Strategies for the Assessment of Risk induced by Seismic Liquefaction on Road Networks

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Seismic risk analysis and management of civil infrastructure systems has undergone an increasing interest among researchers in the recent past. Different methods and approaches have been proposed mainly dealing with the earthquake response of buildings and lifelines. Concerning transportation networks, most of the efforts focuses on the response of bridge stocks to specific earthquake scenarios, but very few examples exist examining the response of transportation networks as a whole. In particular, methods taking into account local site effects induced by liquefaction of the foundation soil are not developed yet. In this paper a novel framework is proposed to estimate the risk given by liquefaction on a road network within the more general EU project Liquefact. The study combines geotechnical analyses and the assessment of the traffic conditions to define hazard, vulnerability and exposure of the transportation network. The methodology has been applied to a rural area located in the district of Terre del Reno (Emilia Romagna, Italy) struck in 2012 by a seismic sequence that produced extensive liquefaction. The micro-zonation of liquefaction potential and the modelling of the transportation network are coupled to assess risk and identify mitigation strategies.

Keywords: Seismic risk, Liquefaction, Embankments, Transportation network, Serviceability.

1. Introduction

Many worldwide events (e.g. Tohoku Oki, 2011; Kumamoto, 2016; Christchurch 2010, 2011 and 2016, Emilia Romagna, 2012) have shown the destructive potential of earthquake induced liquefaction. Damages affect not only the building asset, but also the facilities connected directly or indirectly to the productive systems (roads, waterways, electric and communication lines), undermining in this way the whole social organization and the recovery capacity of the communities. From early nineties, different methodologies have been developed to estimate the potential losses induced by earthquakes implementing engineering knowledge in geographic information systems (GIS). The following National and International projects represent the most remarkable examples:

- Applied Technology Council project (ATC-25, 1991) sponsored by the Federal Emergency Management Agency (FEMA). The project aims to understand the impact of the disruption caused by seismic events on lifelines and to identify and prioritize mitigation;

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- RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters, 1996) from the Secretariat of the International Decade for Natural Disaster Reduction (IDNDR 1990-2000), aimed at develop tools for seismic risk assessment on urban areas and at addressing the implementation of disaster mitigation measures;
- GEMITIS project (1997) promoted from the French Ministry of the Environment to integrate Risk Reduction Strategy improving seismic risk-assessment in urban areas and considering critical scenarios for mid or long-term impact assessment;
- RISK-UE (IDNDR 1990-2000) aimed at achieving plausible assessment of direct and indirect damages caused on cities by earthquake events, increasing benefits deriving from a deeper knowledge of the seismic risk and from the implementation of "Action Plans";
- JICA promoted in 2002 by the Japan International Cooperation Agency, Ministry of Home Affairs, Government of Nepal, to mitigate earthquake disaster in the Kathmandu Valley;
- HAZUS®, (2004), a tool developed by FEMA and NIBS (National Institute of Building Sciences) to estimate losses at federal, state, regional and local scale and to plan earthquake risk mitigation, emergency preparedness, response and recovery;
- SYNER-G UE-project, 2009, a European Collaborative Research Project focused on systemic seismic vulnerability and risk analysis of buildings, lifelines and infrastructures.

From the specific viewpoint of Transportation Networks and Infrastructures, other relavant projects are:

- Project AllTraIn (2013-2015): All-Hazard Guide for Transport Infrastructure was supported by the European Commission, with the aim to cover both man-made hazards (intentional and exceptional) and natural hazards on European bridges, cuts, embankments and tunnels.
- EU project SecMan (2012): supported by the European Commission with the aim to provide a practical process for the identification of critical infrastructures, only in terms of man-made hazard vulnerability, on European highways (especially bridges and tunnels) for both network and element analysis.
- EC-funded project SeRoN - Security of Road Transport Networks project: was funded by the EC Seventh Framework Programme (FP7/2007-2013) with the aim to investigate the impacts of possible terrorist attacks on the transport network. The project considered both direct (i.e. fatalities and structural damage to the infrastructure) and indirect consequences (i.e. economic costs, additional travel time, etc.).
- Project STRIT - Tools and Technologies for Risk Management of Transport Infrastructure (2012-2015) was a research project developed by public and private Italian research centres with the aim to introduce innovative bridge monitoring, Decision Support System (DSS) for maintenance strategies and new technologies improving seismic resistance of structures.
- REDARS™ (Risks from Earthquake Damage to the Roadway System) which is a methodology implemented in a software package for the seismic risk analysis.

