13th Wold Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2035

SEISMIC VULNERABILITY ASSESSMENT OF HIGHWAYS AND RAILROADS – APPLICATION TO THE GREAT LISBON AREA

Luís Guerreiro, João Azevedo[1]

SUMMARY

A methodology for the characterization and analysis of the seismic vulnerability of road and railroad networks is presented. It aims at the development of a seismic simulator that allows the seismic damage assessment of such networks in the great Lisbon area in Portugal. Also presented are some criteria for the definition of damage classes associated to the network elements, such as bridges and viaducts, considering the dynamic effects of the structural response, liquefaction and landslide occurrence.

Some results are presented using the seismic simulator and considering some seismic scenarios. A sensitivity analysis of the network performance as a function of the magnitude is also shown.

INTRODUCTION

The implementation of preparedness strategies aiming to evaluate and minimize the consequences of earthquakes and the elaboration of emergency plans to be activated in case of major disasters, are two main objectives of the civil protection services. The awareness of the potential seismic scenarios is fundamental, for it allows the safety assessment of the existing infrastructures for different seismic action levels and the definition and clarification of intervention procedures, optimizing the emergency plans.

This paper presents some methodologies and some undertaken steps for the construction of a seismic vulnerability assessment model of the Great Lisbon Area road and railroad networks, in Portugal. The project, part of a major study coordinated by the Portuguese Civil Protection Service, aiming at the development of a seismic vulnerability assessment model of the building stock, strategic structures and lifelines.

The impact of earthquake damage in the transportation lifelines is usually relevant not for the number of casualties, typically quite reduced, but for the inflicted economical damage. Economical losses can be direct or indirect. The direct ones, with two examples depicted in figure 1, correspond to the sum of the repair costs, while the indirect, much more difficult to evaluate, are related to the way the economy is affected by the transportation network disruption, which increases with the economic development in the

[1] ICIST, Dept. of Civil Engineering and Architecture, Instituto Superior Técnico, Lisbon, Portugal

affected zone. In the Northridge (1994), Kobe (1995) and Taiwan (1999) earthquakes, although a clear quantification of the indirect damage has not been made, it is believed it exceeded the direct damage.

Figure 1: Damage in transportation lifelines

For a correct damage assessment it is convenient to separate the analysis of the roads and railroads from that of bridges and viaducts. In the roads, damage essentially occurs due to rupture of the foundation or obstruction induced by liquefaction, fault movements or landslides. Damage in bridges can be divided in two groups according to the inducing cause: foundation rupture or dynamic vibration.

While damage induced by foundation rupture essentially depends on the level of soil deformation, damage due to the dynamic effects depends on the bridge structures dynamic characteristics and on their capacity to withstand cyclic actions. Bridge seismic design rules and, as a consequence, their seismic resistant capacity, has improved in the last decades, and so the age of the bridges is an essential indicator to evaluate their behavior. Description of last occurrences confirms that the date of construction is one of the parameters that most influences the level of observed damage.

IDENTIFICATION AND SURVEY OF THE NETWORKS

A GIS was created, containing all information concerning the highways, other major roads and the railroads of the region under study, as well as all the significant bridges, viaducts and tunnels. Figure 2 displays such information for the highways and other major roads as well as for railroads.

The earthquake simulator, implemented in the GIS, contains the information regarding the two lifeline networks (roads and rail roads) defined by means of line segments and nodes. The nodes correspond to the locations of the bridges or to singular points such as intersections between roads or between roads and the limits of the geographic zones used to define soil characteristics, liquefaction or landslide potential.

The site dependent seismic action characterization has in consideration the magnitude, proper attenuation laws and the local soil characteristics.

