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ALTERNATIVE RESILIENCE MEASURES FOR URBAN SYSTEMS SUBJECTED TO SEISMIC AND LANDSLIDE HAZARDS

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Abstract

Seismic events represent nowadays a major challenge for the worldwide scientific community. Besides, novel methodologies for a prompt and efficient response are needed to ensure adequate levels of resilience to global communities, allowing they to be capable of recovering from a disaster to a target performance level which is at least equivalent to the pre-event condition.

Resilience can also be evaluated as a proxy of the recovered urban damage. Despite the traditional approach to the single-structure damage assessment, the overall urban environment and mutual connectivity among its components may be considered. As a point in matter, the human part of a city is the most important one, as citizens rule urban dynamics being the principal end-users of local services. Hence, when studying urban environments, a multi-faceted and human-centric approach is required to account for both physical and human components. This means that infrastructure damage can be assessed through a systemic methodology where the loss of functionality of single buildings and services as well as the entire city are considered.

To this aim, an integrated framework for quantitative resilience assessment is used, where any urban system can be modelled through the graph theory. The social and infrastructure sub-systems of the urban centre are separately modelled as complex networks and overlaid to account for their interrelations as a hybrid social-physical network (HSPN).

In this study, first of all efficiency measures are evaluated on the HSPN and systemic damage is assessed as a proxy of the city efficiency, soon after the earthquake occurrence. Resilience is evaluated by means of two alternative approaches proposed in the literature. Further resilience measures are proposed to evaluate urban resilience accounting for the initial state of the city damage and the ratio between the numbers of displaced citizens and inhabitants.

Given that many urban systems are subjected to multiple hazards, the proposed resilience metrics are evaluated in the case of a urban centre threatened by both seismic and landslide hazards. The municipality of Sarno, Italy, which lies in an earthquake-prone region and was affected by a severe hydrogeological event in 1998, is assumed to be a case-study. Resilience is computed in relation to a hazard-compatible seismic scenario and a landslide scenario to assess the robustness and efficiency of the proposed resilience metrics under different scenarios. As a matter of fact, earthquakes are low-probability/high-consequence events whereas landslides have got a high occurrence rate in Italy, particularly in the form of flow-type events. Furthermore earthquake damage typically involves the whole urban system whereas flow-type landslides strike some sectors only. Fragility curves are used to model the vulnerability of reinforced concrete and masonry buildings located in the case-study urban centre, both in the case of seismic and landslide risks. Also, the probability of street links to get inaccessible is considered as a function of the buildings' height. The results show that the response and resilience of the urban system strongly changes with the type of disaster, emphasizing the role of systemic damage and population involved.

Keywords: seismic resilience; landslide resilience; urban ecosystems; social resilience; critical non-nuclear infrastructures.

1. Introduction

Most of recent events which have threatened local and global communities are natural disasters. These events cause severe human losses and damages to urban environments every year. In this respect, the need for novel approaches supporting mitigation and enhancing disaster resilience is widely recognized. Particularly, recent approaches to disaster management highlight the importance of dealing with issues related to the occurrence of natural disasters at local level. Approaching pre- and post-event actions at the urban scale has got, in fact, the potential to guarantee higher efficiency in management and greater control in coordination and resource use. The effectiveness of actions against natural disasters can be potentially enhanced in the pre- and post-event stages, and also during the recovery, whether they are undertaken at the urban scale. As a result, disaster resilience can be improved to respond to natural events as best as possible.

In this context, and when dealing with local resources and the built environment, several, diverse components contributing to a city's functioning should be considered. A city can be defined as the set of people, infrastructure, buildings and services, which are all embedded within the same geographical space. Hence, in order to monitor the performances of a city, interrelations between its components should be considered. Urban environments can thus be modelled as ecosystems, that is single components and mutual interactions can be studied as complex network. In this study, apart from the physical components of the urban environment, also social actors are considered and the whole urban system is modelled as networked system, i.e. the hybrid social-physical network (HSPN) [3]. According to the proposed approach to the city's modelling, the HSPN efficiency can be assessed as the level of connectivity that it can guarantee in the pre-event stage, in the aftermath of a disaster, and in each stage of the recovery process. Besides, the assessment of the city efficiency level according to the complex networks theory enables us to perform a systemic measure of the urban damage. Finally, the convolution of the performed efficiency measures over the city's life cycle is used to quantify the urban resilience. Resilience is specialised to its engineering definition in the field of ecosystems. Therefore, resilience is defined as the capability of an urban system to face an adverse event and to reconfigure in an equilibrium condition, which can be the same of the pre-event or a new one [1][2].

