shishido and Imamura [23] used this fragility function to evaluate the potential human loss following a tsunami in Japan. This model included adjustment parameters that were obtained from field surveys.

Focusing on the coupled effects of earthquake and tsunami on coastal communities, few works can be found in literature. Raskin and Wang [24] discussed fifty-years resilience strategies for the Oregon's coastal communities at the regulatory and policy level. Three scenarios were presented: maintaining the current conditions (low post-disaster recovery), limited resilience, high resilience. Bonacho and Oliveira [25] proposed a way of combining earthquake shaking damages with tsunami damages through an additive function of selected fragility curves that are computed by a home developed software (earthquake hazard) and collected from published literature (tsunami fragility curves). However, they did not perform the fragility functions combination, neither propose a reasonable methodology that can be applied to coastal communities. Goda and De Risi [26] presented a probabilistic multi-hazard loss methodology for coastal communities to represent spatially correlated hazard values. However, the coastal community resilience with respect to both earthquake and tsunami hazards still needs to be developed.

In this paper a way to estimate community losses and resilience due to multiple hazards has been proposed. It considers both the earthquake and tsunami effects. Two existing methodologies are originally integrated: the HAZUS [27,28] procedure is used for assessing direct losses and damages on buildings and infrastructures. Moreover, the community disaster resilience is evaluated through the MCEER framework [6]. Finally, the case study of Seaside city in Oregon is used to show the implementation of the procedure and to discuss the essential outcomes.

3. METHODOLOGY

Losses due to earthquake and tsunami hazards can be of two types: direct and indirect. Direct losses are straightly quantifiable losses such as the number of people killed and damaged buildings, infrastructure and affected natural resources. Indirect losses include decays in output or revenue, and impact on people welfare, and generally arise from flow disruptions of goods and services. In detail, disasters may produce dislocations in economic sectors not sustaining direct damage. Indeed, all businesses are forward-linked (rely on regional customers to purchase their output) and backward-linked (rely on regional suppliers to provide their inputs). Therefore, due to their interconnection, all productions are potentially vulnerable to interruptions in their operation. Such interruptions belong to the indirect economic losses.

In this section, the procedure to estimate earthquake and tsunami direct losses to buildings and bridges is reported. Furthermore, the estimation of casualties due to such disastrous events is also described with the direct economic losses assessment as well. The methodology has been adopted with reference to HAZUS Methodology [27,28], specifically designed to produce loss estimates for nearly all aspects of the built environment due to earthquakes and related effects (e.g. tsunami). The last step of the methodology is focused on the community resilience assessment [6]. The flowchart in Figure 2 illustrates the framework in a sequence of steps.

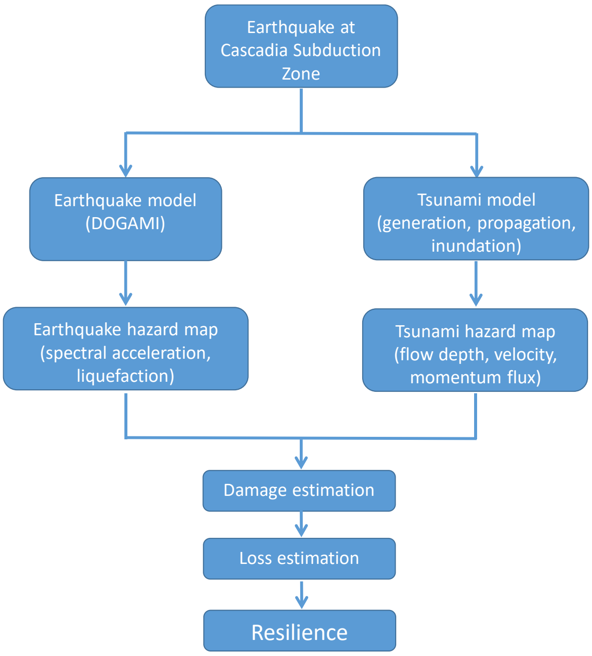

Figure 2. Framework for developing physics-based multi-hazard earthquake and tsunami fragility analysis.

3.1 Earthquake damage to Bridges and Buildings

Bridges failures usually result in significant disruption to the transportation network, particularly bridges that cross waterways. Past earthquake damages reveal that bridges are vulnerable to both ground shaking and ground failure.

Fragility curves for highway bridges are modeled as lognormal-distributed functions that give the probability of reaching, or exceeding, different damage states for a given level of ground motion or ground failure. Each fragility curve is characterized by a median value of ground motion or ground failure and an associated dispersion factor (lognormal standard deviation). Ground motion is quantified in terms of peak ground acceleration (*PGA*) and spectral acceleration (S_a). Ground failure is quantified in terms of permanent ground displacement (*PGD*).

Bridges are classified based on the seismic design, the number of spans, the material, the pier type, etc. This classification scheme incorporates various parameters that allow estimating damage through fragility analyses. Twenty-eight classes (HWB1 through HWB28) are defined in this way reflecting the maximum number of combinations for 'standard' bridge classes. For each class a parameter (K_{3D}) can be evaluated that modifies the piers' 2-dimensional capacity to allow for the 3-dimensional arch action in the deck. Furthermore, a Boolean indicator (I_s) is also associated to each class for converting cases for short periods to an equivalent spectral amplitude at T=1.0 second. Attributes such as the bridge skewness and number of bridge spans are accounted for in the evaluation of potential damage through a modification scheme [27].

Five damage states are defined for highway bridges as shown in Table 1. These are *None* (ds_1), *Slight/minor* (ds_2), *Moderate* (ds_3), *Extensive* (ds_4) and *Complete* (ds_5). Twenty-eight primary bridge types and the corresponding five damage states are identified with the corresponding fragility curves. For the secondary bridge types, fragility curves of the 28 primary bridge types are modified to reflect the expected performance of the specific bridge [27].

Table 1. Damage states for bridges.

Damage state	**Characteristics**
None (ds_1)	-
Slight/minor (ds_2)	Minor cracking and spalling to the abutment, cracks in shear keys at abutments, minor spalling and cracks at hinges, minor spalling at the column (damage requires no more than cosmetic repair) or minor cracking to the deck.
Moderate (ds_3)	Any column experiencing moderate (shear cracks) cracking and spalling (column structurally still sound), moderate movement of the abutment, extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure or moderate settlement of the approach.
Extensive (ds_4)	Any column degrading without collapse - shear failure - (column structurally unsafe), significant residual movement at connections, or major settlement approach, vertical o set of the abutment, differential settlement at connections, shear key failure at abutments.