The occurrence of liquefaction implies the coexistence of two predisposing factors, a relatively high regional seismicity coupled with a local susceptibility of the subsoil deposits, i.e. the presence of relatively shallow loose sandy layers located below the water table, with effects enhanced by impermeable crusts and inclined stratifications. Additionally, the coupling with structures invokes a peculiar interaction between foundations and subsoil, largely different from that caused by other seismic effects. In some of the above recalled projects (e.g. Hazus, 2004), liquefaction is seen as a side effect and the adaptation of analytical tools generally defined for earthquakes gives too generic rules to account for the specific manifestation of the phenomenon. Shocking examples displaying the relevance of liquefaction have led to incorporate specific liquefaction risk assessment into national and international standards (e.g. NZGS, 2016; ICMS, 2017).

The present study carried out in the framework of a European project (Liquefact, #700748), aims at implementing a strategy to assess risk on road infrastructures. Starting from the observation of an urban aggregate, the municipality of Terre del Reno in Emilia Romagna, that in 2012 underwent a severe seismic sequence that produced extensive liquefaction over its territory, a multi-layer database has been created combining subsoil investigations performed for reconstruction, seismic records and analyses to define liquefaction hazard. Vulnerability of road has been then quantified computing with analytical formulas the settlements of embankment on liquefied soils and estimating the loss of functionality based on criteria proposed from previous projects. Finally, the impact on the transportation network is evaluated performing a study on the traffic conditions.

The analysis implies the overlapping of information given in a multi-layered system, achievable thanks to the capability of Geographical Information Systems to interrogate, combine into formulas and map outcomes.

2. Liquefaction risk assessment

Considering the sequence of sub-systems involved in seismic liquefaction, the risk assessment methodology can be expressed quantifying the probability of occurrence and associated uncertainty on earthquake intensity, ground motion, liquefaction manifestation, structural response, physical damage, and socio-economic losses. The scheme of Fig. 1 shows the above formulation applied to the whole chain system.

Partial analyses on subsystems can be performed grouping one or more elements of the chain, defining appropriately demand and vulnerability. In fact, 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.

3. Liquefaction hazard

In the scheme of Fig.1, the earthquake can be generally considered as the primary hazard factor and liquefaction occurs in loose granular materials prone to accumulate volume contraction upon cyclic loading (Iolli et al., 2015; Salvatore et al., 2017 and 2018, Modoni et al., 2018). Sand with limited fine content, sufficiently low density and saturation are paramount factors.

Therefore, the combination of earthquake and subsoil response determines the demand for the structure positioned at the ground level. In the traditional procedures proposed for evaluating liquefaction hazard (e.g. DPC, 2017), subsoil and structural responses are seen in an uncoupled way. According to the seismicity and layering, density and saturation of the subsoil, hazard analyses provides the demand function p(EDP|IM) for the structure. Then physical vulnerability is computed considering the p(DM|EDP) function for the sole structure assuming as EDP indicators of the free field potential damage computed from the results of in-situ tests. A class of methods associates the triggering of liquefaction at the different depths to the outcomes of standard (SPT) and cone penetration tests (CPT) or dynamic wave propagation (e.g. Boulanger & Idriss, 2015).

Exploiting the continuous logs throughout the investigated depth, liquefaction potential indexes (e.g. Iwasaki et al., 1978) are then computed at specific sites by integrating triggering effects over the whole depth, that form the input for the vulnerability analysis of structures. This uncoupled approach suffers for the limitation that the overlying structure, whether a building, a bridge pier or an embankment, is not taken into account while the deviator stress produced by the load transferred to the soil contributes significantly to the triggering of liquefaction.

