

Simplified Approach for Liquefaction Risk Assessment of Transportation Systems: Preliminary Outcomes

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Abstract. In the present study, a strategy to assess liquefaction risk of road infrastructures has been proposed, as combination of liquefaction hazard, infrastructures vulnerability and exposure of transportation network. The proposed methodology includes a capacity analysis of the road network performed on both pre- and post-liquefaction scenarios to evaluate the social cost in terms of delay cost suffered by the transportation system. The approach has been applied to the municipality of Terre del Reno (Italy), that in 2012 suffered a severe seismic sequence that induced extensive liquefaction evidences over the territory. A multi-layer database, on a Geographical Information Systems (GIS) platform, has been created, with the aim to overlap information about subsoil, earthquake intensity, groundwater depth and road network configuration. The Vulnerability of road has been evaluated by the settlements of embankment on liquefied soils and, according to the damage level occurred, a loss of functionality has been assigned. Finally, performing a transportation analysis, the effects on the traffic conditions have been evaluated in terms of Total Delay Cost, suffer by the road users. Preliminary results showed a redistribution of the traffic flows caused by the service loss of crucial road sections due to the liquefaction evidences on the transportation network and the related Total Delay Cost has been quantified.

Keywords: Seismic risk · Liquefaction · Transportation network · Embankments · Serviceability · Social cost

1 Background

The serious consequences of liquefaction induced by earthquakes is worldwide proved by several events as, for example, those occurred in 2010, 2011 and 2016 at Christchurch, in 2011 at Tohoku Oki, in 2012 in Emilia Romagna (Italy) or in 2016 at Kumamoto. The destructive effects could damage all the infrastructure assets of the

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modern societies as buildings, factories, lifelines, transportation networks, which are directly or indirectly connected to the productive systems. In the past two decades, significant efforts have been performed to develop different methodologies for estimating the potential losses induced by earthquakes but the liquefaction phenomenon has been still considered a side effect, although recently the liquefaction risk assessment have been integrated into national and international standards [e.g. 1, 2]. Among the most recent National and International projects and researches, from the specific viewpoint of Transportation Networks and Infrastructures, deserving of attention are: the European project AllTraIn (All-Hazard Guide for Transport Infrastructure; 2013–2015) and the Italian project STRIT (Tools and Technologies for Risk Management of Transport Infrastructure; 2012–2015) which provide an economic losses estimation performing element analysis, especially bridges and tunnels that are intrinsically considered the most vulnerable of the network [3, 4]. Other European projects, with different approaches and degrees of details, perform analysis at network level considering both natural hazards [5–7] and intentional and exceptional man-made hazards [8, 9]. Seville e Nicholson [10], showed the results of an analysis of the risk of closure of a strategic road section in New Zealand (State Highway 1 which constitutes the major north-south road link). The authors performed a transport analysis at network level, including the assessment of the cost due to: additional travel along the alternative routes, increased accident exposure and loss of user benefit for cancelled trips. As far as seismic risk assessment and mitigation interventions decision-making on transportation systems are concerned, at least the network-level analysis is requested and so far studies have mainly examined the earthquake hazard regarding to bridges, consequently the focus of the researches has been primarily on bridges retrofitting. For example, the seismic risk reduction decision-guidance process proposed within the REDARS 2 (Risks from Earthquake Damage to the Roadway System) Project, would select retrofit sequence that provides the optimum seismic performance of the system, within tentatively hypothesized mitigation strategies (alternative priorities could be

Table 1. Summary of the main research projects/methodologies proposed.

Project/methodology	Hazard		Losses estimation		Transportation analysis
	Natural	Man-made	Element level	Network level	
AllTraIn [3]	Yes	Yes	Yes		
STRIT [4]	Yes		Yes		
HAZUS [5]	Yes			Yes	
SYNER-G [6]	Yes			Yes	Yes
[7]	Yes			Yes	
SecMan [8]		Yes		Yes	
SeRoN [9]		Yes		Yes	Yes
[10]	Yes			Yes	Yes
REDARS 2 [11]	Yes			Yes	Yes
[12]	Yes			Yes	Yes

evaluated in terms of the means and standard deviations of the resulting total costs) [11]. Furthermore, in order to improve the post-earthquake transportation analysis, a more refined methodology has been proposed by Chang [12]. According to the author, it is possible to improve the retrofitting analysis modifying the post-earthquake origin-destination (O/D) matrix respect to the pre-earthquake (static) O/D matrix as an input for traffic flow analysis, in order to take into account the change of traffic pattern after the seismic event and the damage of transportation infrastructures. In particular the trip generation and distribution stages of a traffic analysis are modified to consider the earthquake-induced damage. In the Table 1 are summarized the main features of the aforementioned projects and methodologies.