Complete (ds_5)	Any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.

So, globally 224 bridge fragility functions are defined, 112 due to ground shaking and 112 due to ground failure. A complete description of the theoretical background can be found in [29]. Only incipient unseating and collapse (*extensive* and *complete* damage states respectively) are considered as possible types of damage associated to ground failure. Therefore, the initial damage to bearings (*slight* or *moderate* damage) from ground failure is not considered. The damage algorithm for bridges consists of eight steps [27] that are summarized as follow:

- Step 1: bridge location coordinates, class (HWB1-HWB28) and characteristics (skew angle, spans, length, etc.) are collected;
- Step 2: shaking characteristics at the bridge site are evaluated (PGA, S_a, PGD);
- Step 3: modification factors (e.g. K_{3D}) are computed;
- Step 4: ground shaking characteristics for the fragility curves are eventually modified accordingly with the Boolean indicator I_s associated to the bridge class;
- Step 5: evaluation of the ground shaking-related damage state probabilities;
- Step 6: PGD characteristics for the fragility curves are modified accordingly with modification factors as function of the bridge characteristics (skew angle, spans, length, etc.);
- Step 7: Probability of ground failure-related damage state is computed;
- Step 8: the damage state probabilities are combined and then the bridge functionality is evaluated.

Considering the building damage and loss functions, the main components of the HAZUS earthquake building damage assessment consist in the capacity and fragility curves. The first ones are defined through engineering parameters that drive the nonlinear structural response (pushover) of different model buildings. Besides, the fragility curves identify the damage of a model building: (i) structural system; (ii) nonstructural components sensitive to drift; (iii) nonstructural components; (iv) contents sensitive to acceleration. As used for bridge structures, fragility curves characterize damages between four physical states: slight, moderate, extensive, and complete.

Buildings are by HAZUS classified in terms of their use and structural system. Besides, damage is predicted based on model building type, since the structural system is considered the key factor in assessing overall building performance. Occupancy class (Residential, Commercial, Education, Industrial) is also important in determining economic loss due to the building value is function of its use. E.g. hospitals have higher value with respect to commercial buildings due to their expensive equipment and contents rather than their structural system.

3.2 Loss of functionality in residential buildings due to earthquakes

Loss of function or habitability of buildings due to earthquakes can cause a predictable numbers of displaced households. Family, friends, relief organizations, etc. could provide alternative short-term shelter supporting the emergency response organization. However, when the repair phase lasts longer, alternative long-term housing has to be provided by local governments.

The loss of functionality for residential buildings is estimated using two parameters: (i) the number of displaced households (due to loss of habitability) and (ii) the number of people requiring short-term shelter only. These parameters are estimated from experience on past disasters.

The first parameter (*loss of habitability*) is estimated from the damage to the residential occupancy inventory and from the loss of water and power. The total number of uninhabitable dwelling units are determined using as input the census data [27], while the total number of displaced households are derived by the corresponding occupancy rate for each building.

The second parameter describes the total number of displaced persons looking for public short-term shelter, considering that part of them will stay with friends and relatives. The input data of this parameter is obtained by default census data and displaced households' calculation of previous step.

3.3 Damage in buildings and bridges caused by Tsunami

The probability of damage for general building stock (i.e. buildings of a given area from census) due to tsunami inundation is described in [28]. The damages are described using the same generic limit states of the Earthquake Model to permit direct combination of damage states probabilities due to tsunami with those due to earthquake. Moreover, same types of building damages can occur due to either tsunami flood hazard or tsunami flow hazard. Tsunami damage assessment on buildings consider structural and nonstructural components, content, building type and tsunami flood or tsunami flow. Damage to the structural system is assumed to be governed exclusively by tsunami flow. Damage to nonstructural systems and content (in structures that survive) are assumed to be governed solely by tsunami flood hazard (water depth as function of maximum inundation). Of course, nonstructural systems and contents are also damaged by tsunami flow, but such damage is assumed to be adequately captured by damage due to inundation. Nonstructural systems and content in fully inundated areas are considered 100% damaged. The structure is considered undamaged until lateral forces due to hydrodynamic loads, including the effects of debris impact, exceed the yield-force capacity of the structural system. Structure damage increases with tsunami force until tsunami flow and debris forces exceed the ultimate-lateral-force capacity of the system. The hydrodynamic loads can also cause localized damage to structural elements, e.g. out-of-plane failure of walls, which could lead to progressive collapse of the building. Tsunami flow can also compromise the foundation by erosion. The quantification of building damage due to failure of individual structural elements, e.g. progressive collapse, would require detailed structural information and analyses, usually not available on a large scale.

The HAZUS damage model applied for buildings can be consistently used also for bridges, considering also the different static schemes characterizing them. Furthermore, non-structural components in bridges are different and of limited impact, if compared to the buildings case [28].

3.4 Direct physical damages combination

According to HAZUS Methodology [27], direct damages in buildings and bridges caused by tsunami are combined with earthquake damages assuming that the damage states are statistically independent. Furthermore, the following heuristic, rules for damage combination have been adopted [30]:

- Extensive damage due to tsunami occurring to a building and a bridge that already has extensive damage due to earthquake would result in complete damage to the building and bridge. This concept applies to structures, as well as nonstructural and contents damage states.
- Moderate damage due to tsunami occurring to a building and a bridge that already has Moderate damage due to earthquake would result in Extensive damage to the building and bridge. This concept applies to structures, as well as nonstructural and contents damage states.
- Nonstructural systems and content are completely damaged in a building that sustains complete damage to the structural system. This concept applies to all nonstructural and contents damage states.