The methodology described in this paper is applied to the case study of the city of Sarno (Italy), in order to prove effectiveness and robustness of the proposed metrics. With regards to resilience to natural disasters, a specific focus on seismic and flow-type landslide events is done and alternative metrics for the resilience assessment are proposed.

Primarily this study aims to compare urban damage and resilience assessment when changing the typology of the natural event potentially occurring, hence according to diverse areas and modes of impact. This is the reason why the methodology (shown in Fig. 1) is implemented for the case study of the city of Sarno, which is contextually a seismic- and landslide-prone area. Sarno is located about 50 kilometers from the city of Naples, Campania Region, and suffered a severe flow-type landslide in 1998.

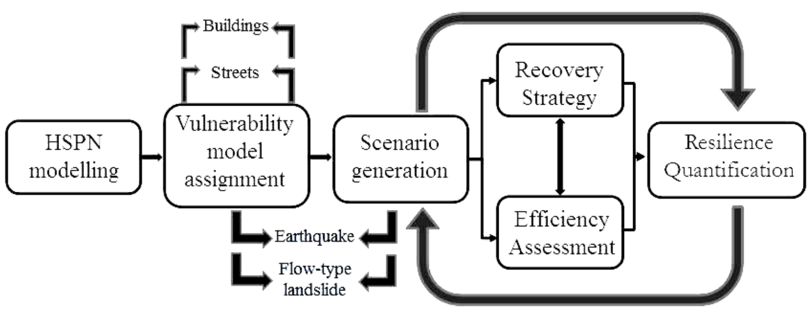


Fig. 1 – Flowchart of the presented methodology

The city of Sarno was modelled as a HSPN and its efficiency level was assessed in case of seismic and landslide scenarios. Based on the type of natural event being simulated, vulnerability of the built environment was modelled through fragility curves selected from the literature. Fragility curves refer to masonry and reinforced concrete (RC) buildings, which are typical structural typologies in Sarno. The intensity measure of the fragility models being used is peak ground acceleration (PGA) in case of seismic scenarios and debris flow velocity (v) in case of landslide scenarios.

The probability of street interruption was set as a function of the ratio between the height of each building and the width of the adjacent street in case of seismic scenarios. Conversely, all the streets links within areas affected by a landslide were considered to be inaccessible according to the physical propagation of the debris flow.

After that damage to buildings and streets was evaluated, efficiency was computed to the HSPN configuration before and after the event occurrence, and for each stage of the assumed recovery process. The systemic damage was then evaluated by means of the efficiency assessment, and finally resilience was quantified as a synthetic indicator of the city's response to natural disasters.

The computational methodology described in this paper allows different response modes to be compared to diverse event types in terms of efficiency, systemic damage and resilience. Particularly, resilience is evaluated according to alternative metrics that depend on either the ratio between the number of inhabitants and displaced people, or on systemic damage in the aftermath of the simulated event.

2. Experimental framework for disaster resilience quantification

The framework described is aimed at assessing the HSPN efficiency and systemic damage at the local scale as a proxy for city efficiency in case of catastrophe occurrence. According to the efficiency level that the studied system is able to fed to its inhabitants, engineering resilience in the sense of ecosystems is evaluated.

Two different types of hazard scenarios – earthquake and flow-type landslide – are analysed in order to compare results in terms of efficiency, systemic damage and resilience, depending on the way the event impacts the HSPN.

The methodology consists of four main phases described in the following subsections:

- HSPN modelling;
- Seismic and landslide vulnerability assessment;
- HSPN's efficiency and damage assessment;
- Resilience quantification.

2.1 HSPN modelling

At this stage, physical and social city components are modelled as planar graphs. Hence they are overlapped to account for mutual interactions in the complex hybrid social-physical network, i.e. the HSPN [2][3].

First of all, the physical network of streets is modelled as a set of street nodes intersections N_s and a set of street links L_s. Then, the physical network of buildings can be modelled too. Particularly, at this stage, also the social network is contextually modelled by accounting for the number of people that live in each building and the number of users for each urban service, which is represented by the building which the service is supplied from. Hence, the set of building nodes N_b and the set of door links L_b, connecting each building to street junctions, are modelled. Finally, the two graphs are overlapped in the final HSPN, being defined as $\Gamma = (N, L)$ and whereas $N = N_b$ U $N_s = \{1, 2, \ldots, \text{n}\}$ and $L = L_b$ U L_s, being $L \subseteq N \times N$.