2 Levels for Road Transportation Network Analysis

With the aim to evaluate the socio-economic impact due to destructive events by means of a risk based analysis, two main approaches can be usually followed to identify the period analysis: *short-term period*, focused on the emergency actions, assuring the accessibility for rescue crews and machines also to smaller and more isolated communities and *long-term period*, which includes the recovery phase needed to perform repair actions for restoring initial conditions of the transportation network.

According to recent literature [6] a systemic analysis of transportation networks, according to the level of assessment of their functionality have been proposed:

- *Vulnerability Analysis*, which, according to a specific post-earthquake scenario, is related to the damage level of each single component of the transportation network (as bridge, tunnel, embankment, etc.);
- *Connectivity Analysis*, which, according to a specific post-earthquake scenario, evaluates the accessibility to specific or strategic areas despite the loss of service of some connections;
- *Capacity Analysis*, which, related to the network capacity to accommodate traffic flows, provides direct and indirect losses due to damage levels occurred of the whole network;
- *Serviceability Analysis*, which, taking into account both direct and indirect impacts on the economic sectors, provides a more realistic estimate of total loss on the long-term period.

In the current economic and social contest, it is worth to be highlighted that, although the objectives in terms of performance and safety of the transportation networks are increasingly ambitious, a marked reduction in investment budgets is observed. In order to cope the limited budget availability, although the *Serviceability Analysis* could return results (in terms of socio-economic losses) more comprehensive than the others, because of the extent and complexity of its input data, it is not carried out. Therefore, the *Capacity Analysis* seems represent a satisfying compromise, while still guaranteeing reliable results in terms of socio-economic impacts related to the traffic flows.

3 Risk Assessment Induced by Liquefaction

Seismic liquefaction may occur when strong earthquake affects loose saturated sand. The pore-water pressure build-up causes a reduction of effective stress that, in critical condition may lead to a considerable loss of shear strength.

The probability of liquefaction occurrence in a soil deposit is mainly due to the combination of several factors, i.e. susceptibility of the soil, depth of groundwater, intensity and duration of the seismic event. While the above factors represent hazard, the presence of infrastructures and the vulnerability of the latter have to be taken into account for risk assessment. In order to formalize the methodology for liquefaction risk assessment, the likelihood of occurrence and the associated uncertainty on earthquake amplitude, ground shaking, liquefaction experiencing, structural response, physical damage, and socio-economic losses have to be quantified and combined. It can be summarized into the synthetic formal definition of *Liquefaction Risk* as the combination of *Hazard*, *Vulnerability* and *Exposure*.

As far as the liquefaction phenomenon is concerned, the seismic event is usually considered the mainly hazard factor combined with the presence of loose granular materials with limited fine content, sufficiently low density and saturation. Hence, the coupling of earthquake and subsoil response induces the demand for the infrastructure at the ground level. According to the proposed methodology, for evaluating the liquefaction hazard, the coupled approach for subsoil and infrastructural responses is proposed. In particular, the formula of Karamitros et al. [13] has been customized to this specific case, comparing the results with an effective stress calculation performed with an advanced numerical model [14]. Generally, according to a specific infrastructure, the vulnerability is its predisposition to suffer a fixed damage state, due to a liquefaction event. In this study, for the definition of the damage state limits for highway embankments, the SYNER-G classification [15] summarized in Table 2 has been adopted:

Table 2. Definition of damage state for highway embankments [15].

Damage	PVG displacement [m]			Description	Serviceability
State	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	Closed

For completing the *Liquefaction Risk* assessment, the *Exposure* concept for road transportation network, has to be introduced.

4 Road Transportation Network: Exposure and Indirect Losses

As previously mentioned, the probability of occurrence and the associated uncertainty on seismic intensity, ground motion, liquefaction evidences, structural response, physical damage, and socio-economic losses contribute to the seismic liquefaction risk assessment. Indeed, according to a specific transportation network asset, the combination of the Hazard, the Vulnerability and the Exposure defines the risk related to a possible seismic/liquefaction scenario. As far as the liquefaction risk of transport network systems is concerned, the concept of Exposure is expressed as the quantification of the socio-economic damages that a community can suffer, for this reason, it is strongly related to the evaluation of the *Social Costs*, which, in turn, can be defined as all the social and economic *Losses* affecting a community after a catastrophic event and they are usually divided in *direct* and *indirect* losses. The first group consists mainly into repair or replacement cost of the damaged element of the transportation infrastructure and the second one is mainly due to cost derived from temporary reduction or interruption of the transportation network service, which in turn, could implicate losses and missed earnings into others economic sectors. The consequences of loss of serviceability of the transportation networks could depend on the features of the transportation system such as the network configuration, the redundancies, the traffic demand and capacity, the presence, the quantity and the location of critical components (e.g. bridges, tunnels, embankments,…). The impacts on the traffic flows and the trips could affect agriculture, industry and services sectors which use the transportation networks for daily activities. In this study, the indirect losses have been evaluated by means of the *Total Delay Cost, TDC*, as a consequence of loss of serviceability of the transportation networks, within the Capacity Analysis. This approach implies that the travel time is one of the most significant component among the different terms contributing to the *Generalized Transport Cost, GTC*, which is defined as the sum of all the contributes that compose the cost (travel time included) that a generic transport user holds up to perform a specific trip, within a specific analysis area, on a daily basis.

