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Risk and Resilience in Practice: Vulnerabilities, Displaced People, Local Communities and Heritages

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A. Nuno Martins, Liliane Hobeica, Adib Hobeica, Pedro Pinto Santos, Nuha Eltinay, José Manuel Mendes

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A. Nuno Martins, Liliane Hobeica, Adib Hobeica, Pedro Pinto Santos, Nuha Eltinay, José Manuel Mendes

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Risk analysis of the built environment: understanding strengths and weaknesses of both quantitative and qualitative methodologies

Mariantonietta Morga [a,*], Federica Pascale [a], Rose Line Spacagna [b], Luca Paolella [b], Giuseppe Modoni [b], Keith Jones [a]

[a] Anglia Ruskin University, UK
[b] University of Cassino and Southern Lazio, Italy

Abstract

Strategies to protect built environment against natural disasters changed over the past decades to focus more broadly on the consequences for the community. Several quantitative and qualitative methods were proposed for risk assessment and estimation of losses, time and sources for the recovery. The suitability of those methods depends on the specific natural disaster and the build and social environment. Moreover, the definition of hazard, exposure, vulnerability and risk depends on the risk assessment level. In this work, a general framework for natural risk assessment at the community level is presented. Than it is customized for earthquake-induced soil liquefaction, which causes extensive damage on built assets and implying huge repair costs and delays of the community recovery, and tested on San Carlo district (Italy) case study, hit by such disaster in May 2012. The results demonstrate the limits of quantitative methods for risk assessment at community level and those of qualitative methods for risk assessment at geotechnical level.

Keywords: Risk assessment, Soil liquefaction, Qualitative method, Quantitative method.

1. Introduction

Natural hazards hit the environment where human communities live. Risk analysis is used to assess their impact on the communities. Multiple definitions of risk were proposed. The most applied one defines risk as a combination of hazard (H), vulnerability (V) and exposure, i.e. elements at risk, (E) (UNDRO, 1979). While the latest factor refers to population or buildings and infrastructures or economic activities and utilities, the vulnerability is the quantity of loss or damage of the exposed element.

The existing literature distinguishes two categories of methods for risk assessment : quantitative and qualitative methods. The former relate risk to physical quantities used to measure hazard, vulnerability and exposure and commonly apply the above risk definition; the latter are based on natural absolute or comparative scales used to measure the different components of the risk. Risk analysis methods based on multidisciplinary approach are called holistic. They employ indices measuring risk obtained by aggregating weighted indicators related to the effects of different aspects of the complex reality. Davidson (1997) stated that the quantitative approaches conduct to replicable results, while those qualitative are holistic and characterized by comprehensive risk understanding.

From the risk management prospective, quantitative risk analysis methods aim to provide generalized advice for land management and planning and inform decisional processes for mitigation (Chang et al., 2014). Their outcome is often a geographical distribution of the risk at different geographic scale, city or region, that enables the stakeholders to identify the weaknesses of the system of elements at risk (Brink and Davidson, 2015). On the contrary, the results of qualitative risk analyses represent the overall functional capacity of a system, thus they are not used to identify the weakest elements of built assets. The major strength of qualitative methods is the capacity of capturing the socio-cultural aspects of geographically distributed systems related to risk. Whereas, quantitative approaches to natural disaster risk analysis border the geographic area to which the analysis refers making impossible to understand the interaction between it and those surrounding. To overcome those limits some scholars proposed hybrid methods integrating aspects of both qualitative and quantitative risk analyses and sometimes attempting to quantify the socio-economic and cultural aspects. Hybrid methods quantify risk thriugh complex indices where factors measuring each contributing aspect are weighted with coefficients obtained by qualitative approaches.

* Corresponding author. E-mail address: mariantonietta.morga@anglia.ac.uk

Nowadays, risk analysis is used to estimate losses of a specific or multiple categories of systems located in an area due to a disruptive event. The issues about both the geographic definition of each system and the identification of the aspects of the interdependent elements at risk are problematic in case of much localized natural hazard, such as earthquake-induced soil liquefaction.

This work aims to highlight the strengths and weaknesses of liquefaction risk analysis with qualitative and quantitative methods at different levels of system complexity.