The city HSPN is defined in the Euclidean space to evaluate the probability of existence of a link between a pair of nodes, so the Euclidean distance is used as a metric. Furthermore, the HSPN is considered to be undirected, due to the modelling of people and vehicle flows being tricky. As a consequence, the existence of a link which connects the generic nodes i and j implicitly implies the converse link to exist [3][4].

Substantially basic information needed to model an urban context is usually related to the population of buildings, i.e. their number, structural typology and geographical position. Hence, any city context, which this information is available for, e.g. from national databases, can be modelled as a HSPN. Furthermore, by processing statistics on buildings together with those on population, it is possible to obtain the number of citizens for building, enabling modelling of the social urban component. For instance, in this study, data are referred to the Italian National Institute of Statistics (ISTAT). According to ISTAT, the city social component can be considered by accounting for the mean square meters of buildings that are occupied by each citizen, depending on their use classifications.

The HSPN is modelled in a geografic information system (GIS) that enables to manage lots of heterogeneus data and to get even more data while georeferencing and documenting them.

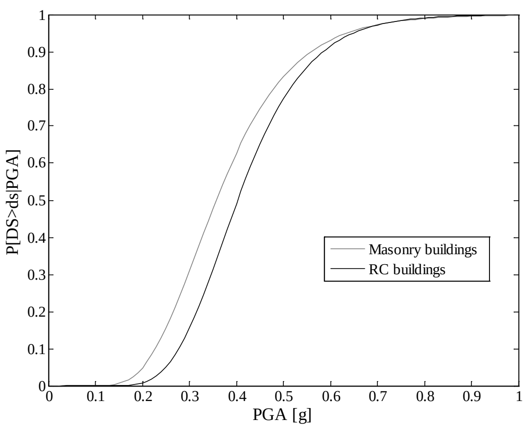
2.2 Seismic and landslide vulnerability assessment

Once the HSPN is built up, structural vulnerability is computed, that is the response that structures can explicate to different levels of loads.

Based on the random nature of parameters affecting the buildings' response capability, fragility functions are used to compute vulnerability, that give a measure of the conditional probability of exceedance of a discrete set of damage states under the occurrence of an event with a certain intensity.

According to the structural typology, the susceptibility to damage can be regarded for each building of the HSPN. Keeping with this, fragility models for masonry and RC buildings were selected from the literature for seismic and landslide events. As a case in point, earthquake fragility curves in terms of PGA are used [5] whereas landslide fragility curves in terms of debris flow velocity v are considered [6][7]. In both cases, fragility models were associated only to an extensive state of damage or collapse of the building.

Fig. 2 shows the fragility curves selected from the literature, the statistics of which are given in Table 1 in terms of logarithmic mean μ and standard deviation σ.



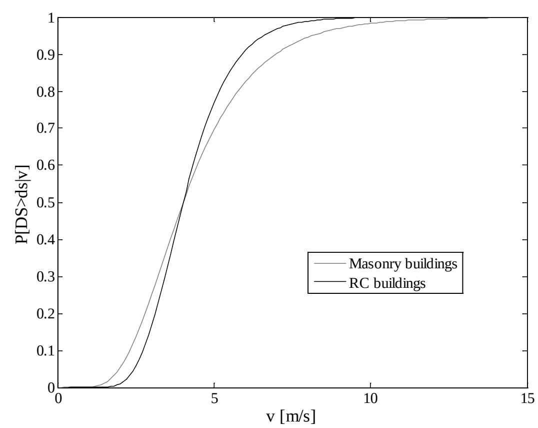


Fig. 2 – Seismic fragility curves by Ahmad et al. [5] (left side) and flow-type landslide fragility curves by Parisi et al. [6] and Corominas et al. [7] (right side)

Table 1 – Parameters of the seismic fragility curves by Ahmad et al. [5] and landslide fragility curves by Parisi et al. [6] and the FP7-funded SafeLand project [7]

Natural Event's Typology	Structural Type	μ	σ
Earthquake	Masonry buildings	–1.03	0.35
	RC buildings	–0.91	0.29
Flow-type Landislide	Masonry buildings	1.39	0.43
	RC buildings	1.39	0.30

Given the intensity of the simulated event, fragility curves provide the probability of exceedance of the extensive damage state. Hence, a stream of uniform pseudo-random numbers is generated and a value on the interval (0,1) is selected for each building of the HSPN. The comparison between these numbers and the probability values obtained from the fragility decide whether the building will survive or not.

