Transportation Infrastructures Exposed to Seismic Risk: Evaluation of Social Costs for Resilience Design

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Abstract. Seismic risk assessment and management of civil infrastructure systems are prominent topic for researchers. Different methods and approaches were proposed in the past and in this study, a methodology to evaluate social cost due to reduction or loss of serviceability of road network caused by catastrophic event as the liquefaction phenomenon, was developed. The strategy involves the combination of hazard, vulnerability and exposure of the transportation network by means of geotechnical and traffic analyses.

The methodology was applied to the Municipality of Terre del Reno (Italy), that in 2012 was hit by a strong seismic sequence which caused severe liquefaction phenomena on the territory.

Five different seismic events with increasing seismic intensity were simulated and, according to the damage level occurred, a grade of serviceability to the road network, was assigned. For each scenario, a traffic analysis, to evaluate the travel time, was performed and the social cost in terms of Over Delay Cost were evaluated.

The results show an increasing Over Delay Cost as the seismic intensity increases, until the isolation of the Municipality, when a reduction was observed. It can be due a huge number of daily trips forcibly suppressed.

Although the methodology refers to damage caused by liquefaction phenomena, it is simply adaptable to any catastrophic event.

Keywords: Seismic Resilience · Transportation Network · Social Cost · Embankments · Serviceability · Liquefaction

1 Introduction

The long and forced coexistence with the global pandemic has led to rethink the modern societies and innovative economies by improving speed and multi-level communications: information, knowledges, services, goods, people move more quickly than before. Reliability, efficiency, and safety are key aspects required to both emerging and

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traditional communication networks, especially when extreme and disastrous scenarios happen. Catastrophic phenomena, as liquefaction induced by earthquakes, affecting conventional transportation systems as rail or road networks, can cause both direct and indirect economic losses. In fact, several events in the world (as Christchurch 2010, 2011 and 2016; Tohoku Oki, 2011; Emilia Romagna, 2012; Kumamoto, 2016) have shown the destructive potential and economical damages of liquefaction due to seismic events.

From early nineties, several national and international projects and methodologies have been promoted with the aim to estimate the potential losses induced by catastrophic events [1–5]. As far as transportation networks and infrastructures are concerned, the most significant researches and projects, with their main features, are summarized in the Table 1.

Table 1. Summary of the main research projects/methodologies for losses estimation.

Project/ methodology	Ref.	Hazard type	Losses Estimation	Transportation Analysis
AllTraIn	[6]	Natural, Man-made	Element level	No
STRIT	[7]	Natural	Element level	No
HAZUS	[8]	Natural	Network level	No
SYNER-G	[9]	Natural	Network level	Yes
Molarius et al	[10]	Natural	Network level	No
SecMan	[11]	Man-made	Network level	No
SeRoN	[12]	Man-made	Network level	Yes
Seville et al.	[13]	Natural	Network level	Yes
REDARS 2	[14]	Natural	Network level	Yes
Chang L.	[15]	Natural	Network level	Yes

It is understandable that as far as catastrophic risk assessment and mitigation interventions decision-making on transportation systems are concerned, the element level (bridges, tunnels, …) analysis is insufficient and, at least the network-level analysis within a long-term period, is required. According to the transportation network analysis classification [9], summarized in the Table 2, the *Capacity Analysis* seems represent a minimum requirement for guaranteeing reliable results in terms of socio-economic impacts related to the traffic flows rearrangement.

Table 2. Summary of the transportation network analysis classification [9].

Transportation network analysis type	Description
Vulnerability	related to the damage level of each single element of the transportation network (as bridge, tunnel, embankment, etc.), according to a specific post-seismic scenario
Connectivity	according to a specific post-earthquake scenario, evaluates the accessibility to specific or strategic areas when the loss of service of some connections occurs
Capacity	related to the network capacity to accommodate traffic flows, provides direct and indirect losses due to damage levels occurred of the whole network
Serviceability	provides a more realistic estimate of total loss on the long-term period, considering both direct and indirect impacts on the economic sectors

Follow this direction the main aim of this study is to present a methodological approach for the evaluation of social losses due to liquefaction damage suffered by a transportation system and its application on a case study.