Formulas for computing combined probabilities of damage to the structure (STR) due to earthquake and tsunami (*EQ*+*TS*) hazards are given by Equations (1-3) for Complete (C_{STR}), Extensive (E_{STR}) and Moderate (M_{STR}) structure damage states:

$$\begin{aligned}\mathrm{P}[C_{STR}\,|\,\mathrm{EQ+TS}] = {} & \mathrm{P}[\mathrm{C}_{STR}\,|\,\mathrm{EQ}] + \mathrm{P}[\mathrm{C}_{STR}\,|\,\mathrm{TS}] - \mathrm{P}[\mathrm{C}_{STR}\,|\,\mathrm{EQ}]\mathrm{P}[\mathrm{C}_{STR}\,|\,\mathrm{TS}] + \\ & (\mathrm{P}[\geq \mathrm{E}_{STR}\,|\,\mathrm{EQ}] - \mathrm{P}[\geq C_{STR}\,|\,\mathrm{EQ}])(\mathrm{P}[\geq \mathrm{E}_{STR}\,|\,\mathrm{TS}] - \mathrm{P}[\geq C_{STR}\,|\,\mathrm{TS}])\end{aligned} \tag{1}$$

$$\begin{aligned}\mathrm{P}[\mathrm{E}_{STR}\,|\,\mathrm{EQ+TS}] = {} & \mathrm{P}[\mathrm{E}_{STR}\,|\,\mathrm{EQ}] + \mathrm{P}[\mathrm{E}_{STR}\,|\,\mathrm{TS}] - \mathrm{P}[\mathrm{E}_{STR}\,|\,\mathrm{EQ}]\mathrm{P}[\mathrm{E}_{STR}\,|\,\mathrm{TS}] + \\ & (\mathrm{P}[\geq \mathrm{M}_{STR}\,|\,\mathrm{EQ}] - \mathrm{P}[\geq \mathrm{E}_{STR}\,|\,\mathrm{EQ}])(\mathrm{P}[\geq \mathrm{M}_{STR}\,|\,\mathrm{TS}] - \mathrm{P}[\geq \mathrm{E}_{STR}\,|\,\mathrm{TS}])\end{aligned} \tag{2}$$

$$\mathrm{P}[\mathrm{M}_{STR}\,|\,\mathrm{EQM+TS}] = \mathrm{P}[\mathrm{M}_{STR}\,|\,\mathrm{EQ}] + \mathrm{P}[\mathrm{M}_{STR}\,|\,\mathrm{TS}] - \mathrm{P}[\mathrm{M}_{STR}\,|\,\mathrm{EQ}]\,\mathrm{P}[\mathrm{M}_{STR}\,|\,\mathrm{TS}] \tag{3}$$

This approach has been also followed for combining probabilities of damage to nonstructural systems and building contents.

3.5 Direct social losses - casualties

3.5.1 Earthquake

Casualties' estimation caused by earthquakes is developed in this section following the approach proposed in HAZUS [27] that is based on the assumption that a strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties exists. In particular, when smaller earthquakes are considered, nonstructural damage most likely controls the casualty estimates. On the contrary, in severe earthquakes, with a large number of collapses and partial collapses, a proportional larger number of fatalities is expected.

The estimate of the expected number of killed occupants ($EN_{occupantskilled}$) is the product of the number of occupants of the building at the time of the earthquake ($N_{occupants}$) and the probability of an occupant being killed (P_{killed}).

$$\mathrm{EN}_{occupants\ killed} = \mathrm{N}_{occupants} \cdot \mathrm{P}_{killed} \tag{4}$$

The method excludes casualties caused by heart attacks, car accidents, and incidents during post-earthquake rescue, tsunami, fault rupture, dam failures, fires, etc. Furthermore, psychological impacts of the earthquake on the exposed population are not modeled.

Four severity levels of injuries are calculated at the census tract level and they are aggregated in the study region. They are: (i) *Severity 1 - Injuries requiring basic medical aid*, (ii) *Severity 2 - Injuries requiring a higher medical care and the use of medical technology such as x-rays or surgery without life threatening*, (iii) *Severity 3 - immediate life threatening*, (iv) *Severity 4 - instantly killed or mortally injured*. The selected four-level injury scale is a compromise between the demands of the medical community in order to response plan and the estimation ability of the engineers.

The methodology provides the information necessary to produce casualty estimates with respect to the *time in the day* (2.00 am nighttime, 2.00 pm daytime, 5.00 pm commuting time). These scenarios are expected to generate the highest casualties for the population at home, the population at work/school and the population during rush hour, respectively. The default population distribution is calculated for each census tract population (residential, educational, industrial, etc.). The population distribution is inferred from census data and, therefore, it presents an associated inherent error.

In this methodology, the only roadway casualties are those from bridges damage or collapse. This requires the user to estimate the number of people located on bridges during the seismic event. The methodology provides for a user- defined Commuter Distribution Factor (*CDF*) that corresponds to the percentage of the commuting population located on bridges. The estimate is then computed as follows:

$$\mathrm{NBRDG} = \mathrm{CDF} \cdot \mathit{Commuter\ Population} \tag{5}$$

where *NBRDG* is the number of people on bridges in the census tract. The value of *CDF* is assumed 0.01 during the day and night and 0.02 for the commuting time. This value is fixed assuming an overpass every two miles for a typical major urban freeway or highway.

The model also considers the number of casualties that occur outside buildings due to falling debris. Indeed, outside but close to buildings, the people could be hurt by structural or non-structural elements falling from the buildings (e.g. roofs). The model estimates also casualties to people either on bridges that experience complete damage, both simplest common bridges (e.g. single span) and major ones.

3.5.2 Tsunami

Hazus methodology [28] provides estimates of the number of casualties $N_j\ R_{casualty}$ caused by tsunami for a given population block *j*. Then, the tsunami number of fatalities NF_j and injuries NI_j are given by

$$\mathrm{NF}_j = \mathrm{N}_j \cdot \left(0.99R_{fatality} + \frac{1}{2}(R_{casualty} - 0.99R_{fatality})\right) \tag{6}$$

$$\mathrm{NI}_j = \frac{1}{2}\mathrm{N}_j \cdot (R_{casualty} - 0.99R_{fatality}) = \mathrm{N}_j \cdot R_{casualty} - \mathrm{NF}_j \tag{7}$$

where N_j is the number of people in the population block corrected by casualties induced by the earthquake. Thus, total fatalities and injuries for the community are $\Sigma_j NF_j$ and $\Sigma_j NI_j$, respectively.

Casualties caused by tsunami are computed considering the *evacuation travel time* that corresponds to the time needed to reach a safe higher soil level. This information is used to identify tsunami-risk areas for coastal communities. The evacuation travel time does not take into account the tsunami arrival time and the timing of the tsunami warnings, so this information is used to determine potential casualties. The model considered in this analysis considers only pedestrian evacuation. Furthermore, the possibility to evacuate tall and tsunami-resistant buildings is not considered. The community is divided in population blocks with similar evacuation conditions. For a given tsunami event some data are required for casualty-rate assessment such as the map elevation, the population in each block that depends on the season and the time of the day, the vulnerability of people (i.e. age and gender) that affects the evacuation and is included through the *evacuation walking speeds*. The crucial parameter to be determined is the *critical time* that represents the time difference between the evacuation time and the available time to evacuate, but of course, the promptness of tsunami warnings is also crucial.