Basing on these premises, the *TDC* can be defined as:

$$TDC = GTC_{post} - GTC_{pre} \tag{1}$$

where:

GTC_{post} is the Generalized Transport Cost in the post - catastrophic scenario;

GTC_{pre} is the Generalized Transport Cost in the pre - catastrophic scenario.

Since the Eq. (1) provides the costs on a daily basis, in order to evaluate the *Overall Social Cost, OSC*, within a specific analysis area, the *TDC* has to be multiplied by the overall amount of days needed to bring back the transportation network to the pre-earthquake event conditions. In order to perform the TDC evaluation, a transportation demand forecasting model, within the analysis area, has to be developed. A brief description is reported below.

4.1 Travel Demand Forecasting Model

The Travel Demand Forecasting Model, TDFM, [16] is one of the most known and used prediction model in Transportation Engineering. The TDFM, historically named four-step travel demand model, is a mathematical four-stage model which, from the entire Origin-Destination (O/D) trip matrix of the analysis area, provides, on an hourly basis, all the trips occurring in a specific analysis area, according to its purpose, time period, origin, destination, path, transport mode and socio-economic role of the user. In particular the TDFM is the ordered combination of four separated sub-models: the traffic emission model, the traffic distribution model, the traffic mode-choice model and the path-choice model. The TDFM can be evaluated by means of the following expression [16]:

$$d^{i}_{od}(s,h,m,k) = d^{i}_{o}(sh) \cdot p^{i}(d/osh) \cdot p^{i}(m/oshd) \cdot p^{i}(k/oshdm) \quad (2)$$

where:

d^{i}_{od} (s, h, m, k) is the average number of trips undertaken by class user (cu) i, starting from origin traffic zone o, finishing in the destination traffic zone d, for a specific purpose s, within the time period h, using the transport mode m, and choosing the trip path k;

d_{io} (sh) is the average number of cu i that undertakes a trip from o, for purpose s, within the time period h;

p^{i} (d/osh) is the fraction of the cu i that travels to d undertaking a trip from o, for purpose s, within the time period h;

p^{i} (m/oshd) is the fraction of the cu i that uses the transport mode m, undertaking a trip from o, to d, for purpose s, within the time period h;

p^{i} (k/oshdm) is the fraction of the cu i that chooses the trip path k, undertaking a trip from o, to d, for purpose s, within the time period h, with the transport mode m.

It is worth to be mentioned that, each conurbation and its relative transportation system present peculiarities which deserve ad hoc preliminary evaluations relating to the identification of relevant spatial dimensions of the transportation network. It consists mainly into the definition of the project area (and study area if needed); the subdivision of the defined area into traffic zones (zoning) and the identification of the basic network [16].

5 Case Study

In May 2012, the Emilian Po Valley was struck by an intense seismic activity with two major events occurred respectively May 20th (Mw = 6.1 − hypocentral depth of 6.3 km) and on May 29th (Mw = 5.8 − hypocentral depth of 10.2 km). Widespread liquefaction was observed in areas located near old abandoned watercourses, especially in the municipalities of Sant'Agostino and Mirabello, located along the old riverbed of the Reno River. The village of San Carlo, Municipality of Sant'Agostino, is the most emblematic area for the greatest concentration of liquefaction evidence [17]. The subsoil of San Carlo is the product of a relatively recent geologic history, characterized

by an intensive depositional sequence of the Reno river and a very shallow water table. Its urban area and road network are mainly built near the paleo-channel and paleo-levees of the Reno River and consequently the subsoil can be categorized in three main units. Starting from the top, fluvial channel deposits few meters deep are located above a stratum of fine-grained materials (swamps) and Pleistocene alluvial plain. Finally, manmade silty sand layers built to protect the area against flooding (paleo-levees) are positioned along the old riverbed. Due to the fact that Terre del Reno is characterized by the strong presence of trough-traffic, the study and project areas do not coincide. In this case the project area can be identified into San Carlo districts and the dimension of study area (which always includes the first one and encompasses most of the transportation variations' effects) has been defined by the results of the sensitivity analysis: three circular areas with a radius of 20 km, 40 km ad 60 km centred in the project area,