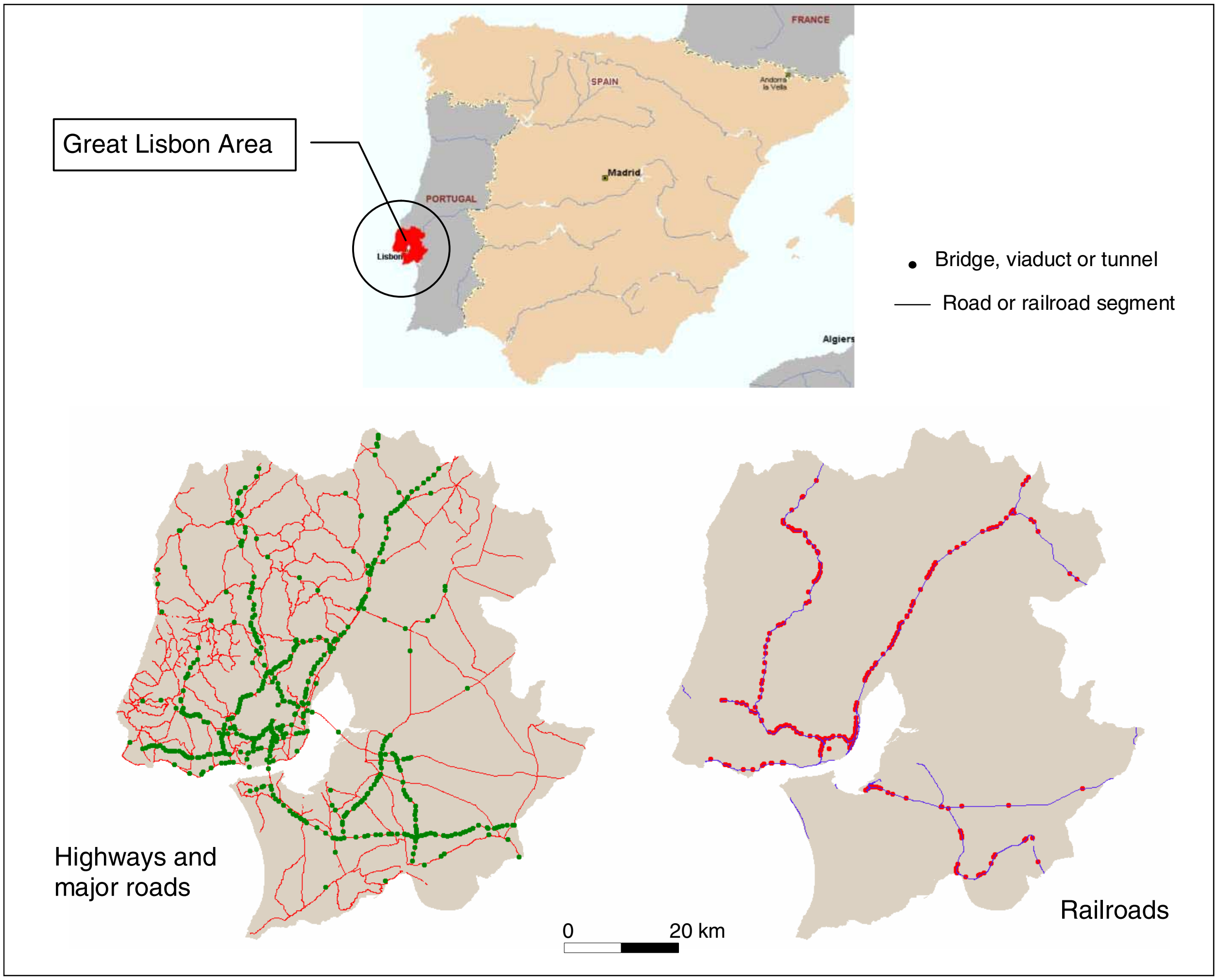

Figure 2: Road (Highways and major roads) and Railroad networks

SEISMIC VULNERABILITY ASSESSMENT OF THE NETWORKS

Methodology for vulnerability assessment

There are several methodologies for the prediction of physical damage in the transportation lifelines such as those described in ATC13 [1] and in HAZUS99 [2], which are based on damage observed in previous events. HAZUS99 presents a methodology based on fragility curves that allow the damage assessment based on direct measures of the seismic action (response spectrum, permanent soil deformation, peak ground acceleration).

Albeit great earthquakes that occurred in the past, such as the 1755 Lisbon earthquake, there is not significant information on past events in the region because of the very large return periods linked to the large magnitude earthquakes affecting the zone. This fact did not allow a direct use of the HAZUS99 methodology and justified some adaptations necessary for a better representation of the Portuguese scenario. This way, damage was classified according to five damage stages, according to its level of severity. A different fragility curve corresponds to each structural typology and each damage stage, which is used to evaluate the probability of occurrence of such damage stage. The following damage stages were considered: No damage (ds_1), Slight damage (ds_2), Moderate damage (ds_3), Extensive Damage (ds_4) and Collapse (ds_5). According to the type of element under analysis (road, bridge, viaduct or tunnel) there is a specific description of each damage stage.

Fragility curves

The fragility curves were modeled as log-normal cumulative distribution functions, similar to those proposed by HAZUS99. These functions are often used to describe the resistance of an element, allowing the evaluation of the probability to attain or exceed a damage level as a function of the seismic action level. Each fragility curve is characterized by its median and dispersion factor (standard deviation of the logarithm of the variable). The input value, which's median and dispersion characterize the fragility curve, is a measure of the seismic action level and can either be a response spectrum value or a permanent soil displacement, according to the type of situation under analysis: damage induced by dynamic actions, liquefaction, landslides.