2. Risk assessment framework

Some natural disasters are cascade effects of others; for example, extreme rainfalls or earthquakes can cause respectively floods or landslides. In those cases, the risk assessment begins by estimating the primary hazards, such as extreme rainfalls or earthquakes, identifying the exposure, and by assessing their vulnerability, i.e. hydrological floodplain vulnerability or slope stability. These elements allow calculating the primary risk, which becomes the secondary hazard by looking to the built environment risk prospective. In fact, these phenomena cause damages to buildings and infrastructures, which are the exposure of the secondary hazard. The vulnerability of buildings and infrastructures is the measure of potential physical damage caused by a specific hazard with a given intensity. The risk of physical damage of built assets is a secondary or cascade risk. Buildings and infrastructures are not the last ring of the chain, which includes service delivery and ends with community. It is possible to state that the assessment of hazard, vulnerability, exposure and risk varies on case-by-case basis depending on the definition of system: what is risk in a case becomes hazard at higher level. At the highest analysis levels, elements at risk are interdependent and form a complex system, for which risk assessment with quantitative methods is inefficient and different metrics to estimate the vulnerability of each single element have to be used. The potential impacts caused by a hazard to complex system are economic, social, environmental and cultural: they produce both direct (immediate effect) and indirect (medium-long term effect, as consequence of the direct impacts) losses, assessed in monetary or non-monetary terms (Mechler, 2005).

3. Risk assessment of soil liquefaction disasters

Soil liquefaction occurs when loose saturated sandy soils are subjected to intense shaking, and then, as result of the applied stress, the soil decreases in strength and stiffness because of the increase in pore water pressure. As consequence, the foundation soil behaves like a liquid (National Academy of Sciences, 2016) and, as past events showed (Tohoku, 2011, Christchurch 2010-2011 (National Academies of Sciences, 2016) and Emilia Romagna, 2012 (Cimello et al., 2013)), loss of shear resistance leads to superstructure collapse. Quantification of expected liquefaction and prediction of its effects are becoming part of the seismic risk assessment because it produces appreciable economic losses and delay of communities recovery.

Soil liquefaction triggering depends on the primary hazard, i.e. ground shaking, specific stationary (SBT) and non-stationary (GWT) soil characteristics (liquefaction susceptibility). Considering the seismic hazard and the soil susceptibility, the soil liquefaction is a primary risk.

Soil liquefaction becomes a hazard affecting buildings and infrastructures: their physical vulnerability combined with such hazard allows estimating the risk of their physical damage. For an area, the risk analysis referred to buildings and infrastructure networks requires the estimate of a seismic input over a time-period and the quantification of the complex system vulnerability (subsoil liquefaction susceptibility and structural vulnerability).

Following the cascade effect, risk of physical damage of built assets is a hazard for their service delivery. Finally, the last level of risk assessment concerns the community, which is harmed by the loss of structure and infrastructure serviceability. This risk can be assessed in terms of deaths, injuries, loss of heritage and incomes. All those measures of community risk are often expressed in terms of economic losses, although such estimate, based on qualitative methods, is not objective. As consequence, the risk assessment of upper level vulnerable systems should include elements based on qualitative methods.

Figure 1 represents the elements involved in the liquefaction risk assessment either by applying quantitative or qualitative approaches. It shows that, as changing the position of the lines bordering the vulnerable system (on the right column of the figure), different definitions of hazard and risk are obtained. The above concepts applied to cities or regions entail the necessity to assess the seismic hazard of that area, the soil susceptibility, the physical and functional response of different structures and infrastructures and the community reactivity. This is possible by applying quantitative methods that provide a spatial representation of the outcomes. Such kind of analysis does not produce an aggregated value of the risk assessment of regions; therefore, it is of limited use in comparative studies or for comprehensive estimation of losses.