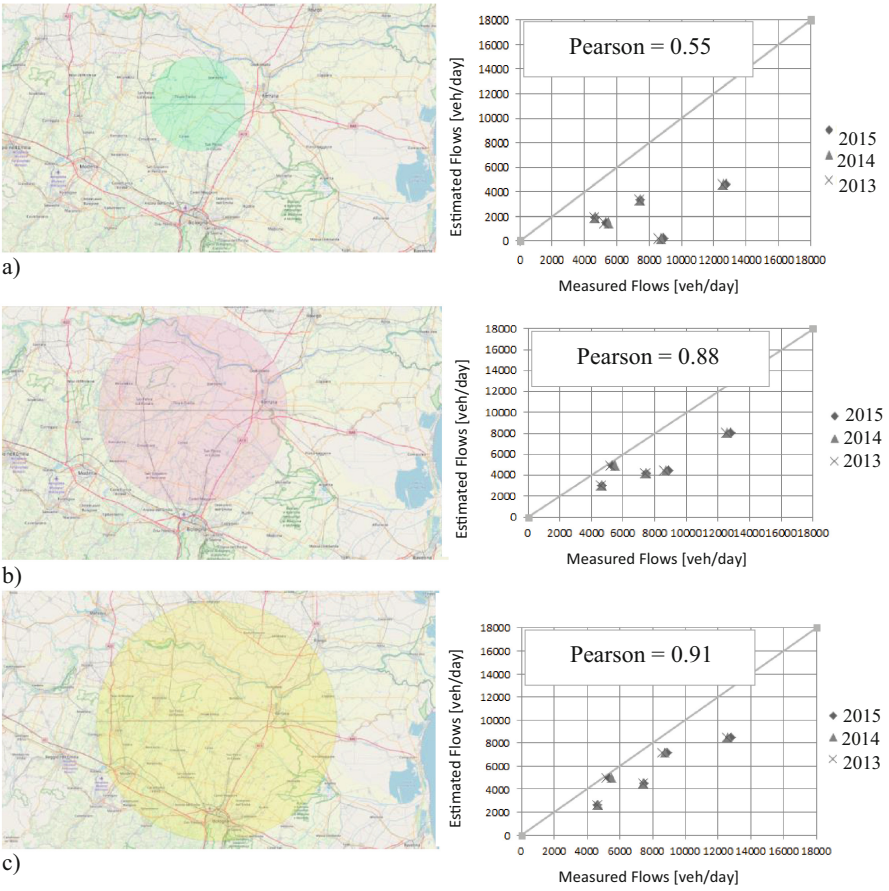

Fig. 1. Sensitivity analysis with study area's radius dimension of a) 20 km; b) 40 km and c) 60 km.

have been used as study areas. A TDFM, for each study areas has been developed and the results has been showed in the following Fig. 1. As shown in the Fig. 1c, the comparison between estimated and measured flows (into three different years: 2013, 2014 and 2015) suggests a size of the study area of at least 60 km of radius.

For this reason, the final version of the TDFM has been developed, calibrated and experimentally validated in a buffer area of 60 km of radius around a rural area located in the district of Terre del Reno. In order to define the model, the following hypotheses have been stated:

- the study area of the model can be considered as a "wide area" (larger than a district but smaller than a regional territorial scale), for this reason the municipal scale has been chosen as zoning size;
- the effects of the seismic events which produce the liquefaction phenomenon are mainly limited to the conurbation of Terre del Reno;
- the trip purpose that can be monetized are usually related to the main home-based trips (home-to-work or/and home-to-study); in this regard, it should be remembered that these types of trip are characterized by the lower rigidity in terms of elasticity of the demand curve respect to other trips purposes;
- home-to-work or/and home-to-study purpose trips are considered prevalent in this mobility scenario, covering more than 80% of the entire mobility, as highlighted by regional traffic studies;
- the daily fluctuation of mobility has been partitioned considering only two scenarios: a "peak" one that occurs mainly in two time slots (from 7:00 to 9:00 and from 17:00 to 19:00) and an "off-peak" for the rest of the day;
- for the aforementioned reasons, the O/D matrix has been preliminarily developed basing on the commuter mobility data derived by 2011 Census provided by Italian National Institute of Statistics (ISTAT) [18] containing only systematic commuting data and corresponding modal split;
- on a municipal basis, it is assumed that the shelter areas will been located close to the main town center, for this reason, the emission and attraction factors of the traffic zones, in the ex-ante and ex-post earthquake scenarios, have been considered invariant;
- finally, because of the wide analysis area and of the higher incidence of long trips in terms of travel times and paths in the examined traffic scenarios a deterministic approach (all-or-nothing), for the assignment sub-model, has been assumed. As a matter of fact, in this case, path choice mechanisms are characterized by an average low epistemic level (also in view of the possible installation of the temporary directional vertical signs).

Following of the identification of the study area, 31 centroids and relative traffic zones have been pointed out (Fig. 2) and the main traffic supply model has been identified (Fig. 3). However in the project area a more refined road network model taking into account also minor roads has been considered in order to capture traffic deviation scenarios in a more realistic manner.