2 Methodology

The probability of occurrence of the risk of liquefaction is associated with the seismic intensity, the motion of the soil, the susceptibility to subsurface liquefaction, the response to infrastructure, physical damage, and socio-economic losses. The assessment of the risk of liquefaction can therefore be summarized as follows (1):

$$LR = f\{H, V, E\} \tag{1}$$

where:
LR = Liquefaction Risk;
H = Hazard;
V = Vulnerability;
E = Exposure.

The factors necessary for the occurrence of liquefaction are:

- The seismic event;
- Sand with limited fine content;
- Low density;
- Saturation.

According to the proposed methodology, the coupled approach for the subsoil is proposed - the infrastructural responses, customizing the formula of Karamitros et al. [16], which was then applied to estimate the settlements of the road embankment [17].

Table 3. Definition of damage state for Roadway embankments [18].

Damage State	Permanent Ground Deformation [m]			Damage description	Road Network Serviceability
	min	max	mean		
Minor	0.02	0.08	0.05	Surface slide of embankment at the top of slope; minor cracks on road surface; minor track displacement	Useful road with speed reduction
Moderate	0.08	0.22	0.15	Deep slide or slump of embankment; medium cracks on road surface and/or settlement; medium track displacement	Partially open during repair works (alternating direction of travel)
Extensive	0.22	0.58	0.40	Extensive slump and slide of embankment; extensive cracks on road surface and/or settlement; extensive tracks displacement	Unusable

As regards the assessment of the vulnerability of road embankments, the SYNER-G classification for the definition of damage status limits has been adopted [18]. The main features have been summarized in Table 3:

A catastrophic event causes damage to the transport network, which can be assessed as a sum of direct losses (such as the cost of repair or repositioning of damaged elements) and indirect (reduction or interruption of the transport network service and its impact on society and the economy). In this methodology the *Capacity Analysis,* which represents a satisfying approach to evaluate socio-economic impacts related to the mobility in the post-seismic scenario, has been performed to evaluate the indirect losses in terms of the *Total Delay Cost*, *TDC*.

In fact, the reduction/loss of serviceability of the transportation networks, which can mainly depend on the features of the transportation system and the traffic demand, has as principal consequence the impact on the traffic flows and the trips of the study area. Assuming that the *Generalized Transport Cost*, *GTC*, is a measure of the overall cost (including travel time cost) that is "paid" by each transport user in a specific study area, the *TDC* can be evaluated by means of the following expression (2):

$$TDC = GTC_{post} - GTC_{pre} \tag{2}$$

where:

TDC = Total Delay Cost computed daily.

GTC_{post} = Generalized Transport Cost in the post-seismic scenario;

GTC_{pre} = Generalized Transport Cost in the pre-seismic scenario.

The TDC multiplied by the number of days needed to ensure the restoration of the situation pre-event provide the total social cost defined by the acronym *OSC*.

This social cost represents the cost to the population of the affected area.

The Capacity analysis requires the development and implementation of the *Travel Demand Forecasting Model*, *TDFM*.

A TDFM [19] is a model consisting of four sub-models.

It is defined cascading because the output of the previous model becomes the input of the next model.

These sub-models essentially define the origin and destination of travel, the route chosen by the user, the means of transport and the time taken to make the travel. It is worth noting that, although the methodology refers to damage caused by liquefaction phenomena, it is replicable and adaptable for any destructive event or calamity.

3 Case Study

The Emilian Po Valley (Italy) has been subject to two major seismic events that have caused a total of 27 victims, about 400 injured, over 15,000 displaced people and significant damage to the cultural and economic heritage of the area. Furthermore, due to the conditions of the subsoil, widespread liquefaction phenomena have been observed. In the municipalities of San Carlo, Sant'Agostino and Mirabello, (see in Fig. 1) along the old riverbed of the Reno River, the greatest concentration of liquefaction evidence, have been detected [20]. These urban areas and their relative road networks have been built near the paleo-channel and paleo-levees of the Reno River where the subsoil can be categorized into (from the top to down): fluvial channel deposits; a stratum of fine-grained materials (swamps) and Pleistocene alluvial plain. Finally, in order to protect the territories against flooding, the artificial silty sand layers have been built along the old riverbed.