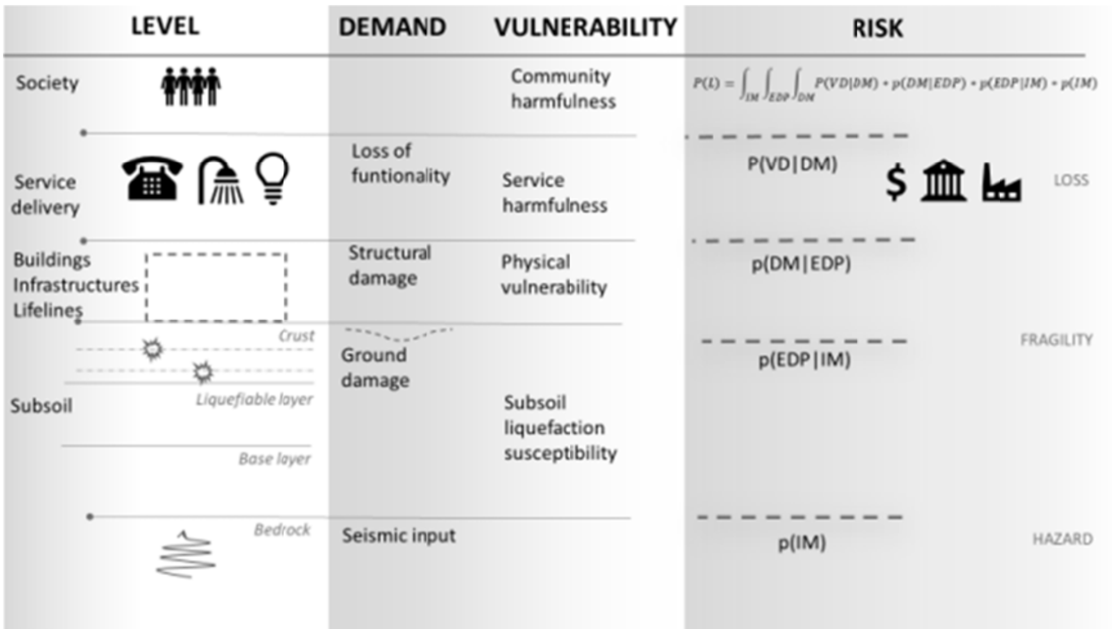

Fig. 1. Definition of risk assessment for seismic liquefaction.

Hence, alternative solutions consist of performing coupled analyses where the subsoil-structures interact each other. An example is given by the Karamitros et al. (2013) who compute the liquefaction-induced settlements of foundations considering the seismic excitation with an energy-based variable, the shaking-degradation of the safety factor of the foundation and the effect of shear-induced dilation of the liquefied subsoil. The formula of Karamitros et al. (2013) has been customized to the present case comparing its outcomes with the results of an effective stress calculation carried out with an advanced numerical model (Modoni et al., 2019). To this aim a reference embankment having base width of 10 m and discharging 50 kPa unit load has been assumed on a three-layers profiles having total thickness of 20 m. The comparison has been made parametrically varying the thicknesses of crust H1 in the range 2-12 m and the thickness of the liquefiable layer H2 in the range 4-8 m (Figure 2.a) and the earthquake intensity by scaling the accelerogram of the May 20th, 2012 earthquake with different factor (1-1.6). The comparison between the numerical and analytical values of the Reference Foundation Settlements (Fig. 2.b) is generally good with some limited discrepancy for the highest values corresponding to lower crust thickness. After validation, Karamitros et al. (2013) formula has then been applied to estimate the settlements of the road embankment over the territory of Terre del Reno.

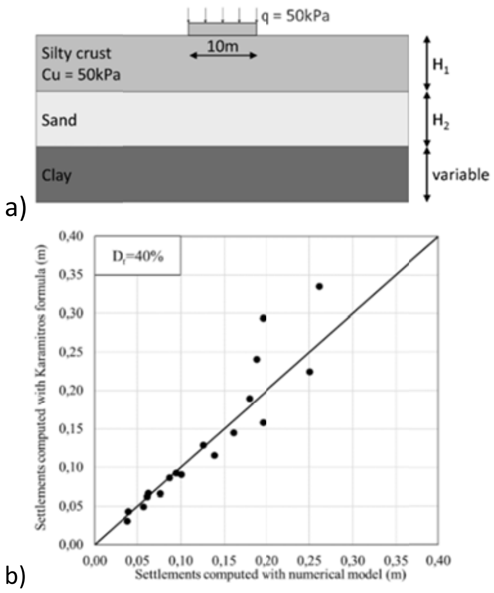

Fig. 2. Parametric model (a) and comparison of settlements computed with numerical analysis and Karamitros et al. (2013) formulation (b).