3.6 Direct economic losses and recovery

HAZUS [27,28] allows also the estimation of damage losses and the restoration time for both earthquake and tsunami hazards. The damage losses are given by

$$\mathrm{E[Loss]} = \sum_{i=1}^{N} Loss_i = \sum_{i=1}^{N} RMV_i (\alpha_i^{SD} \mu_{D_i}^{SD} + \alpha_i^{NA} \mu_{D_i}^{NA} + \alpha_i^{ND} \mu_{D_i}^{ND} + \alpha_i^{CL} \mu_{D_i}^{CL}) \tag{8}$$

where RVM_i is the real market value of the i-th building inventory item, α_i^{SD}, α_i^{NA}, α_i^{ND} are the fractions of the real market values of structural and non-structural (drift-sensitive and acceleration-sensitive) components, α_i^{CL} is the ratio of the contents value to the real market value and $\mu_{D_i}^{SD}$, $\mu_{D_i}^{NA}$, $\mu_{D_i}^{ND}$, $\mu_{D_i}^{CL}$ are the mean damage factors. Therefore, the assessment structural and nonstructural repair costs is also provided. Restoration time includes physical restoration of the buildings' damage, as well as clean-up, inspections and delays due to contractor availability. The restoration of earthquake and flood damage differs in a variety of ways, including:

- Damage due to flooding is likely to be widespread throughout the inundated area while earthquakes cause differing degrees of damage to structures located within the same area.
- In an earthquake, inventory that does not break can be picked up and sold. Flooded-damaged inventory is usually a total loss.
- An earthquake-damaged business may be able to re-open quickly with undamaged inventory in a new location (e.g., alternate space, parking lot) in parallel with clean up. A flood damaged business is less likely to re-open during clean up, in particular, re-opening may depend on resupply of inventory.

Because flood damage is fundamentally different from the earthquake damage, a flood-specific restoration time model has been developed. The repair time differs for similar damage states depending on building occupancy: thus, simpler and smaller buildings will take less time to repair than more complex or larger buildings. It has also been noted that large well-financed corporations can sometimes accelerate the repair time compared to the normal construction procedures.

For some businesses, building repair time is largely irrelevant, because these businesses can rent alternative space or use spare industrial/commercial capacity elsewhere. For none and slight damage the time loss is assumed to be short, with cleanup by staff, and work can resume while slight repairs are done.

It is assumed that hospitals and medical offices can continue operating, perhaps with some temporary rearrangement and departmental relocation if necessary, after moderate damage, but with extensive damage their loss of function time is also assumed to be equal to the total time for repair.

3.7 Resilience

The loss assessment methodology for coastal communities affected by multi-hazard conditions is integrated within a resilience framework. As reported in [6], disaster resilient community can withstand an extreme event, natural or manmade, with a tolerable level of losses, and is able to take mitigation actions consistent with achieving that level of protection. Resilience (*R*) is defined as a function indicating the capability to sustain a level of functionality or performance of a given building, bridge, lifeline networks, or community, over a period defined as the control time T_{LC} that is usually decided by owners, or society (usually is the life cycle, life span of the system etc.). The time T_{LC} includes the building recovery time, T_{RE} and the business interruption time that is usually smaller compared to the other one. The recovery time T_{RE} is the time necessary to restore the functionality of a community or a critical infrastructure system (water supply, electric power, hospital etc.) to a desired level below, same or better than the original, allowing proper operation of the system. The recovery time T_{RE} is a random variable with high uncertainties. It typically depends on the tsunami/earthquake intensities the type of area considered, the availability of resources such as capital, materials and labor following major seismic event. For these reasons, this is the most difficult quantity to predict in the resilience function.

3.7.1 Formulation

The resilience definition provided by Bruneau et al. [8] has been adopted in this work, which has been clarified and extended in Cimellaro et al. [6]. Analytically, Resilience is defined as:

$$R = \int_{t_{0E}}^{t_{0E}+T_{LC}} \frac{Q(t)}{T_{LC}} dt \tag{9}$$

where:

$$Q(t) = [1 - L(I, T_{RE})][H(t - t_{0E}) - H(t - (t_{0E} + T_{RE}))] \cdot f_{\mathrm{Re}c}(t, t_{0E}, T_{RE}) \tag{10}$$

where $L(I,T_{RE})$ is the loss function; $f_{Rec}(t,t_{0E}, T_{RE})$ is the recovery function; $H()$ is the Heaviside step function, T_{LC} is the control time of the system, T_{RE} is the recovery time from event E and; t_{0E} is the time of occurrence of event E.

In Multidisciplinary Center for Earthquake Engineering Research's (MCEER) terminology, the seismic performance of the system is measured through a unique decision variable (*DV*) defined as 'Resilience' that combines other variables (economic losses, casualties, recovery time, etc.), which are usually employed to judge seismic performance [1,4]. Resilience is defined graphically as the normalized area underneath the performance function of a system defined as *Q(t)*. *Q(t)* is a non-stationary stochastic process and each ensemble is a piecewise continuous function, where the functionality *Q(t)* is measured as a dimensionless (percentage) function of time. The recovery time T_{RE} and the recovery path are essential for evaluating resilience, so they should be estimated accurately. Most common loss models, such as HAZUS evaluate the recovery time in crude terms and assume that within one year, everything returns to normal.

However, the resilient system may not necessary return to the pre-disaster baseline performance. It may exceed the initial performance when the system (e.g. community, essential facility, etc.) may use the opportunity to fix pre-existing problems inside the system itself. On the other hand, the system may suffer permanent losses and equilibrate below the pre-disaster performance.

3.7.2 Loss function

Tsunami losses are by their very nature highly uncertain, and are different for every specific scenario considered. However, some common parameters affecting these losses can be identified. The loss function $L(I, T_{RE})$, that consists of the direct casualties losses L_{DC} and the direct economic losses L_{DE}, can be calculated by:

$$\mathrm{L}(\mathrm{I}, \mathrm{T}_{RE}) = \mathrm{L}_{DE}^{\alpha_{DE}} \cdot (1 + \alpha_{DE}\, \mathrm{L}_{DC}) \tag{11}$$

where α_{DE} is a weighting factor related to construction economic terms and α_{DC} is the weighting factor related to the nature of occupancy. These weighting factors are determined based on socio-political criteria.