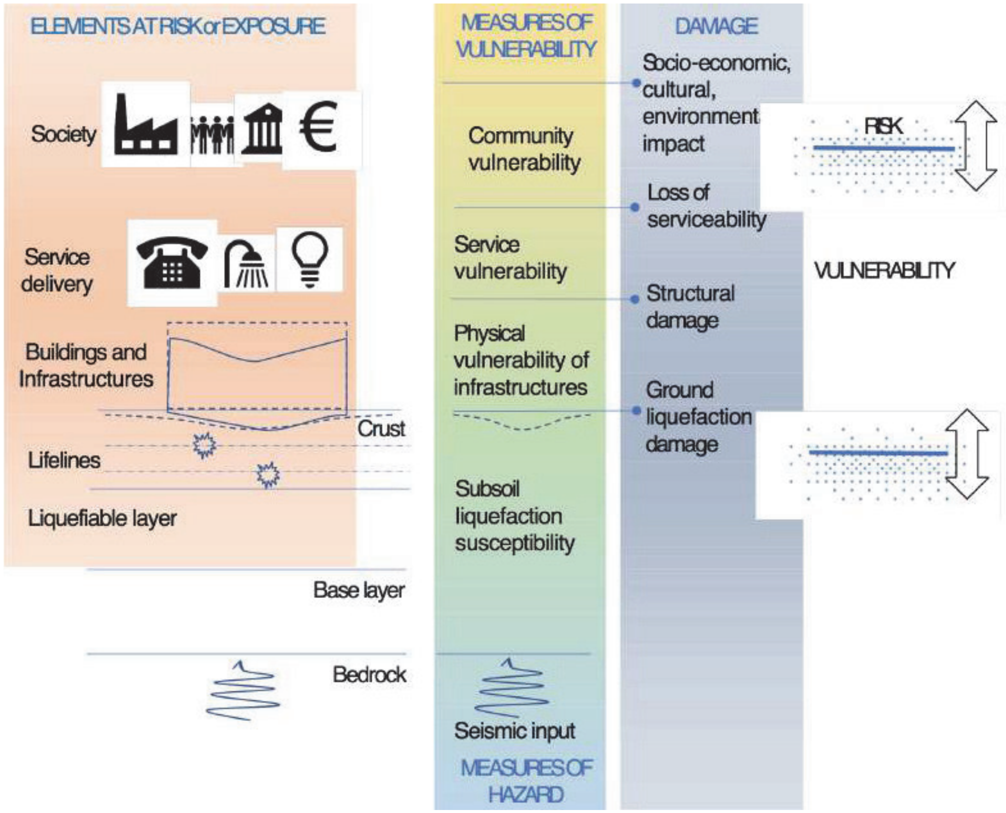

Figure 1: Definition of risk assessment for earthquake induced soil liquefaction.

A large number of geotechnical investigations is needed to characterize the subsoil with sufficient accuracy to estimate its liquefaction susceptibility. Methods based on common in-situ investigations were developed in the last decades. Microzonation maps represent the liquefaction potential calculated through these methods and they are currently used in land management and planning at local level, in particular for risk assessment of structures and infrastructures.

Besides this quantitative assessment of liquefaction hazard, a qualitative one based on events occurred in the past centuries is possible, but meaningless because of long return time and dependency on several non-stationary and uncertain factors. The knowledge of the site geological history allows to identify areas susceptible to liquefaction and plan in-situ tests.

Seismic vulnerability of structures is normally defined for building stocks. For localized phenomena, such as liquefaction, the risk estimation should be done on single structures. In case of infrastructure networks, the failure of single elements might cause disruption of the whole network and accurate microzonation maps are fundamental for risk analysis because it allows identifying the elements at risk and reducing the cost of vulnerability assessment at large scale.

The risk of physical damage of buildings and infrastructure networks is the first element of the risk analysis of service delivery. In this case the system becomes complex because of interdependencies among its elements. At this analysis level, a quantitative method for risk assessment shows limits: the geographic bordering of the analysed area is complicate because service loss can affect elements of built environment outside it.

At the community level, the risk of soil liquefaction disasters is hardly measurable, as this is a localised phenomenon. However, it can have large repercussions on the community in case critical infrastructures are affected, as repairing liquefaction damage can be cost and time–intensive.

4. The case study of San Carlo district (Italy)

The described methodology is applied to a case study: San Carlo district of the municipality of Sant'Agostino (Italy) (Figure 2), which was hit by the 2012 seismic sequence. On 20th May a Mw 6.15 event struck the whole

Sant'Agostino municipality causing damages (186 buildings damaged at different levels only in San Carlo district) and extensive soil liquefaction (sand boils and cracks). At that time, San Carlo district hosted: approximately 1500 inhabitants, housed in 660 buildings (ISTAT, 2018); a school; a church; and an industrial warehouse (Regione Emilia-Romagna, 2018b). San Carlo district,

Reminding soil liquefaction occurs in areas with specific geological features, it is worth highlighting that Galli, et al. (2012) showed the presence of hidden paleochannels in that district (Figure 2, left side) and the topographical survey of the area (Figure 2, right side) evidenced the presence of hidden paleolevees; thus, the area was clearly susceptible to soil liquefaction.