Aside from buildings, also the probability of street interruption is computed due to the important contribution that it gives to the city's connectivity level. In this regard, in case of seismic scenario, a new uniform pseudo-random distribution is generated and values attributed to each street link are then compared with its probability of interruption, that is evaluated according to Eq. 1:

$$P_r(h,l)=\begin{cases}\dfrac{h}{l} & \text{if } 0<h<l\\ 1 & \text{if } h\geq l\end{cases} \tag{1}$$

where h is the height of the building and l is the width of the road.

Obviously, the higher is the ratio between the buildings' height and the road's width, the higher is the probability that the street link will be interrupted in the aftermath of the event.

Conversely, when a landslide scenario is simulated, the interruption of streets located within the area of impact is a sure event, because of all streets are definitely obstructed by the debris flow.

2.3 HSPN's efficiency and damage assessment

According to the complex network metrics, it is possible to assess the HSPN perfomances at this stage. Efficiency can be, in fact, computed as a global feature of the urban network, providing a measure of its global performances [8], in the sense of its capability to ensure for connectivity and citizens accessibility to urban services.

In this context, the vulnerability assessment reveals to be crucial. In each simulated scenario, in fact, a certain number of buildings and streets becomes unfeasible, so they are deactivated within the HSPN. As a result, the city HSPN will not be as efficient as before the event, reducing life quality of the city inhabitants. An additional effect is that private householders will be delocated, due to unfeasibility of their residences, and urban stakeholders could not benefit from urban services any more. This calls for a realocation of citizens through the design, planning and implementation of a recovery strategy.

In this study, scenario analysis are performed on the residential HSPN, which accounts for the vulnerability of the built environment and gives information about the residential buildings that will be damaged after the event occurrence. On the other hand, the number of citizens is estimated according to ISTAT [9] that considers each 30 m^2 of urban buildings to be occupied by one citizen. The knowledge of the floor area and the number of storeys for each building enables the number of its inhabitants to be estimated.

Hence, for both seismic and landslide scenarios the efficiency of the HSPN in connecting couples of residential building nodes as well as street to building nodes is computed as the citizen-to-citizen efficiency.

According to Latora and Marchiori [8], efficiency has to be normalizaed in [0,1] to enable for comparability between diverse scenarios and urban HSPN. It is obtained as the pairwise efficiency, calculated as a function of the ratio between the Euclidean distance d_{ij}^{eucl} and the shortest path distance d_{ij}, as shown in Eq. (2):

$$\begin{aligned} E_{cc} &= \frac{1}{H_{tot}(H_{tot}-1)}\sum_{i\in N_b} H_i\cdot\left[(H_i-1)+\sum_{j\in N_b,\, j\neq i} H_j\,\frac{d_{ij}^{eucl}}{d_{ij}}\right]= \\ &= \frac{1}{H_{tot}(H_{tot}-1)}\sum_{i\in N_b} H_i\cdot\left[(h_i-1)+\sum_{j\in (N_b\setminus I)} H_j\,\frac{d_{ij}^{eucl}}{d_{ij}}\right] \end{aligned} \tag{2}$$

in which N_b is the set of all building nodes, h_i is the number of citizens living in buildings having zero distance from building i, H_{tot} is the total number of city inhabitants, H_i is the number of residents in the building i, H_j is the number of citizens living in building nodes having Euclidean distance d_{ij}^{eucl} from i, and d_{ij} is the length of the shortest path between node i and node j.

The citizen-to-citizen efficiency, when is assessed before and soon after a catastrophic event occurrence, can be understood as a measure of the systemic structural damage.

Based on the efficiency of the residential HSPN, a recovery function at stage zero is defined (Eq. (3)) and provides a measure of the residual HSPN's capacity to function after an event is occurred [4]:

$$\mathrm{Y}(0) = \frac{E_{cc}^{post-event}}{E_{cc}^{pre-event}} \tag{3}$$

being $E_{cc}^{post-event}$ the citizen-to-citizen efficiency evaluated soon after the event occurrence and $E_{cc}^{pre-event}$ the citizen-to-citizen efficiency before the event. Hence, $Y(0)$ is a prompt estimate of the global level of damage suffered by the urban network, differently from the traditional engineering approach in which damage to each single building is assessed.