3.7.1 Simplified Recovery Function Models

Most of the models available in the literature, including the Pacific Earthquake Engineering Research Center (PEER) framework [31] are loss estimation models that focus on initial losses caused by disaster, where losses are measured relative to pre-disaster conditions. The temporal dimension of post-disaster loss recovery is not part of that formulation.

A clear example of the condition is represented by Kobe earthquake that clearly demonstrates that certain kinds of long-term impacts losses do occur, at least in catastrophic disasters. In 1994, prior to the earthquake, the Port of Kobe was the world's sixth largest container port. In 1997, after repairs had been completed, it ranked seventeenth. In fact, performance and recovery of transportation systems often requires longer repair times than other lifeline systems and in the case of Kobe port, it appeared to play a major role in the development of long-term impacts.

Information on comprehensive models that describe the recovery process is very limited. Miles and Chang [9] set out the foundations for developing models of community recovery presenting a comprehensive conceptual model and discussing some related issues. Once these complex recovery models are available, it is possible to describe relationships across different scales and to study the effects of different policies and management plans in an accurate way. Different types of recovery functions can be selected depending on the system and society preparedness response. Three possible recovery functions are the *linear*, the *exponential* and the *trigonometric* ones with the following expressions:

$$f_{rec}(t) = a\left(\frac{t - t_{0E}}{T_{RE}}\right) + b \tag{12}$$

$$f_{rec}(t) = a \exp\left(-b\frac{t - t_{0E}}{T_{RE}}\right) \tag{13}$$

$$f_{rec}(t) = \frac{a}{2}\left\{1+\cos\left(\pi b \frac{t-t_{0E}}{T_{RE}}\right)\right\} \tag{14}$$

where a, b are constant values that are calculated using curve fitting to available data sources, while t_{0E} is the instant of time when the extreme event strikes and T_{RE} is the recovery time necessary to go back to pre-disaster condition evaluated starting from t_{0E}. The model constants can be continuously updated as soon as more data are available, using for example a Bayesian approach. The simplest form is a linear recovery function that is generally used when there is no information regarding the preparedness, available resources and societal response [6]. The exponential recovery function is usually employed when the societal response is driven by an initial inflow of resources, but then the rapidity of recovery decreases as the process nears its end. Trigonometric recovery function can be used when the societal response and the recovery are driven by lack or limited organization and/or resources.

4 MULTIDIMENSIONAL HAZARD ON A COASTAL COMMUNITY

The HAZUS Methodology described above has been applied to a city of Seaside in Oregon that is one of the most vulnerable coastal cities in the Pacific North United States given the threat of an extreme nearfield Cascadia Subduction Zone earthquake and resulting tsunami.

According to the United States Census Bureau, the city of Seaside has a total area of 4.14 square miles (10.72 km^2), of which 3.94 square miles (10.20 km^2) is land and 0.20 square miles (0.52 km^2) is water. Seaside lies on the edge of the Pacific Ocean, at the southern end of the Clatsop Plains, about 29 km (18 mi) south of where the Columbia River empties into the Pacific. The city is developed on both sides of the Necanicum River, which flows to the ocean at the city's northern edge.

The US faces a multi-hazard threat from the Cascadia Subduction Zone (CSZ), a fault that runs from Northern California to British Columbia and is less than 160 *km* (100 *mi*) offshore in most places. Recent paleoseismic studies have shown that there is 7-12% chance of magnitude 9.0 earthquake along this fault in next 50 years which will trigger peak ground accelerations of up to 0.50 g, a massive tsunami over 10 *m* (33 *ft*) high and will hit the Pacific Northwest coast within 20 to 40 *minutes*.

In this work, an earthquake scenario of moment magnitude (*Mw*) 9.2 with a 1000-year event has been considered for the multi-hazard evaluation of the community losses and resilience (PGA 0.455g). The input data has been retrieved on the United States Census website and on the Bureau of Labor Statistics website (Figure 3) and it represents a disruptive event in the area for both the earthquake and tsunami effects. In Figure 3b an example of initial water surface deformation is reported (wave amplitude [m]).

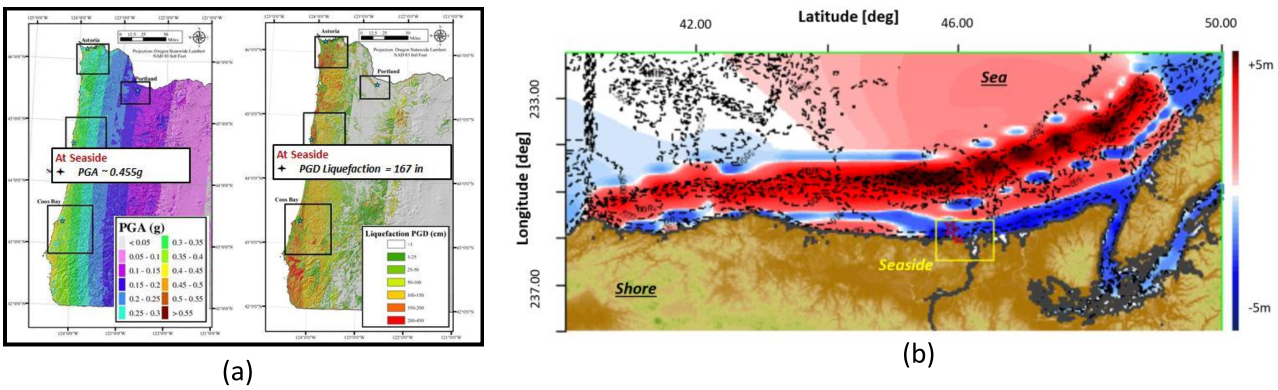

Figure 3. Earthquake (a) and tsunami (b) hazards in Seaside, Oregon (*Tr*= 1000yrs, *Mw*=9.2).