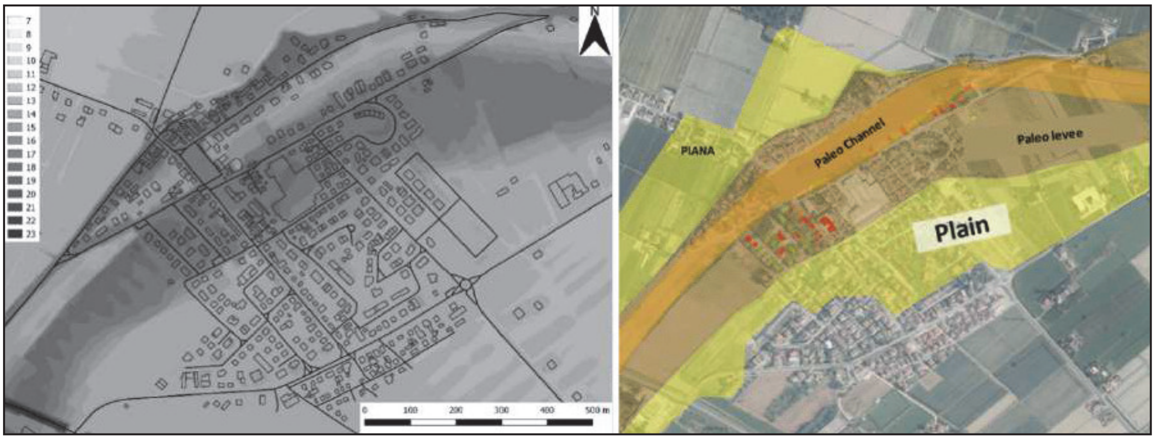

Figure 2: Digital Elevation Model (on the left) and geological map of San Carlo area (on the right).

Liquefaction ground severity (Figure 1) is frequently expressed with indicators summarizing the effects of liquefaction at different depths. One of these is the Liquefaction Severity Number (LSN) that integrates the post-liquefaction deformation over a depth of 20m, divided by the depth to give more importance to shallower liquefaction (van Ballegooy et al., 2014). This value is associated to the expected liquefaction ground damage (see Table 1), which is risk of soil liquefaction considering the primary hazard: earthquakes.

Table 1: LSN ranges and observed land effects (van Ballegooy et al., 2014)

LSN	Related effect
0-10	Little to no expression of liquefaction
10-20	Minor expression of liquefaction
20-30	Moderate expression of liquefaction with some structural damage
30-40	Moderate to severe expression of liquefaction and settlements causing structural damage
40-50	Major expression of liquefaction resulting in severe total and differential settlement of structure
+50	Extensive evidence of liquefaction resulting in severe total and differential settlements affecting structures

This indicator can measure the soil liquefaction hazard threatening structures, if it is computed considering earthquakes having a certain occurrence probability. For San Carlo district, after the 20th May earthquake, 200 values of the LSN are obtained and spatially interpolated, after the CPT data processing (Figure 3).