2.4 Resilience quantification

The recovery function can be assessed at each stage of the recovery, as shown in Eq. (4), being evaluated depending on the citizens' share C that is relocated. This approach is performed to remove any time-dependence of recovery, because of the high number of uncertainties related to time.

$$Y(C) = \frac{E_{cc}(C)}{E_{cc}^{pre-event}} \tag{4}$$

Eq. (5) shows a further simplification that enables the dependence on the total state of damage (1–Y(0)) to be removed:

$$y(C) = \frac{Y(C) - Y(0)}{1 - Y(0)} \tag{5}$$

whereas $y(0)$ represents the function value when no displaced citizens have been relocated yet, and $Y(0) = 0$, that is in the aftermath of the event. It turns out to be that $y(C) = 1$ if $Y(C) = 1$, meaning that the displaced inhabitants have been relocated and the city's HSPN has bounced back to the equilibrium.

Hence, assessing the convolution of the global efficiency on all recovery stages enables the computation of resilience through Eq. (6):

$$R_1 = \frac{\int_0^{C_{\max}} y(C)dC}{C_{\max}} \cong \frac{\sum_{c=0}^{C_{\max}} y(C)\cdot \Delta C}{C_{\max}} \tag{6}$$

where C_{max} is the total number of citizens to relocate after the event.

Such a metric defines resilience as the area under the recovery curve in the E_{cc}-C_{max} plane, denoted as A in Fig. 3:

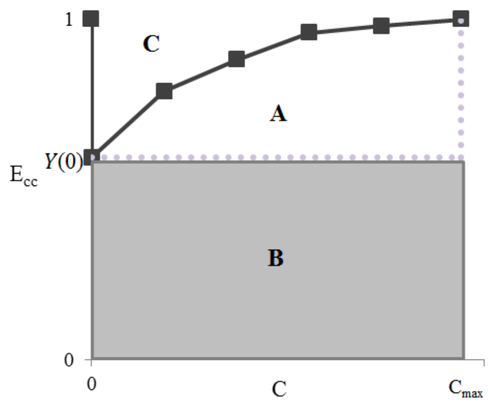


Fig. 3 – Recovery curve as the relationship between the normalized efficiency and the number of relocated citizens

When assessing resilience, it could be fundamental to account for efforts needed to recover from the occurrence of an external shock. Hence, in some cases, the dependence on the total state of damage need to be considered. To that aim, a further metricì related to the HSPN's state of damage in the aftermath of the event, *Y(0)*, is introduced in Eq. (7):

$$R_2 = \frac{\sum_{c=0}^{C_{\max}} Y(C) \cdot \Delta C}{C_{\max} \cdot Y(0)} \tag{7}$$

Basically, an urban HSPN could reveal more resilient than another one in case it suffers less damage, that is it needs less resources and time to recover. Hence, R_2 has got the potential to account for this circumstance while assessing resilience, and to compare different HSPNs according to damages they have experienced. From a physical viewpoint, when looking at the recovery curve (Fig. 3), the resilience metric R_2 represents the area under the curve, that is given by $A+B$.

Two further resilience metrics are finally proposed, R_3 and R_4, which are not directly related to the physical meaning of resilience and account for the damage state in different ways.

R_3 enables to assess resilience by simply summing up the recovery function value soon after the earthquake occurrence to the resilience value evaluated according to Eq. (6), i.e. R_1, as shown in Eq. (8):

$$R_3 = \frac{\sum_{c=0}^{C_{\max}} y(C) \cdot \Delta C}{C_{\max}} = R_1 + Y(0) \tag{8}$$

Besides, R_4 enables to evaluate R_3 and to particularize its dependence on the state of damage, according to the ratio of the number of displaced citizens C_{max} to the total number of city inhabitants H_{tot}, as given in Eq. (9):

$$R_4 = R_3 \frac{C_{\max}}{H_{tot}} \tag{9}$$

R_2, R_3 and R_4 are all damage-dependent resilience metrics but only R_3 and R_4 present the advantage to be defined in [0,1]. Their normalization enables an easier comparison between the resilience indicator's values assessed according to the different event occurred and to different HSPN's topology.

In the present paper, landslide and seismic scenarios are run, hence a recovery strategy is hypothesized and simulated in order to evaluate resilience. The recovery strategy that has been simulated considers that the HSPN, which has been impacted by an adverse event, bounces back from it by restoring its functionality, i.e. the equilibrium condition, that it has prior to the occurrence of the event. According to this strategy, buildings and links are progressively restored and reintegrated into the network, which is also progressively reconnected.