To this aim, maps have been created reporting the thickness of the liquefiable layer (H_2 in Fig. 2a and Fig. 3a), of the overlying crust (H_1 in Fig. 2a and Fig. 3b) and the embankment height (Fig. 3c). The three maps are composed in Fig. 3 together with the map of settlements computed for the road embankment (Fig. 3d).

4. Vulnerability of embankment

For the definition of the damage state limits for highway embankments, the SYNER-G classification (2009) summarised in Table 1 has been adopted:

Table 1. Definition of damage state for highway embankments (SYNER-G, 2009).

Damage state	PVG Displacement [m]		
	min	max	mean
minor	0.02	0.08	0.05
moderate	0.08	0.22	0.15
extensive	0.22	0.58	0.40

Each damage state corresponds to a road section serviceability limit state, which can be summarized as:

- *Minor:* useful road with speed reduction;
- *Moderate:* road partially blocked (alternating direction of travel);
- *Extensive:* road totally blocked.

5. Impact on transportation

If a risk-based approach has to be pursued in order to evaluate the socio-economic impact pertaining the post-earthquake scenario, serviceability of critical infrastructures, among which transportation networks are relevant, has to be taken into account. As far as the analysis period is concerned, two main approaches can be usually identified:

- *short-term effects*, insofar accessibility to small and more isolated communities has to be guaranteed for rescue crews and emergency services in the immediate post-earthquake scenario;
- *long term effects*, since the serviceability of transportation network can be heavily damaged by an earthquake and therefore repair works aimed at restoring initial conditions have to be undertaken.

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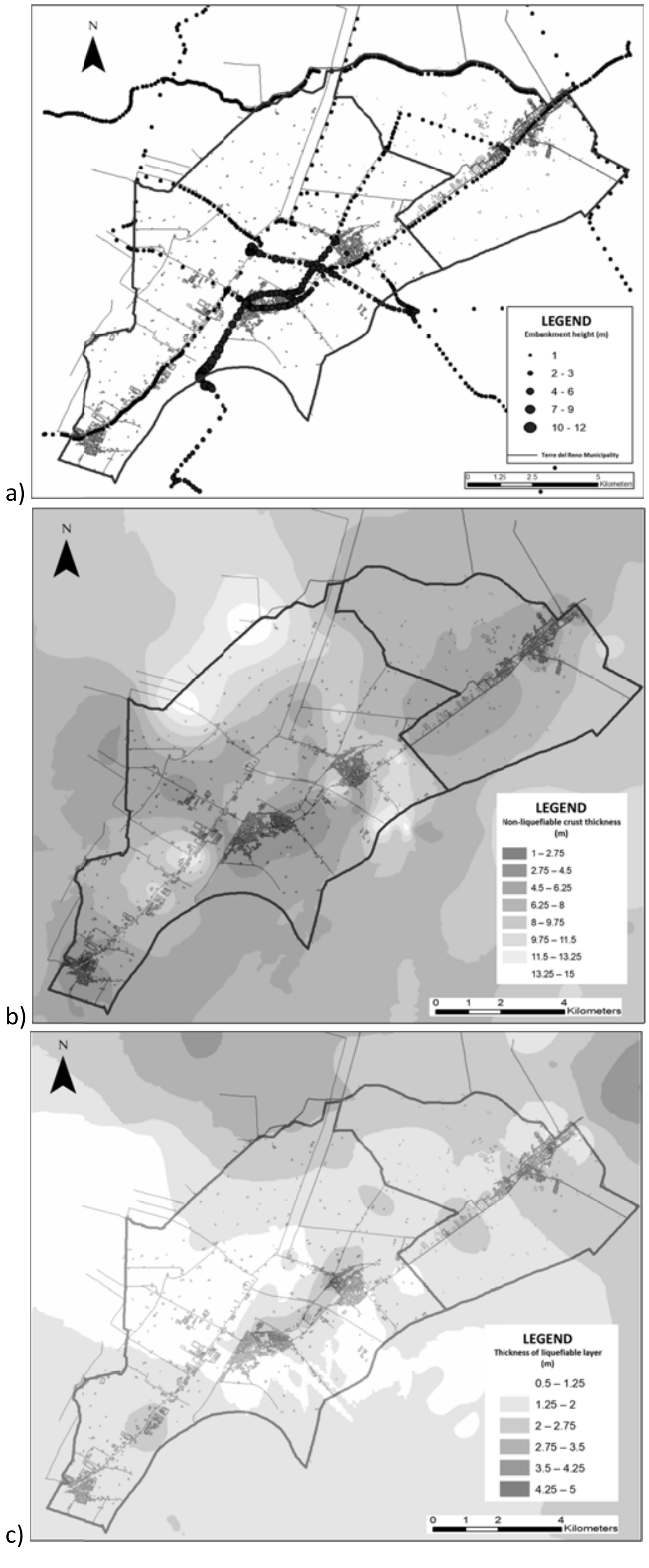