5 RESULTS

5.1 Analysis assumptions

The analysis of Seaside community losses and resilience is performed for three different scenarios: *(i) earthquake-only, (ii) tsunami-only and (iii) earthquake & tsunami scenarios*. The methodology is based upon the following assumptions:

1) Direct economic losses only have been considered at this stage.
2) The recovery function has been assumed linear, because no information regarding the preparedness, resources and societal response are available [6].
3) In the earthquake-tsunami scenario, the recovery time has been estimated as the average between the maximum value of recovery time (due to either the tsunami or the earthquake) and the sum of both recovery times (due to both the tsunami and the earthquake).

$$T_{rec} = \frac{\max(T_{earthquake}, T_{tsunami}) + (T_{earthquake} + T_{tsunami})}{2} \quad (13)$$

where T_{rec} is the recovery time for the earthquake-tsunami scenario, and $T_{earthquake}$ and $T_{tsunami}$ are the recovery times for earthquake and tsunami scenarios, respectively. It is an heuristic assessment of the recovery time for the combined hazards that mediates between a crude overlap of effects and the worst condition due to the individual hazard.

4) The control time T_{LC} has been assumed equal to the maximum acceptable recovery period.

5.2 Tsunami-only and earthquake & tsunami scenarios

The number of casualties due to tsunami hazard consists in the numbers of injuries and fatalities and it is computed accordingly with section 3.5.2. The value of the warning effectiveness and preparation time T_{prep} is not specified but pre-assigned based on one of the three grades of community preparedness. T_{prep} represents the most probable time (i.e. mode) for people to initiate evacuation after a tsunami warning is received (including the natural ground shaking).

$$Mode = T_{prep} = C_{prep}(T_0 - T_W) \quad (14)$$

in which C_{prep} is assumed 0.2, 0.6 and 1 respectively for the three grades of community preparedness: good, fair, poor.

To distinguish a fatality from an injury, a criterion in terms of the inundation depth is defined: 99 % of people would be killed if caught in a depth of more than 2.0 m. With the Evacuation Travel Time for fatality T_{travel} (to the boundary of the 2.0 m depth), the foregoing calculations are repeated to obtain the fatality rate $R_{fatality}$. Here it is assumed that the injury rate decreases linearly from 99 % to zero from the 2 m inundation depth contour toward the maximum inundation. Figure 4 illustrates this logic.

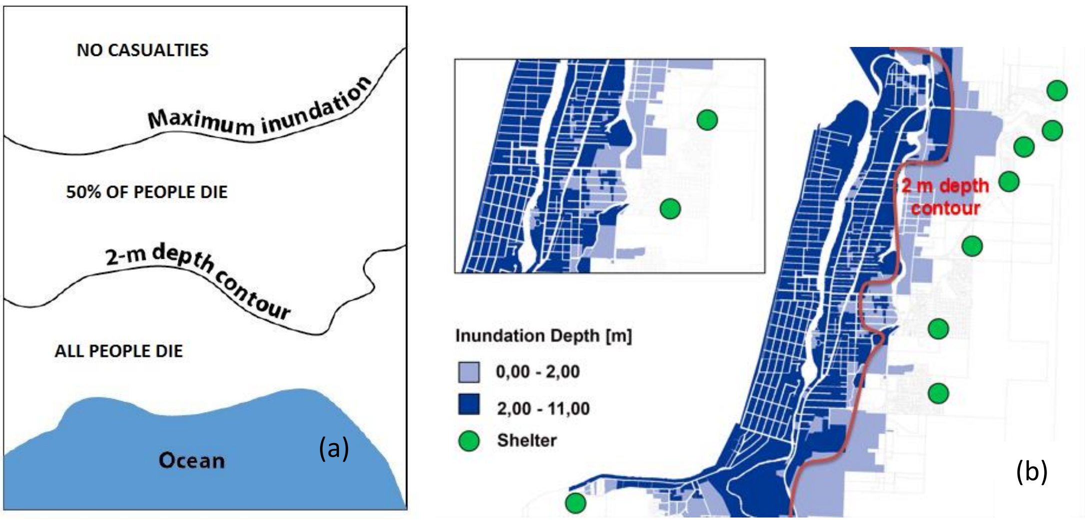

Figure 4. The logic to determine fatalities and injuries: (a) general scheme, (b) Seaside case.

Table 2. Total number of casualties due to ambient conditions for evacuation (percentages are relative to the total people considered).

	Good ambient conditions	Fair ambient conditions	Poor ambient conditions
TSUNAMI			
No. Casualties	1769 (27%)	4609 (71%)	5410 (84%)
No. Fatalities	1761	4585	5392
No. Injuries	8	24	17
EARTHQUAKE-TSUNAMI			
No. Casualties	5387 (83%)	5755 (89%)	6049 (94%)
No. Fatalities	4762	5147	5458
No. Injuries	625	608	591

The numerical results in Table 2 show the number of casualties that consists of the number of injuries and fatalities. The maps in Figure 5 show the percentage of the number of fatalities for each residential building in three ambient evacuation conditions (good, fair, poor) according to two different scenarios. An average number of people per housing unit equal to 2.25 is taken into account.

The highest percentage of fatalities appeared along the coast because the evacuation travel time T_{travel} for these buildings is longer than other ones, while tsunami arrival time is smaller than other ones. Moreover, when the effects of earthquake and tsunami are combined, the number of fatalities dramatically increased because all bridges are assumed to be failed. Furthermore, as the trend is towards poor conditions, and therefore toward more vulnerable conditions, the difference between the number casualties for the tsunami and the combined scenario is reduced.