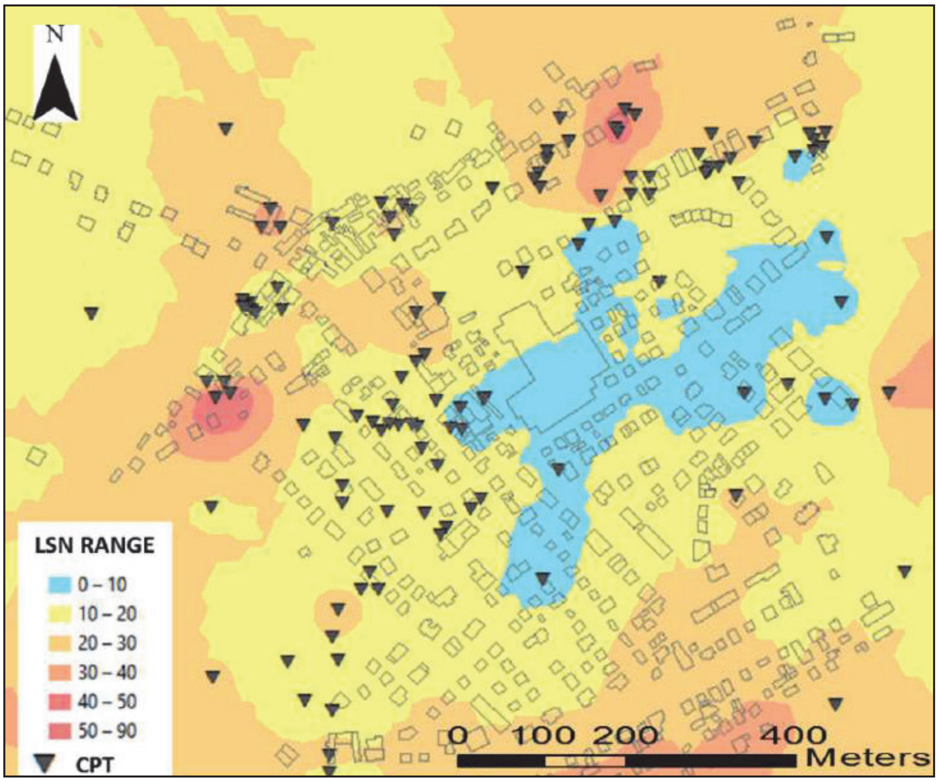

Figure 3: LSN map for San Carlo district.

The comparison between the LSN map (Figure 3) and the observed liquefaction-induced land damages (Figure 4) proves that it is a good proxy of such hazard over a urban or regional scale highlighting the most critical areas. However, the physical risk of structures need a site-specific analysis based on more accurate geotechnical model and method to simulate the combined response of structure and foundation soil.

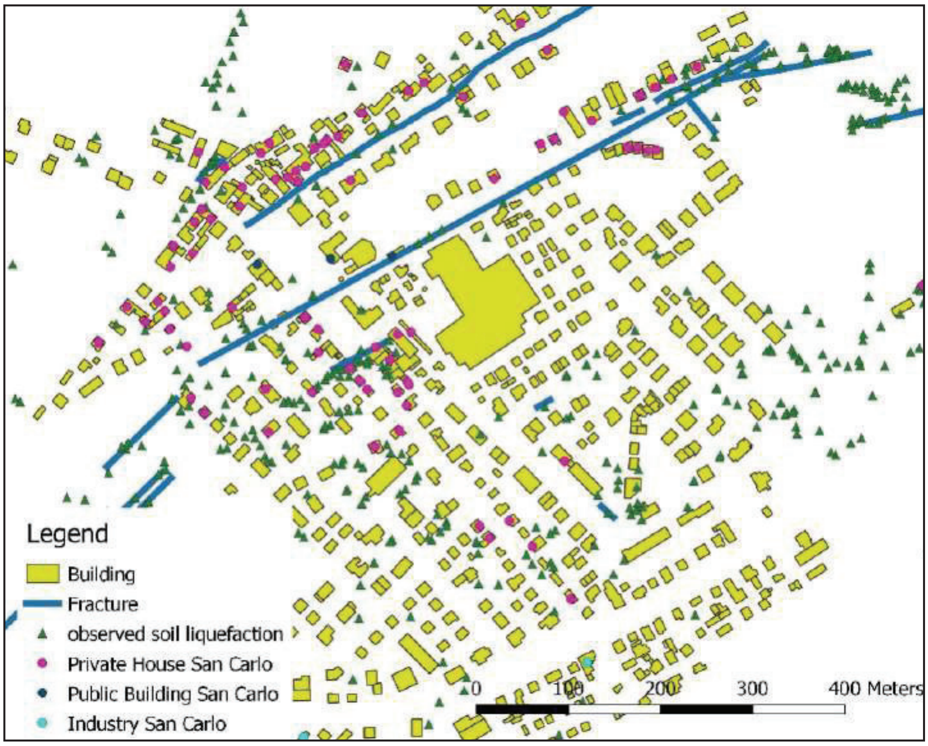

Figure 4: Map of San Carlo district with damaged building and sand boils.

By overlapping the LSN and damaged buildings maps, it is assumed that all those buildings were damaged by soil liquefaction besides ground shaking. According to O.P.C.M. n.14 (2013), in S. Carlo district 21 buildings were in operational level B/C, 3 in level E0, 7 in level E1, 10 in level E2 and 43 in level E3. The operational level B-C and E0 are used for buildings with low damage and not needing repair. The operational levels E1 and E2 indicate heavy building damage and need of repair. Finally, the operational level E3 is used for buildings so heavily damaged to be needing demolition and reconstruction. Those operational levels defined in O.P.C.M. n.14 (2013) are a post-event measure of the building damage and capacity of service delivery; therefore, they are a combination of the damage state and vulnerability.