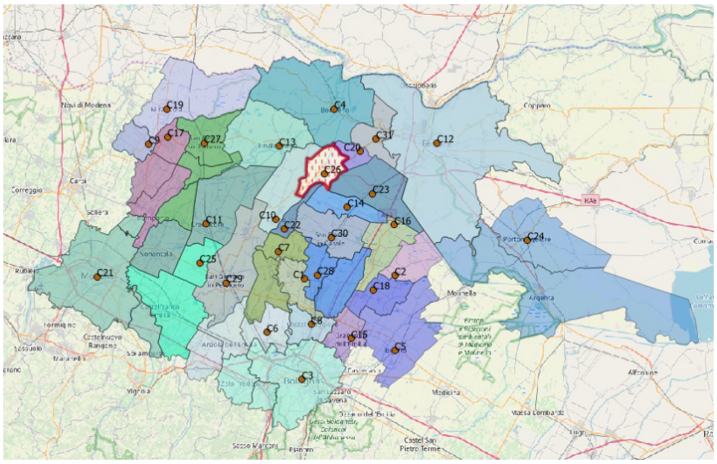

Fig. 2. Centroids and traffic zones identification.

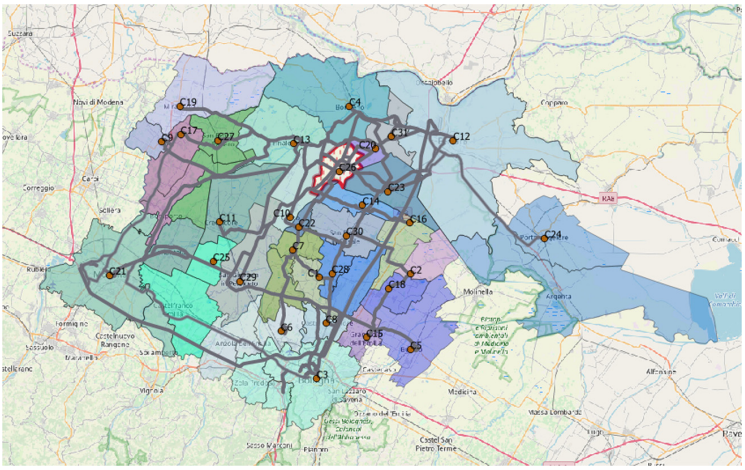

Fig. 3. Identification of the corresponding traffic supply model (main road network).

The Karamitros formula [13] has then been applied to estimate the settlements of the road embankment over the territory of Terre del Reno, thanks to the use of geoinformatics [19], combining seismic hazard with the subsoil and the road network features, spatial databases have been developed, and the results, in terms of the thickness of the liquefiable layer (Fig. 4), the thickness of the overlying crust (Fig. 5) and the embankment height (Fig. 6) have been represented. Finally, according to the specific seismic event of May 20th 2012, the map of the road embankment settlements has been computed and reported in the Fig. 7.

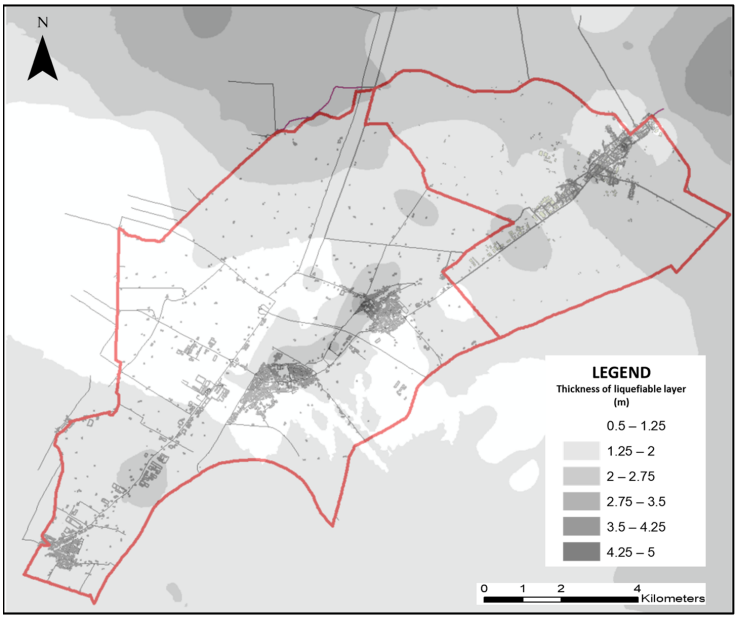

Fig. 4. Map of the thickness of the liquefiable layer.