3. Development of a case study for the city of Sarno

Sarno is a small town of 32,000 inhabitants about 50 km from Naples (Campania Region) in Southern Italy, which is surrounded by mountains. Buildings within the urban environment are located in the valley floor, with the oldest part up the hill, and the rest situated down the highest mountain peak, the Mount Saro.

Sarno is considered a high risk area because of its built environment being very old and also due to its geomorphological characteristics. Indeed, Sarno is a medium seismicity area according to the Italian seismic hazard map [10], and it is also known as it was hit by severe flow-type landslide events in 1998 whose typical scheme is shown in Fig. 4. The Sarno's landslides were in number of 14 and caused damages to the city, as well as, more than 100 fatalities, affecting the municipalities of Sarno, Quindici, Siano, Bracigliano and San Felice a Cancello [11].

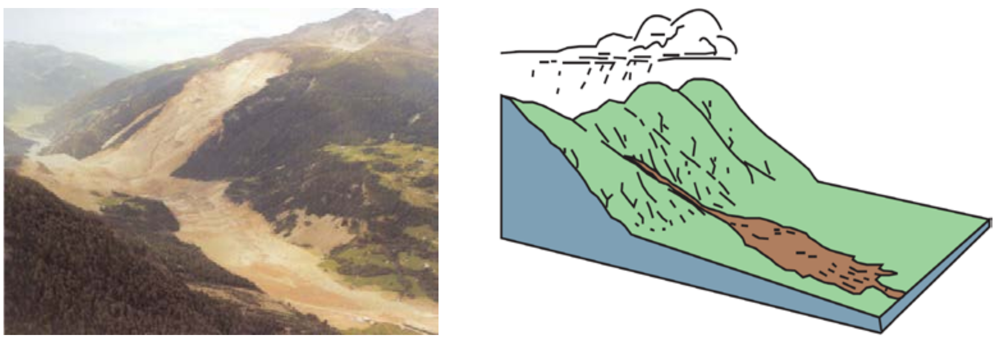


Fig. 4 - Typical flow-type landslide and flow-type landslide scheme [12]

First of all, the city of Sarno was modelled as a HSPN, based on GIS data from national databases about the morphology of the area and census data about the population of residential buildings and inhabitants. The result is shown in Fig. 13:

Fig. 5 –City map and HSPN of Sarno (light grey points represent residential buildings and black lines represent street patterns)

Integrating GIS and census data made possible to identify the buildings' location, structural typology (37% of reinforced concrete buildings and 63% of masonry) and height (hence the number of storeys, that is between 2 and 5). Moreover, the length of the streets and the number of residents were also computed, the latter by considering 1 citizen each 30 m^2. By contrast, the width of the streets was randomly assigned according to mean typical values.

3.1 Discussion of results

Once the HSPN was modelled, seismic and flow-type landslide scenarios were run. In the first case, as Sarno is a medium seismicity area with expected PGA between 0.15g and 0.25g, a seismic event with PGA = 0.25g was simulated. To study and check the sensitivity of results, each simulation was run five times using Monte Carlo techniques. As discussed in Section 2.2, the vulnerability of buildings was assigned according to the fragility models from Ahmad et al. [5].

According to the proposed methodology, in each simulation, damage to the built environment was randomly generated and a certain quantity of building nodes and street connections became unusable. As a result, a number of citizens were considered to be deallocated because of such damage, and the related set of street connections and building nodes were removed from the HSPN.

A flow-type landslide scenario was also generated. In particular, a back-analysis of the 1998 Sarno event was performed, so the flow velocity was set to v = 10 m/s.

The main difference of the two scenarios under study is related to the way street links and junctions are considered to become unfeasible. When a seismic scenario was run, the damaged street links were randomly modelled depending on the buildings' height. On the other hand, when the landslide was simulated based on site surveys after the 1998 event [13], specific landslide travel paths were recognised and all the street links located within them were removed from the HSPN.

This is because of the different type of the event simulated. In case of earthquake, streets can potentially be obstructed by the debris from adjacent damaged buildings. Conversely, in case of landslide, all streets involved in the flow are congested by mud material of the landslide.