Table 2: Operational level of damaged buildings in San Carlo district and evacuated living units.

Operational level	B/C	E0	E1	E2	E3
Inhabitants affected	75	9	30	41	163
Living units	43	5	23	19	96

At the community level, several factors must be assessed to estimate the risk. First of all, the effect of the operational level of buildings on their residents: buildings classified to have operational levels E were evacuated. In addition, at the community level the first measure of the risk is the total costs of provisional housing for the evacuated population. After the May 2012 earthquake sequence, the Government of the Emilia Romagna region paid 200€ per person to evacuated families each month as grant aid for the provisional housing and 350€ per person living alone (Regione Emilia-Romagna, 2018a). The grant aid was available for a maximum of twelve months from 1st June 2012 to 31st May 2013 and families could ask it for the time they could not live in their house because of repair or reconstruction works. The first of those works ended on 31st May 2013; therefore, all evacuated families asked for the maximum amount of grant aid. The buildings classified to have an operational level E were 63. Some buildings had more than one living unit and Table 2 show the total number of evacuated people (Regione Emilia-Romagna, 2018b).

The estimated total costs of provisional housing for the population of San Carlo district was 482,000 Euro. These costs are indirect and they are the only one easily to estimate. At the community level, the liquefaction risk assessment concerns the estimation of repair and rebuilding cost of damaged buildings. For San Carlo district, it includes the costs of private houses, public buildings, infrastructures and provisional public buildings, such as prefabricate schools. For that district the total costs of demolition and rebuilding or repair and strengthening of private houses was around 32,000,000 Euro (Table 3), including an increase of the total costs equal to 15% because of soil liquefaction disaster (Emilia Romagna, 2012). As consequence, the shaking-induced damages costed 27,800,000 Euro and the liquefaction-induced damages 4,200,000 Euro. The regional government paid the full costs of repair and rebuilding of industrial and service buildings and partially refunded the costs of damaged equipment and tools. The total cost of public buildings was 4,600,000 Euro (Table 3), which includes both repair and rebuilding of buildings and construction of provisional ones (schools).

Regarding infrastructures, only the repair cost of the damaged road of San Carlo District is known, i.e. 41,000 Euro (Table 3). Additionally the repair of the sport centre damaged by ground shaking and soil liquefaction costed 46,000 Euro (Table 3). All those costs are direct. At the community level, the rough estimation of the soil liquefaction risk of San Carlo district is around 37,000,000 Euro. This is obtained by using a quantitative method and excludes factors related to social impact of the disaster, such as the feeling of insecurity at home or in the work place, the loss of school months, the distress owing to the provisional housing, etc.. For instance, the damages to the historical building of the district, a church, were repaired, but the community distress due to this temporary outage could not be estimated. Those factors can be estimated only by applying qualitative methods for the community risk assessment, which require the involvement of community representatives in participatory research activities.

Table 3: Known direct costs of soil liquefaction disaster in San Carlo district.

	Total costs for repair, strengthening and reconstruction (Euro)
Private houses	32,000,000
Public buildings: infrastructures (schools, public offices)	1,580,000
Public buildings: cultural heritage	2,500,000
Industry and service sector: buildings	530,000
Industry and service sector: instruments and tools	49,000
Infrastructures	41,000
Leisure centre	46,000

5. Conclusions

The study described the complexity of community risk assessment to natural hazards and in particular to earthquake induced soil liquefaction disaster. Elements at risk and hazards for each level of complex system of systems are identified together with the different risk assessment level: from the geotechnical primary risk to the community one. The case study of a small Italian district is proposed. First, the soil liquefaction risk is assessed by a quantitative method, as damage at soil or LSN. Then, the physical and service delivery risk of built assets is presented by using a quantitative method based on post-event data. For this level of risk assessment, the private buildings are classified based on their capacity to deliver their service: housing people. Finally, the community risk is assessed by costing direct and some indirect damages. However, an analysis of the results shows that some factors of the community risk cannot be quantified. Hence, it is concluded that: at community level a disaster risk assessment is possible only with qualitative methods that includes the active participation of the community itself.

Acknowledgements

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