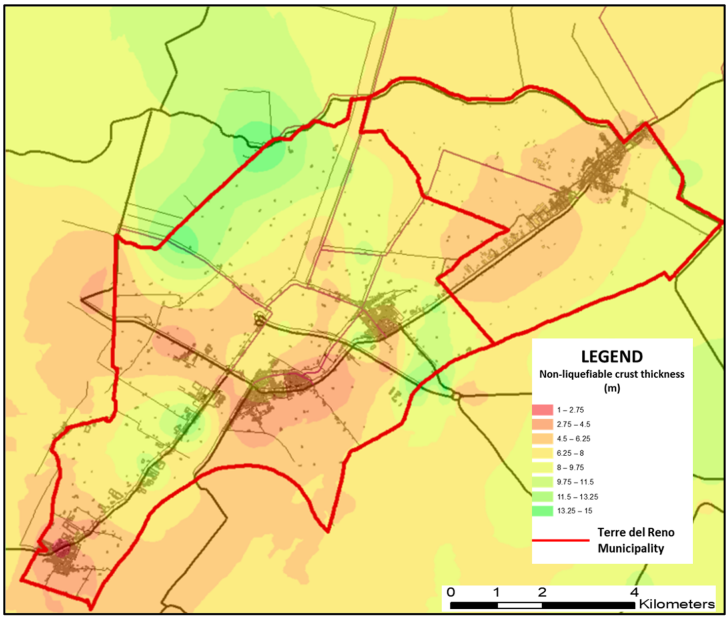

Fig. 5. Map of the thickness of the overlying crust.

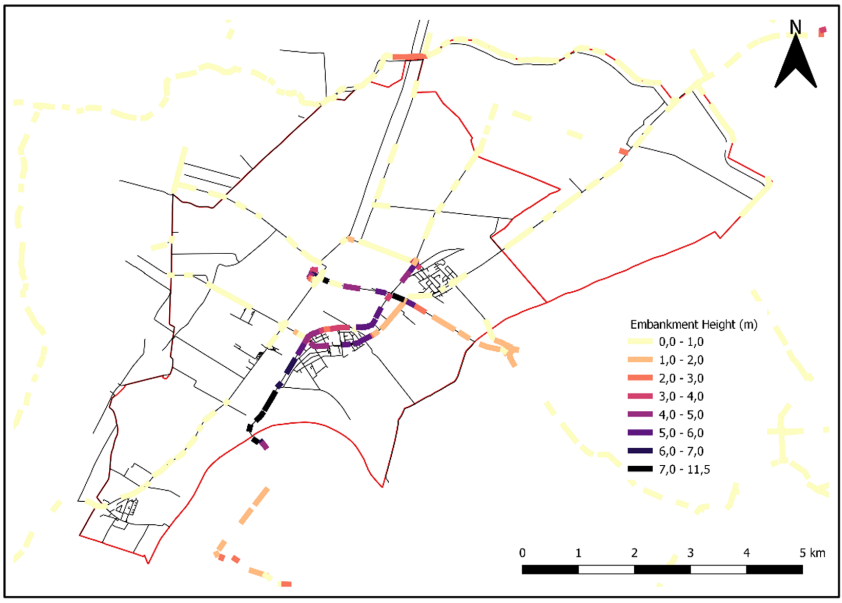

Fig. 6. Map of the embankment height.

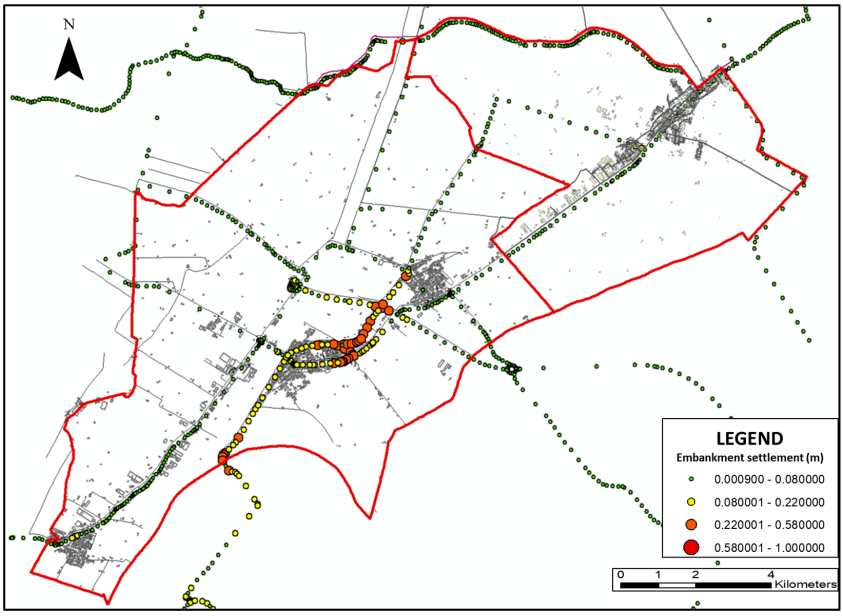

Fig. 7. Map of evaluated embankment settlements.

According to the SYNER-G classification [15] (see Table 2) the evaluation of the damage state limits for highway embankments has been performed and the results, in terms of Serviceability level have been showed in the Fig. 8.