Fig. 6 shows the HSPN configuration after seismic and landslide events were simulated:

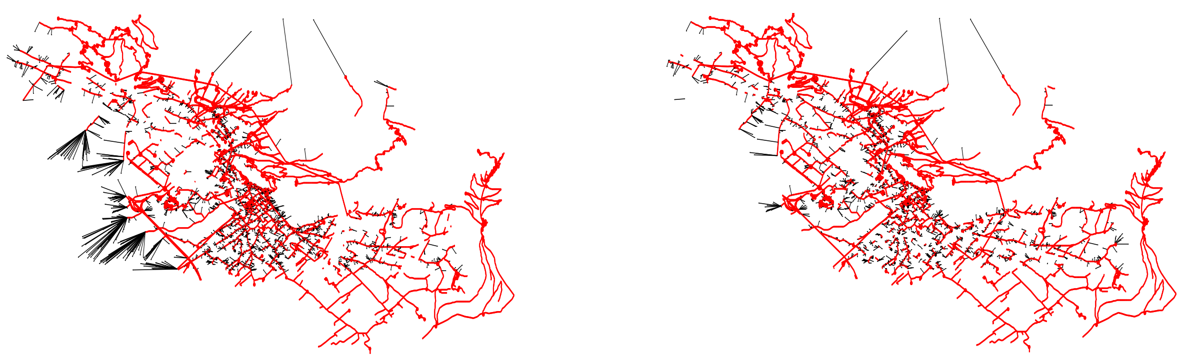


Fig. 6 – Sarno's HSPN configuration after landslide (left side) and earthquake (right side) scenarios

The graphs show the effect of the simulated events. Comparing the earthquake to the landslide event, a more significant drop in post-event efficiency is recognised. This highlights the higher spread of damage in case of earthquake event.

The systemic damage in terms of recovery function further confirms experimental evidence. In detail, the simulations provided $Y(0)$ = 0.04 in the seismic case and $Y(0)$ = 0.26 in the landslide case. In fact, the drop in normalized efficiency was found to be 71% in the case of landslide and 94% in the case of earthquake. This is because the number of interrupted street links was higher in the case of an earthquake (1949) than in the case of landslide (1301). As a consequence, more severe decay of urban connectivity, and hence global efficiency, is observed after a landslide consistently with a larger area impacted by the earthquake. On the other hand, the landslide affected a higher number of buildings (19.8% higher than that estimated after seismic scenarios).

Following the scenario analysis, urban resilience was calculated with reference to the four different formulations proposed, according to Eqs. (6) through (9).

Table 2 outlines results in terms of urban resilience to the earthquake scenarios and the flow-type landslide back-analysis.

Table 2 – Results in terms of resilience in case of seismic and landslide events

RESILIENCE	Earthquake							Landslide
	μ	σ	Simulations					
			1	2	3	4	5	
R_1	0.45	0.03	0.45	0.42	0.49	0.50	0.44	0.52
R_2	12.83	5.90	20.06	5.91	6.22	13.82	12.83	2.45
R_3	0.49	0.21	0.47	0.50	0.57	0.49	0.48	0.78
R_4	0.05	0.02	0.06	0.05	0.06	0.05	0.05	0.11

The proposed resilience measures performs differently depending on the type of simulated event. With reference to the case study of Sarno, when observing resilience in terms of R_1, R_3 and R_4, it can be argued that the landslide event affected the HSPN to a limited extent, whereas the seismic scenarios were more catastrophic events. Conversely, the measure R_2 shows that the case-study city is more resilient to seismic events. This comes from the fact that this measure is strictly related to the recovery function at stage zero, i.e. $Y(0)$. As a result, R_2 outlines the higher efforts needed to recover from a seismic event, which is more widespread than a flow-type landslide.

Experimental observations emphasise the complementarity of the proposed resilience metrics. For instance, R_1 indicates damage-independent resilience, as it is fully normalized with respect to the observed damage. Accordingly, R_1 gives a resilience perspective that is strictly related to the pre- and the post-event efficiency, regardless of the initial damage level.

R_2 is highly influenced by the damage level soon after the event occurrence, i.e. $Y(0)$, enabling engineering assessment of the structural damage suffered by the HSPN in the aftermath of a catastrophe.

R_3 and R_4 are both damage-dependent measures. R_3 measures urban resilience depending on the post-event damage, with the same approach used for R_2. R_4 emphasises the social dimension of resilience, which is evaluated as dependent on the total number of citizens. The measures R_3 and R_4 exhibit similar trends with R_4 tending to R_3 if the ratio between C_{max} and H_{tot} tends to unity, as shown in Table 2.