Due to the importance of the series of seismic events and the numerous and relevant observations of liquefaction phenomena, the area of the municipalities of S. Carlo,

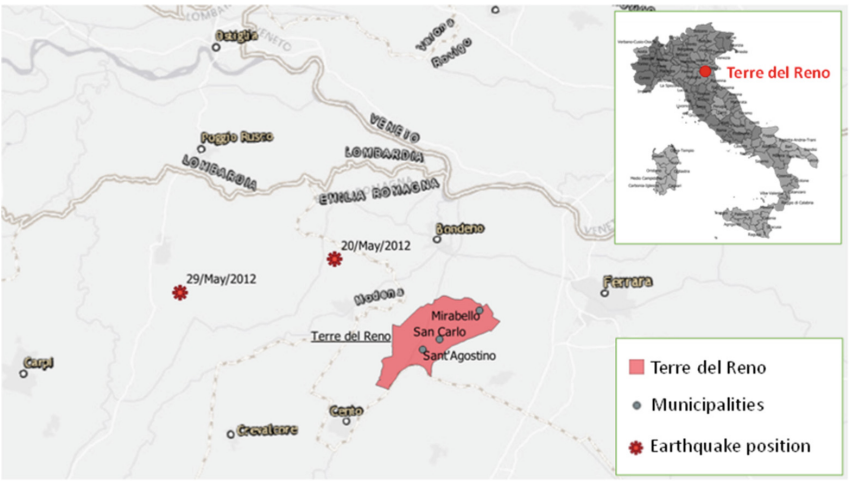


Fig. 1. The Terre del Reno areas, the municipalities of Sant'Agostino, San Carlo and Mirabello and the position of the two major seismic events occurred in 2012. [26]

Sant'Agostino and Mirabello, called Terre del Reno, has been therefore selected as the case study in the analysis of resilience due to liquefaction damage on the road network.