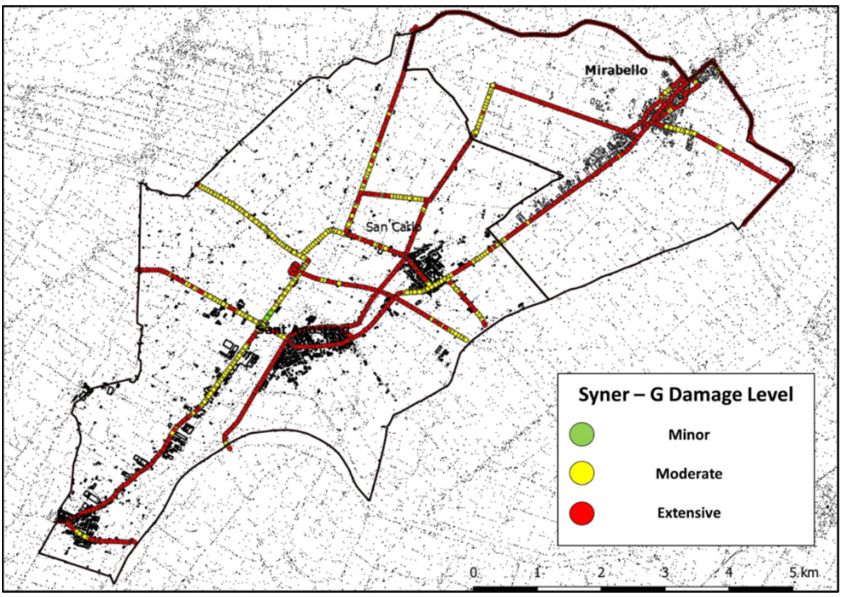

Fig. 8. Map of the embankment damage levels.

Due to the variations of the traffic flows occurring within various time frame during the day and different days in a week, several simulations, with different traffic data characterizing the "peak" periods (early morning and afternoon) and "off-peak" periods have been performed, with the aim to simulate the actual traffic hourly volume on the road network in a typical working day. In this case study, for each scenario (both pre-liquefaction and post-liquefaction), the previous traffic hourly volume values have been assigned according to a "all-or-nothing" conventional rule.

By way of example, the pre and post scenario (related to the specific seismic event of May 20th 2012) within the morning peak period and in the project area, have been reported in the Figs. 9 and 10, respectively. As it can be easily observed from the simulation the disrupt of some road links induced by liquefaction, is responsible for a re-distribution of original traffic flows yielding an increase of travel time and, in turn, of *Social Costs*. For each scenario, the travel times on the whole road network, considering a typical working day and the home-to-work and home-to-study purpose trips, have been evaluated. Comparing the travel times along the road network in the post and pre-liquefaction scenarios, the overall hourly delay suffered by the entire network system, because of the damage occurred (in this case necessarily translates into substantial extensions of travel routes), has been evaluated. Therefore, following the assessment of the hourly delays for both peak and off-peak hours, a daily delay of approximately 16700 min has been calculated.

In the Fig. 11, the cumulative curve of the Delay distributions (i.e. number of road users perceiving a delay lower or at least equal to a defined value), providing an indirect estimate of the cumulated probability associated to a given class of delay within both Peak and Off-Peak hours, has been reported.

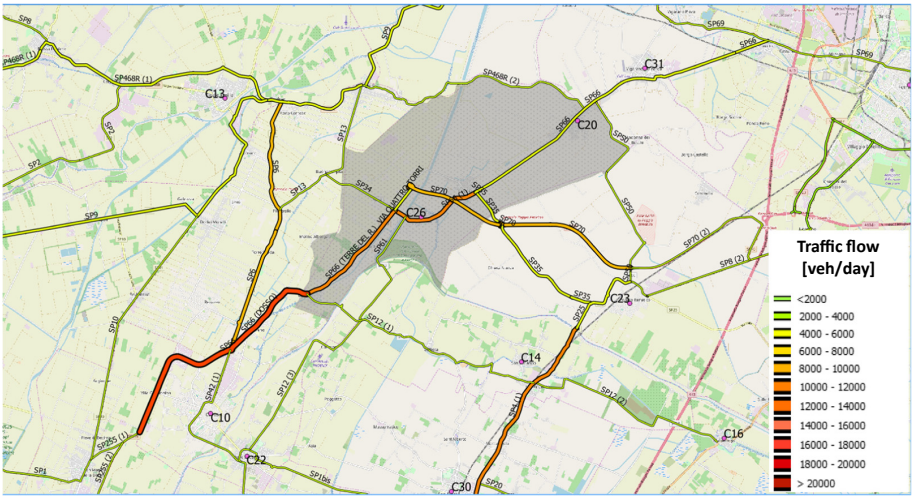

Fig. 9. Daily traffic flow distribution produced by a TDFM in the pre-liquefaction scenario.