A very important aspect is related to the interval of the proposed metrics: R_2 is defined in $[1,+\infty[$, whereas R_1, R_3 and R_4 are defined in [0,1]. Having the resilience values defined in a restricted interval is very useful to ensure comparison of results related to different HSPNs and extreme events, according to an upper bound.

In particular, R_3 and R_4 can enable a sort of ranking between different types of event (the difference between the two ones being an order of magnitude). For example, $R_4 = 0.11$ in case of a landslide and $R_4 = 0.05$ in case of an earthquake. Potentially, local authorities could use this measure to choose a mitigation strategy. For instance, the most appropriate choice could be the seismic retrofit of residential buildings, exhibiting a seismic resilience that is lower than landslide resilience.

It is also worth noting that R_1 reveals to be a more objective measure to compare different urban networks and different types of event scenario.

On the other hand, R_2 shows the recover capability depending on the efficiency drop. In the present work, in fact, R_2 is the only metric that is higher in the case of an earthquake (12.83) than a landslide (2.45). As a result, the dependence on the residual efficiency, $Y(0)$, which is equal to 0.26 in the case of a landslide and 0.04 (median value) in the seismic case, reveals to be almost linear.

4. Conclusions

Contemporary cities emerge as complex systems where physical and social components coexist and are strictly interrelated. This means that nowadays enhancing city resilience against catastrophic natural events is a major issue.

In this paper, a particular focus was made on earthquakes and flow-type landslide events. In general, when a natural catastrophe occurs, urban physical components and utility systems are hit, in addition to citizens.

As a consequence, structural damage and drop in life quality level of citizens are contextually observed.

The proposed methodology aims to quantify the level of resilience of urban centres as their copying capacity, according to the event typology they experience. The city of Sarno (Campania Region) was evaluated as a case study.

The urban centre was modelled as a hybrid social-physical network (HSPN), accounting for both physical and social components. GIS and census data were integrated to complete the HSPN with information such as the number of citizens, the structural types of residential buildings (and their incidence on the overall building portfolio), and the location of buildings and streets. Those data can be obtained from national databases, i.e. from ISTAT in the case of Italy.

After the HSPN was modelled, scenario analyses were performed for two different events: an earthquake with PGA = 0.25g and the 1998 flow-type landslide, with estimated velocity v = 10 m/s. Vulnerability was modelled by means of fragility curves collected from the literature. As expected, the fragility models show that masonry buildings are more vulnerable than reinforced concrete buildings. This was confirmed in terms of resilience as the area of Sarno was proved to be extremely susceptible to both earthquake and landslide risks, given the prevalence of masonry buildings.

The generation of seismic and landslide scenarios was different because of the diverse areas of impact that typically result from these two phenomena. In fact, earthquakes are low-probability/high-consequence events which can cause widespread damage to an entire city, whereas flow-type landslides usually affect restricted areas of the urban centre. Accordingly, in this study, infrastructure damage was assessed through the use of fragility curves for the entire built environment. When dealing with landslide scenarios, specific travel paths were determined based on empirical evidence of the damage from the 1998 Sarno landslide, enabling a back-analysis to be carried out.

Four resilience metrics have been proposed and were tested for those two hazardous events.

Experimental results show a clear major downfall of the HSPN efficiency in the aftermath of the seismic event, rather than in the landslide scenario analysis. In both cases, efficiency was gradually recovered towards a recovery strategy, assuming the pre-event level of city functionality to be restored.

It should be also considered that urban functionality can be restored through the implementation of different reconstruction strategies. The proposed metrics enable alternative recovery actions to be compared each other, as a possible support to disaster management. In this way, local authorities could assess in advance the potential of diverse strategies to enhance their city’s resilience and to promptly implement them according to available resources, ultimately choosing the strategy that better meets the city’s needs.

The case-study HSPN was found to be less resilient to seismic events than flow-type landslides. This difference is inherently due to the nature of the simulated disasters and resilience metrics. The proposed metrics outline comparable, but also complementary results. In order to compare different urban systems that are prone to the same hazards, the R_1 metric can be used to compute resilience in the case in which no dependence on damage is considered. On the other hand, R_1 can be used together with the damage-dependent metrics R_2 and R_3 – or equivalently R_4 – when the comparison has to be performed for a single urban environment that is prone to different disaster typologies. A preliminary assessment of mitigation actions can be performed by considering the capacity to withstand each event typology shown by the city model. This approach would enable to support urban management choices with engineering-based evaluations, resulting in the enhancement of urban resilience.

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