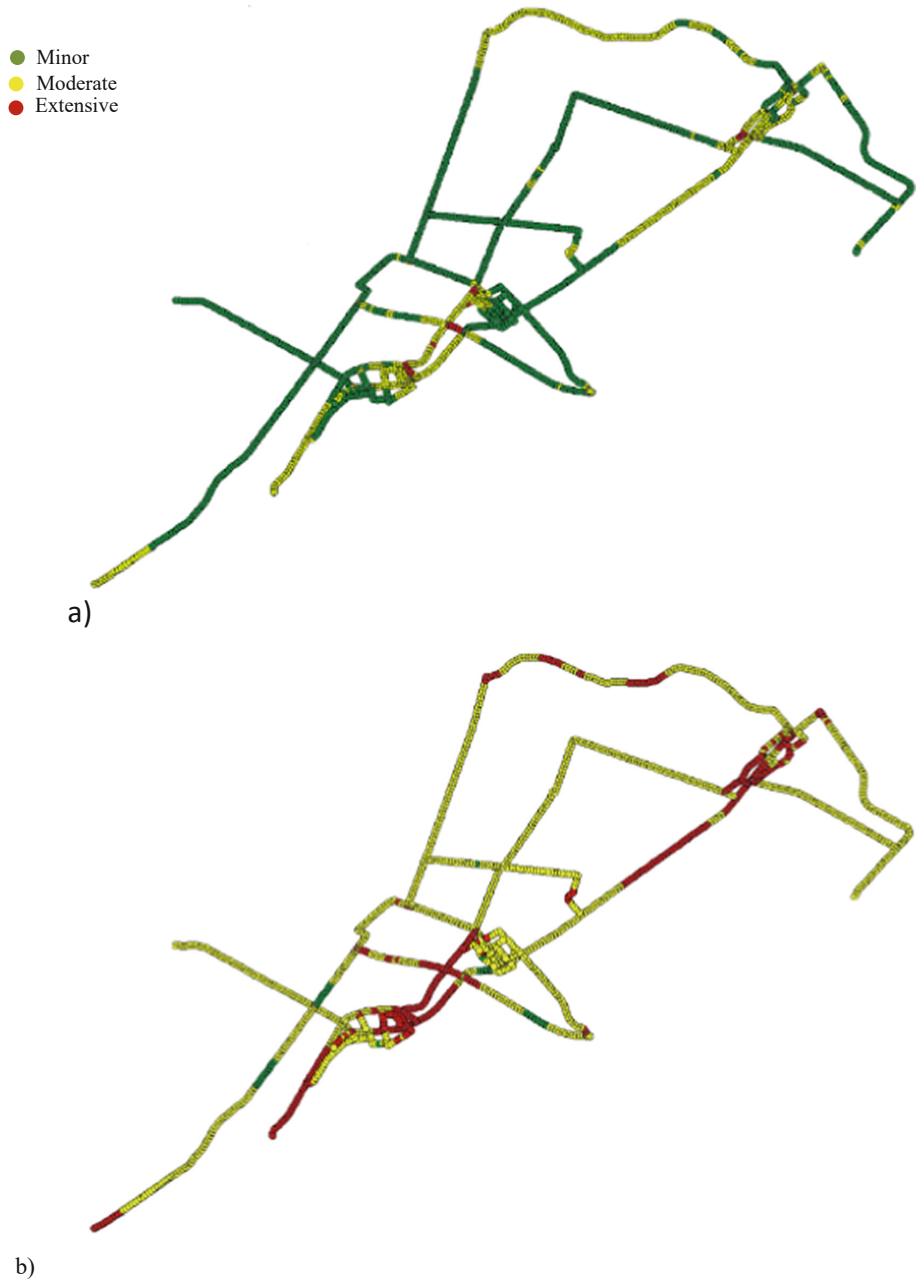


Fig. 2. Maps of the embankment damage levels for a) RP 30Y and b) RP 975Y.

3.1 Liquefaction Phenomenon and Damage Evaluation

According to the liquefaction risk assessment proposed in [21], the coupled approach for subsurface and infrastructure resettlement has been adopted. Indeed, from a comparison with an effective stress calculation using an advanced numerical model [17], the formula of Karamitros et al. [16] has been adapted to calculate the sets induced by the liquefaction of the banks of Terre del Reno. To apply a probabilistic approach, four increasing seismic events have been simulated for the road network damage evaluation. Return Periods (RPs) of 30, 50, 475 and 975 years, have been selected.

By way of example in the b).

Figure 2 is reported the road network damage level for RP 30 years and 975 years.

3.2 Travel Demand Forecasting Model of Terre del Reno

A Terre del Reno TDFM was developed which, after sensitivity analysis [22] was calibrated and experimentally validated in a 60 km radius buffer area around a rural area in the Terre del Reno district [22]. In the Fig. 3 the graph of the study area has been reported.



Fig. 3. Graph of the Study area [26].

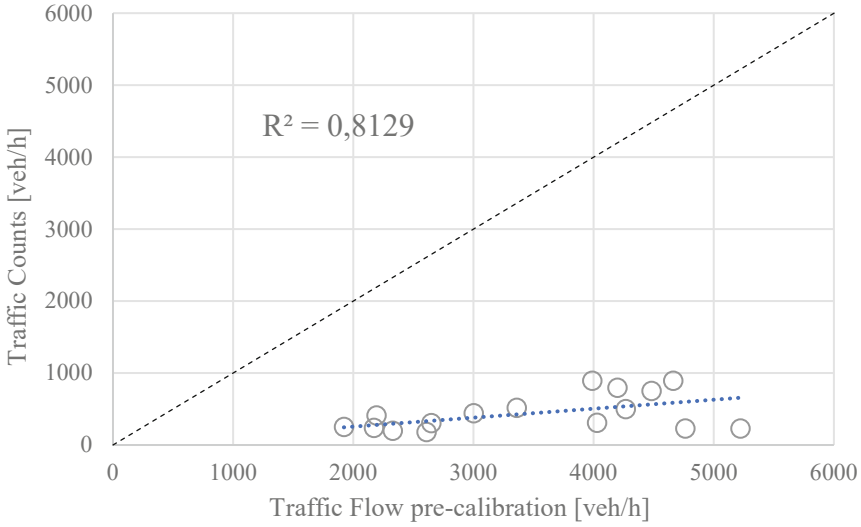
In particular, the scenarios chosen for the case study are divided according to different "schedules":

- "Peak" which occurs mainly in two-time bands (from 7:00 to 9:00 and from 17:00 to 19:00)
- "Median peak" (12:00 to 14:00)
- "Off-peak" for the rest of the day.