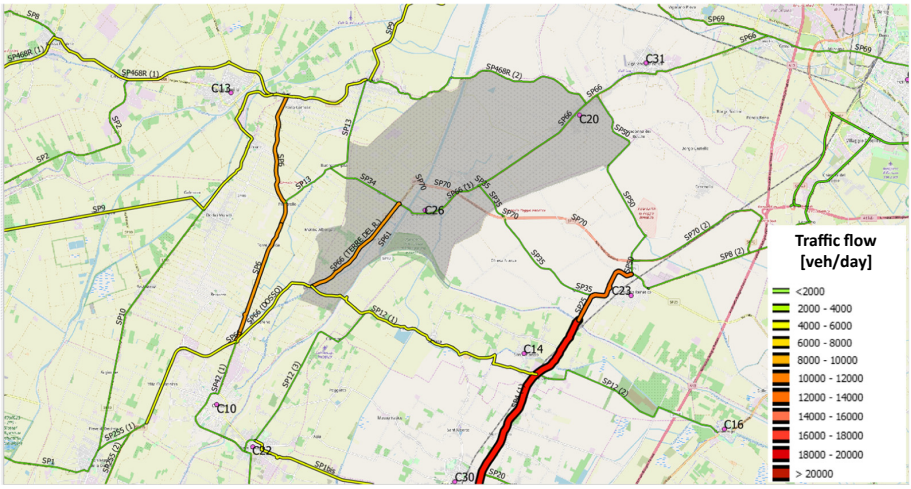

Fig. 10. Daily traffic flow distribution produced by a TDFM in the post-liquefaction scenario.

Finally, according to the travel time cost for heavy and light vehicles, the average transportation generalized cost, have been calculated.

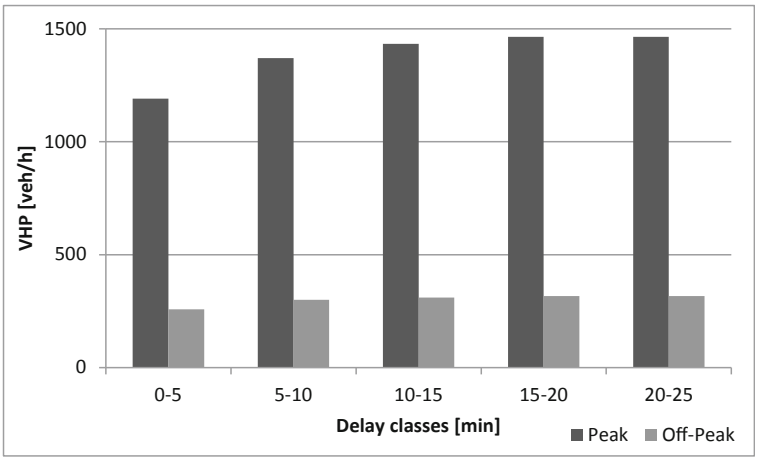

Fig. 11. Cumulative Delay distribution within peak and off-peak hours.

By means of the Eq. 1, the *Total Delay Cost* for each post-scenario have been evaluated and, in order to assess the *Overall Social Cost*, the *Total Delay Cost* should be multiplied by the overall amount of days needed to restore the pre-liquefaction event conditions of transportation network (no variations in travel demand have been considered during the post-liquefaction event period since, as previously stated, the study area is much more larger than the size of the project area and it has been assumed that the prevailing through traffic travelling in the study area will not be dramatically affected by the seismic event).

It is worth to be underlined that the *Overall Social Cost* so far evaluated could be incorporated into a Decision Support Systems within a prioritization scheme that can be developed in order to identify candidate road sections for liquefaction mitigation countermeasures.

6 Conclusion

A seismic liquefaction risk assessment of a road transportation network has been performed: the territorial distribution of hazard, vulnerability and exposure has been estimated and preliminarily evaluations in terms of social cost, have been conducted.

The strategy has been applied on an Italian road system affected by a severe earthquake in 2012: seismic hazard, subsoil features and road network characteristics have been combined in a geo-informatics databases. Then a Capacity Analysis of the road network has been performed, with the aim to evaluate the effects of the loss of functionality due to liquefaction evidences.

Pre- and post-seismic scenarios have been simulated and preliminary outcomes showed a redistribution of the traffic flows, on the road network, caused by the service loss of strategic road sections and preliminary analysis, to evaluate the social effects in terms of Total Delay Cost, have been performed.

The original framework so far developed appears to be a promising screening procedure that can allow to detect, on one hand, liquefaction risk-prone road sections and, on the other, *Overall Social Costs* associated to earthquake-induced road disruptions. It is believed that *Overall Social Costs* can represent an additional factor that can be easily implemented into a prioritization procedure helping Road Managers in identifying vulnerable road sections needing seismic retrofitting interventions against seismic liquefaction scenarios.

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