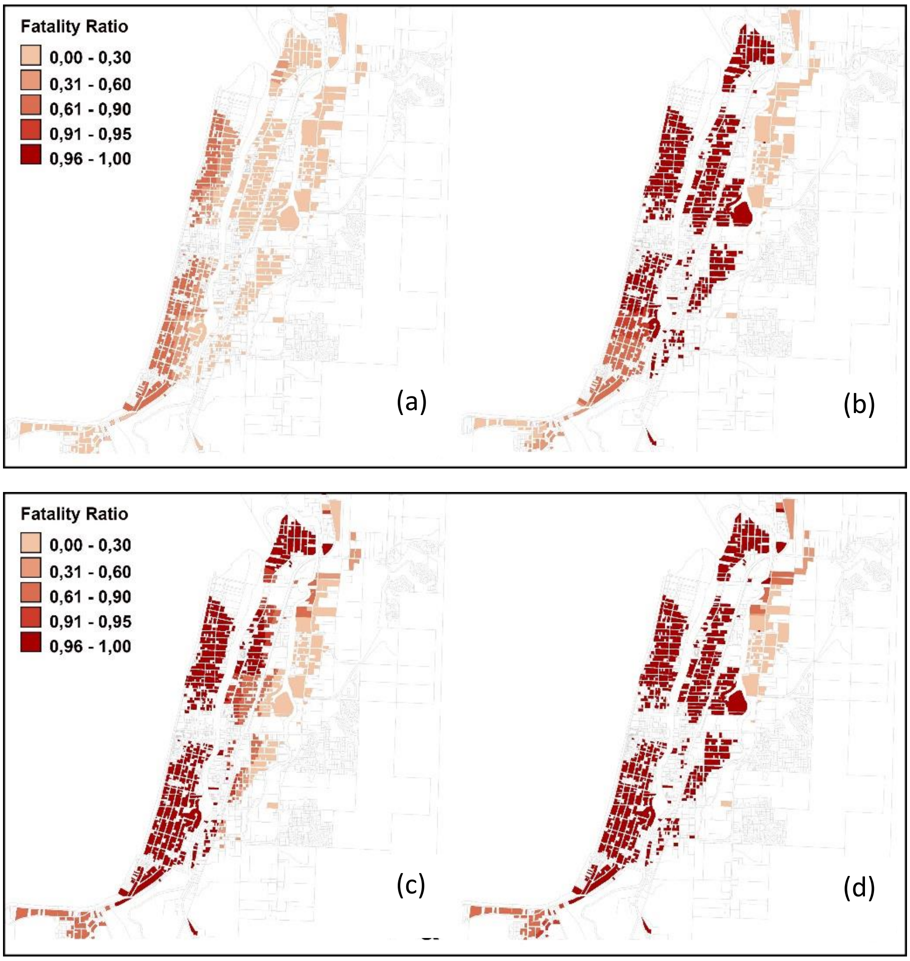

Figure 5. Fatalities for each building in good (a, b), fair (c, d) and poor (e, f) ambient condition. Tsunami-only scenario (left - a,c,e). Earthquake & tsunami scenario (right - b,d,f).

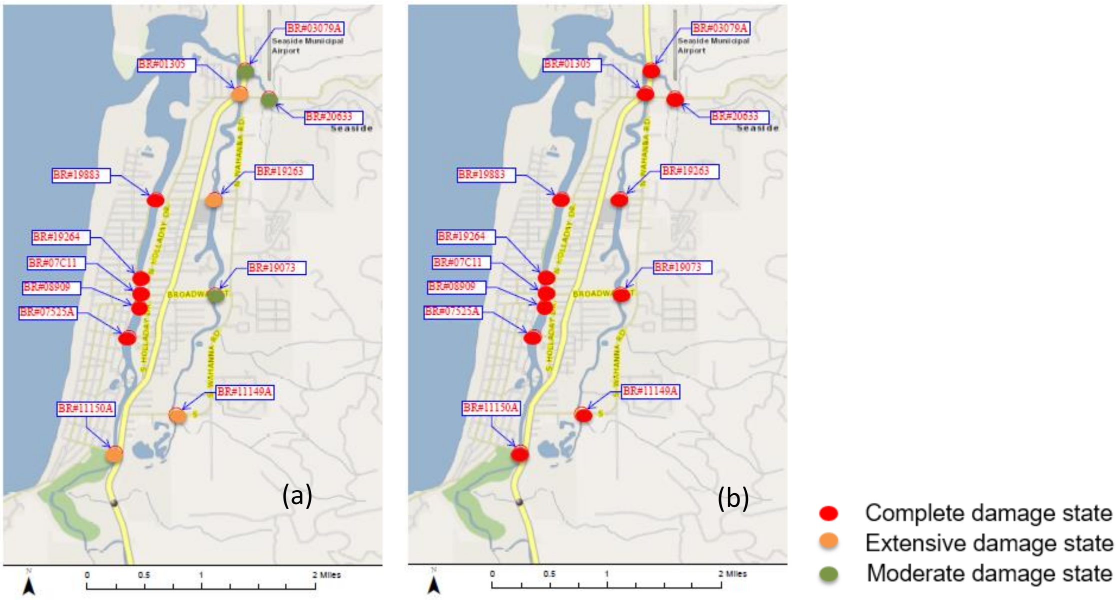

Figure 6. Damage to lifelines components: highway bridges in Seaside. Tsunami-only scenario (a) and Earthquake & tsunami scenario (b).

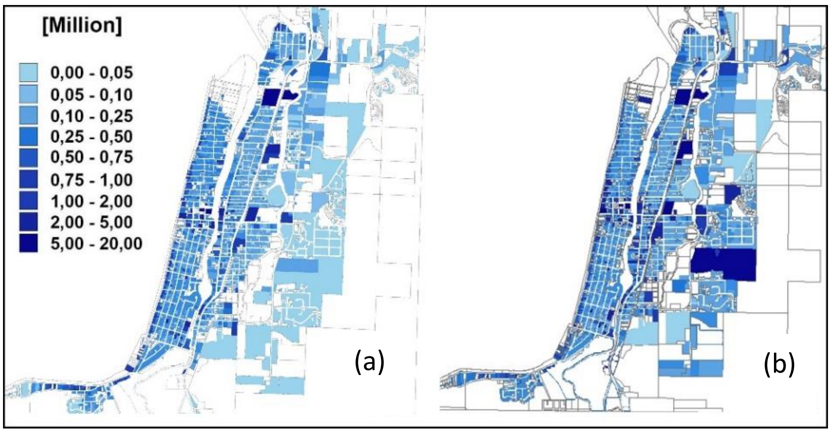

Figure 7. Direct Economic Losses for each building in Seaside: (a) Tsunami-only scenario; (b) Earthquake-Tsunami scenario.

Figure 6 reports the damage state for the tsunami and earthquake-tsunami scenario for highway bridges in Seaside area. If the tsunami scenario is considered, the bridge structures closer to the sea highlight a complete damage state after the event. On the contrary, a complete damage for all bridges in seaside is verified when the earthquake & tsunami scenario is evaluated.

About direct economic losses, the map in Figure 7 compares the value in dollars for each building of Seaside according the two different scenarios. The effect of tsunami is lower with respect to the coupled effect earthquake & tsunami that show the highest economic losses. As highlighted for the bridges damage state, it can be noted how the tsunami scenario highlights direct economic losses along the seaside in particular, where the effect of inundation is concentrated.

To calculate the community resilience value for Seaside city area due to the considered multi-hazards scenario, direct losses have to be firstly estimated for each type of buildings, along with the recovery time.