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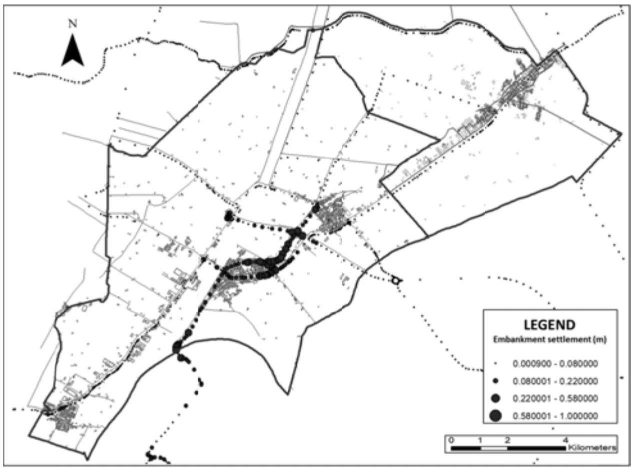


d)

Fig. 3. Maps of the (a) thickness of the liquefiable layer; (b) thickness of the overlying crust; (c) embankment height and (d) embankment settlements.

A recent review of methodological approaches (SINER-G, 2009) so far developed for critical infrastructures has identified the followings:

- *Level 0* or *Vulnerability Analysis* dealing with the damage level experimented by each road component (bridge, tunnel, embakment, etc) according to a specific seismic scenario;
- *Level I* or *Connectivity Analysis* where the accessibility to a specific area is evaluated in the post-earthquake scenario, following the loss of service of some connections;
- *Level IIa* or *Capacity Analysis* dealing with decay of performance level of the whole network itself that in turn will cause a degraded fruition of the infrastructure and a dramatic increase of the user costs.
- *Level IIb* or *Serviceability Analysis* where all the interdependencies and the effects of a seismic scenario are evaluated to the extent that they can affect all the aspects of the inhabitants' and stakeholders' life and related economic impacts, following an earthquake occurring in a specific area.

Basing on these premises, it is worth to be noticed that transportation managers have to cope with the issue of an optimal planning of seismic mitigation countermeasures with limited budget available.
In this connection, although the *Serviceability Analysis* seems the most exhaustive in evaluating all the socio-economic aspects impacted by an earthquake scenario in the short and long-term, it requires an in-depth knowledge of all the social and economic framework of an analysis area that is not always available at local level.
Therefore, a *Capacity Analysis* seems the most feasible approach to evaluate, even to a lesser extent, socio-economic impacts related to the mobility that, in turn, represents a significant aspect in overall evaluation of quality of life in the post-earthquake scenario.
This approach is mainly based on the assessment of the *Total Delay Cost, TDC*, in the analysis area, as a consequence of loss of serviceability of a transportation networks. The *TDC* can be evaluated by means of the following expression:

$$TDC = GTC_{post} - GTC_{pre} \quad (1)$$

where:
GTC_{post} is the *Generalized Transport Cost* in the *post-earthquake* scenario;
GTC_{pre} is the *Generalized Transport Cost* in the *pre-earthquake* scenario.

GTC is a measure of the overall cost that is sustained by each transport user in a specific analysis area; it is mainly related to the travel time cost and it is computed on a daily basis.
Therefore, it is possible to assess the *Overall Social Cost, OSC*, related to the mobility in a specific analysis area, if the *TDC* is multiplied by the overall amount of days needed to restore the original conditions of transportation network.
Conversely, once that the *OSC* pertaining to specific earthquake scenario has been evaluated, it is possible to identify critical transportation links that should undergo to seismic mitigation countermeasures, in order to alleviate the socio-economic mobility-related impacts induced by a post-earthquake scenario.
In order to accomplish this task, a *Travel Demand Forecasting Model, TDFM*, has to be developed. A *TDFM* (Cascetta, 2009) is a mathematical four-stage model able to reproduce on a daily basis, all the trips occurring in a specific analysis area, according to its purpose,

user class, time period, origin, destination, transport mode and path (see Fig. 4).