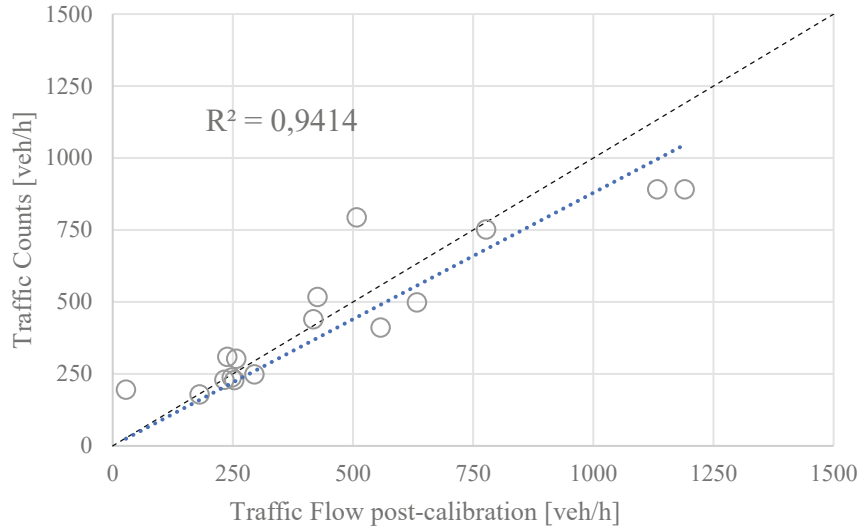
The O/D matrix was assessed from the commuting data provided by ISTAT [23] and then calibrated with traffic counts provided by the Emilia - Romagna region [24].

As an example, in Fig. 4 the results of the TDFM calibration have been reported, in terms of traffic flows for the morning peak hours.

To convert the traffic delay into Overall Social Cost, a cost of 45€ for heavy vehicles and 12€ for the others, has been applied.



a)



b)

Fig. 4. Comparison of Traffic Counts VS Predicted Traffic Flow a) pre-calibration and b) post-calibration [26].

4 Results

For each scenario, including the actual scenario of May 2012, the infrastructure damage incurred was assessed and identified in the TDC and OSC both expressed in the Eq. (2). The results in terms of traffic and OSC can be seen in Table 4.

Table 4. Summary of the results in terms of traffic delay and OSC, suffered by Terre del Reno, for different return periods.

Return Period	Traffic Delay [h]	Overall Social Cost [€]
30 Years	1014	34.354.989
50 Years	1118	38.003.367
May 2012 Event	1636	62.481.661
475 Years	1063	46.689.300
975 Years	1019	48.569.595

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Table 4, in the last two analyzed return periods, a reduction, in terms of both traffic delay and OSC, has been highlighted. While it may seem counterintuitive, the reduction is correctly related to the damage level suffered by the road network. In fact, in the last two return period scenarios, a complete isolation of the Municipality of Terre del Reno occurred. In these cases, a considerable number of trips, which generally take place the territory of Terre del Reno, is suppressed. These lost trips are also a cost suffered by the community which must renounce to the movements of its normal everyday life.

5 Conclusions

A liquefaction risk assessment methodology to estimate the social cost suffered by a community after a seismic event has been presented. The strategy involves the evaluation and combination of the territorial distribution of hazard, vulnerability, and exposure also by means of geoinformatics [25].

A probabilistic approach has been performed on the Municipality of Terre del Reno, by simulating five different seismic events with increasing return periods. The relative liquefaction damage levels suffered by the road network have been evaluated and, for each scenario, a traffic analysis, to evaluate the travel time, has been performed.

The analysis shows that traffic delays suffered by the population increase considerably as the seismic intensity of the event increases.

This implies, at a given intensity of event, also the isolation of the Municipality.

This in isolation would appear to decrease the amount of traffic on the network but, generates additional costs that the community faces. Further analyses are needed to quantify in a proper way, the economic value of the suppressed trips due to the loss of accessibility to the Municipality.

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