Figures 9 and 10 reports the recovery time and the direct losses for both the tsunami and the coupled earthquake & tsunami hazards. The worst effect of hazards combination can be already noted. However, it can be also highlighted as the earthquake hazard is the most demanding in terms of required recovery time because it shots a larger number of structures with respect to the tsunami. Besides, direct losses for each building is mainly due to the tsunami hazard due to losses in the buildings content, equipment and installations.

The resilience value has been computed for each occupancy class. The maps in Figure 11 show the variation of the resilience value for each building, according to the different scenarios of tsunami and earthquake & tsunami. It can be noted how when the coupled effect is considered, resilience value visibly drops down.

Table 3 describes how the mean value of resilience for each occupancy class changes according to the different scenarios. When the tsunami hazard is considered the Residential and Commercial occupancy classes that are more concentrated along the seaside show the lowest resilience values. Combining the earthquake hazard to the tsunami the resilience values drop down and the Education and Industrial occupancy classes are mostly hit.

Figure 9. Recovery time value for each building in Seaside: (a) tsunami-only scenario;

(b) earthquake-tsunami scenario.

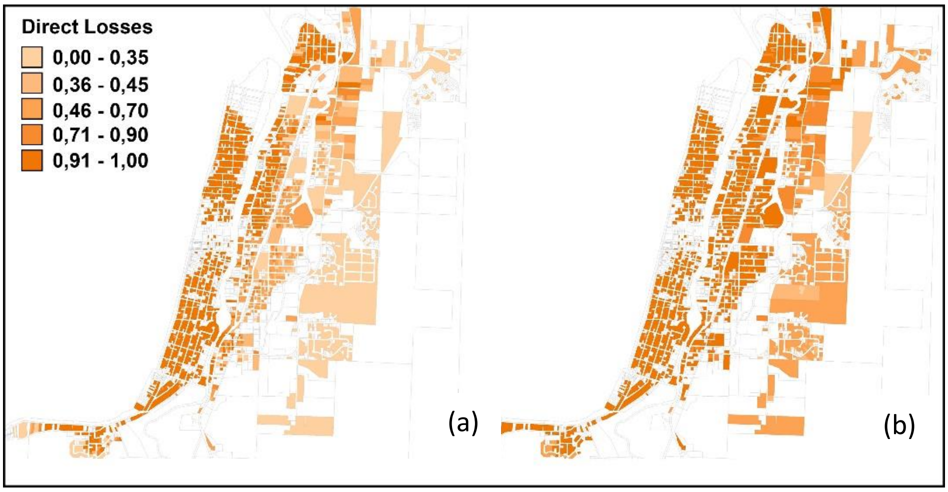

Figure 10. Direct losses value for each building in Seaside: (a) tsunami-only scenario;

(b) earthquake-tsunami scenario.

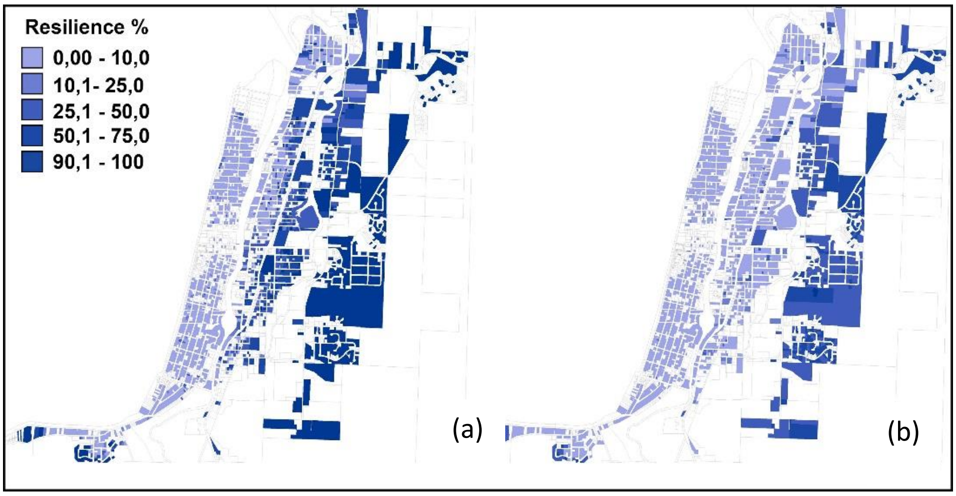

Figure 11. Resilience value for each building in Seaside: (a) tsunami-only scenario;

(b) earthquake-tsunami scenario.

Table 3. Mean resilience value for each occupancy class.

Occupancy Class	TSUNAMI	EARTHQUAKE & TSUNAMI
Residential	41.99 %	17.30 %
Commercial	42.58 %	14.50 %
Education	71.56 %	0.90 %
Industrial	71.91 %	0.05 %

6. CONCLUDING REMARKS

A methodology to assess direct losses and community resilience of a coastal city affected by multi-hazard conditions due to offshore earthquakes is presented in this paper. It combines two existing frameworks: the HAZUS methodology for direct losses estimation with MCEER approach for the community resilience assessment. The case study of the Seaside city in Oregon is used to implement and test the procedure.

The comparison between the tsunami and the earthquake & tsunami scenarios on the selected case study of Seaside highlights the following concluding remarks:

- the effect of vulnerability determines the number of casualties in the coastal community. Therefore, if poor ambient conditions are considered the effect of tsunami and the earthquake & tsunami hazard are equivalent. On the contrary, for good ambient conditions, the worst case of earthquake in combination with tsunami generates the highest number of casualties.

- Considering direct losses, the effect of tsunami is always lower if compared to the earthquake & tsunami combination. Furthermore, it can be noted how the tsunami scenario specifically determines direct losses along the seaside, where the effect of inundation is concentrated. Therefore, special tsunami retrofit measures should be provided within this area for reducing the community vulnerability.

- The worst effect of hazards combination can be also noted in the estimation of the recovery time. However, the earthquake hazard results as the most demanding in terms of required recovery time because it affects all the structures within the whole Seaside city area.

- Resilience value depends by both losses and recovery time, therefore the multi-hazard scenarios remains the most severe.

The proposed methodology can be applied to *existing* cities to evaluate possible countermeasures and solutions to inherent vulnerabilities. Furthermore, for *new* districts, it allows to identify optimal solutions during the design phase for improving resilience and preparedness.

Future developments in this research would include the assessment of the indirect economic losses and the infrastructure interdependencies to enhance the accuracy of the methodology.

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