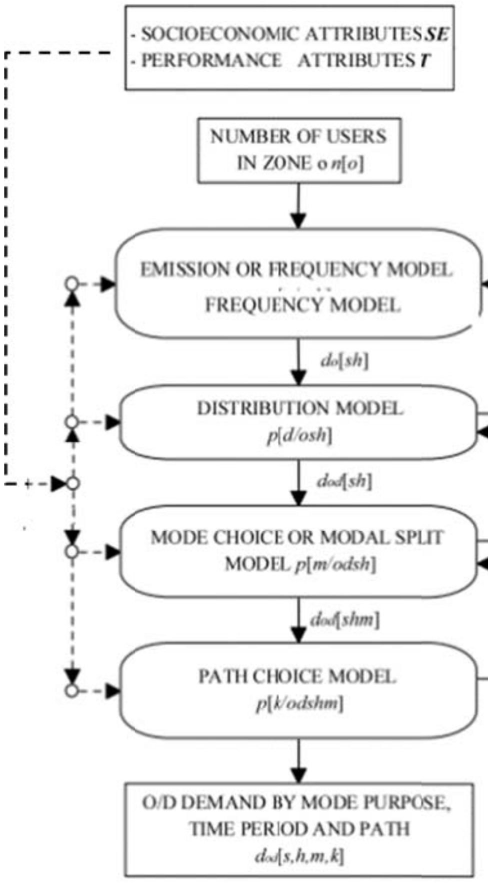
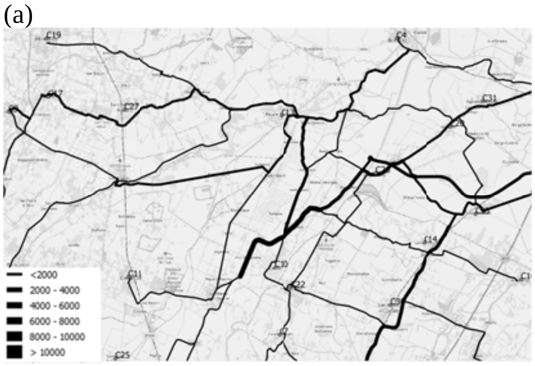


Fig. 4. Conceptual representation of a Travel Demand Forecasting Model from Cascetta (2009).

Following these premises, a *TDFM* has been developed, calibrated and experimentally validated in a rural area located in the district of Terre del Reno (Emilia Romagna, Italy).

In the following figure a graphical representation of the daily traffic flow pertaining the examined area are reported in the pre (Fig. 5a) and post-earthquake scenario (Fig.5b).

(a)



(b)

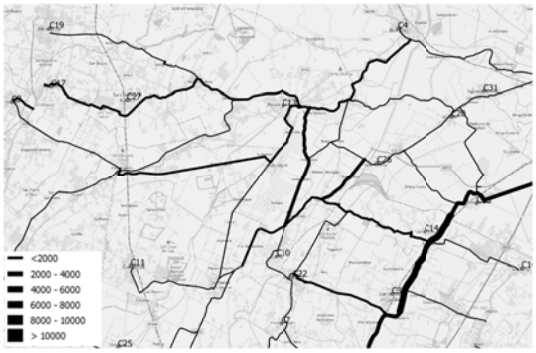


Fig. 5. Output expressed in terms of daily traffic flow distribution produced by a TDFM in the pre-earthquake (a) and post-earthquake (b) scenario.

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.*

6. Conclusions

A comprehensive risk assessment strategy to estimate the territorial distribution of hazard, vulnerability and exposure has been outlined to address mitigation and optimize budget allocation.

The holistic assessment of liquefaction risk has been attempted on a road system affected by a severe earthquake in 2012.

Thanks to the use of geoinformatics (Spacagna et al., 2017), spatial databases have been created combining seismic hazard with the characteristics of the subsoil and of the road network.

A mechanical based scheme has been adopted to estimate and map the loss of functionality. Preliminary results of the liquefaction effects on the road network showed a redistribution of the traffic flows due to the service loss of crucial road sections.

Further analysis are needed to evaluate how the traffic flows redistribution affects the entire road network also in terms of Total Delay Cost.

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