In the bridges and viaducts, the analysis of the damage caused by the dynamic effects imposed by the soil movements is made using the acceleration response spectrum corresponding to a 1.0 sec. period and a damping coefficient equal to 5%. The use of this reference period is justified for it is not far away from the fundamental periods of a large number of examined structures. To estimate the damage induced by liquefaction or landslides, the permanent soil displacement is used as input value.

In the road segments, the dynamic effects are negligible and damage only depends on the permanent ground displacement, liquefaction and landslides.

The fragility curves assume the following expression:

$$P\,[\,Ds \geq ds\,] = \Phi\left(\frac{\ln[\text{Median}] - \ln\,[X]}{\beta}\right) \tag{1}$$

where:

- Φ – log-normal cumulative distribution function;
- X – Input variable;
- Ds – Damage value;
- ds – Reference characteristic value of a given damage stage;
- β – Dispersion coefficient (dispersion around the median).

The medians and dispersion coefficients are essential values for the definition of the seismic behavior of the network elements. Being impracticable to classify each one of the bridges, a division by classes was made, as suggested by HAZUS99. For the tunnels and road segments, the classes adopted in HAZUS99 were adopted for it was assumed that no significant differences exist between the USA and the Portuguese realities. For the bridges, classes adapted to the Portuguese situation were considered because there are some significant differences between the structural solutions used in both countries. The establishment of bridge classes considered in the study resulted from the observation made at the time of the survey about the existing typologies and from expert opinions. The considered classes take into account not only the structural typologies, but also the time of design and construction, given that the characterization of the seismic behavior depends on the evolutions that took place at the level of code regulations.

The considered classes take into account, among other aspects: the type of material (masonry or reinforced concrete), the type of solution (arches, single span, multiple spans), the type of connection to the abutments (free or monolithic), the type of deck (slab or slab with girders), the number of column alignments in the transverse direction, the type of bridge or viaduct (passage over the freeway or under it) and the date of design (before or after 1985, the year the current Portuguese seismic code was implemented).

To determine the values of the medians and dispersion coefficients that characterize the seismic behavior of the different classes of bridges, it would be important to have statistical data about seismic damage in Portugal, as is the case in California. As such information does not exist, it was necessary to adapt the available information to the Portuguese situation, according to the design codes and rules existing in each country. For that purpose the HAZUS99 bridge classes with counterparts in Portugal were identified. Albeit the fact that the HAZUS99 values are relatively large (given the differences in the seismic action levels between Portugal and the U.S.A.), it was assumed that the ratios between the median values associated to each damage level should be similar in the two cases. Given that assumption it is only necessary to determine the median value associated to a specific damage value.

According to the current Portuguese seismic code, the characteristic value of an action corresponds to a 95% probability of non-excess [3]. The materials resistance characteristic values also correspond to a 5% probability of non-excess. Design values shall be obtained based on calibrated safety coefficients, so that the probability of being exceeded does not reach 0.5%. For the current materials, steel and concrete, these safety coefficient values are respectively equal to 1.15 and 1.5, which, assuming a lognormal distribution function to characterize the materials resistance, correspond to variation coefficients respectively equal to 0.15 and 0.45.

To define the resistance of the structural cross-sections responsible for the bridge safety, it was considered that it follows a lognormal distribution with a variation coefficient equal to 0.30 (value between those considered for the steel and concrete), that the Portuguese code design criterion (ultimate limit stages) corresponds to a damage stage that can be considered as "Moderate" and that the design value of the cross-section resistance equals the one corresponding to the seismic action effects for its combination value. Assuming, for design purposes, that the effective resistance value corresponds to a probability of not being exceeded equal to 0.5%, the ratio between its value and the median is equal to 2.13. As the design value corresponds to the combination value of the code seismic action, the median value of the curve associated with the "Moderate damage" can be obtained multiplying by 2.13 that combination value (Sa(T=1.0)=0.28g). To define the median values associated to the design codes before 1985, based on serviceability limit stages, it was considered more adequate the comparison with the damage stage defined as "Slight", being the combination value, Sa=0.15g.

Based on these values, it was possible to obtain the reference median values presented in Table 1. Assuming these median values and the same dispersion coefficient assumed by HAZUS99 (β=0.4), the fragility curves displayed in Figure 3 were obtained.

Table 1: Fragility curves median values for bridges and viaducts (g)

Damage stage	Before 1985	After 1985
Slight	0.32	0.49
Moderate	0.40	0.60
Extensive	0.48	0.76
Collapse	0.69	1.01

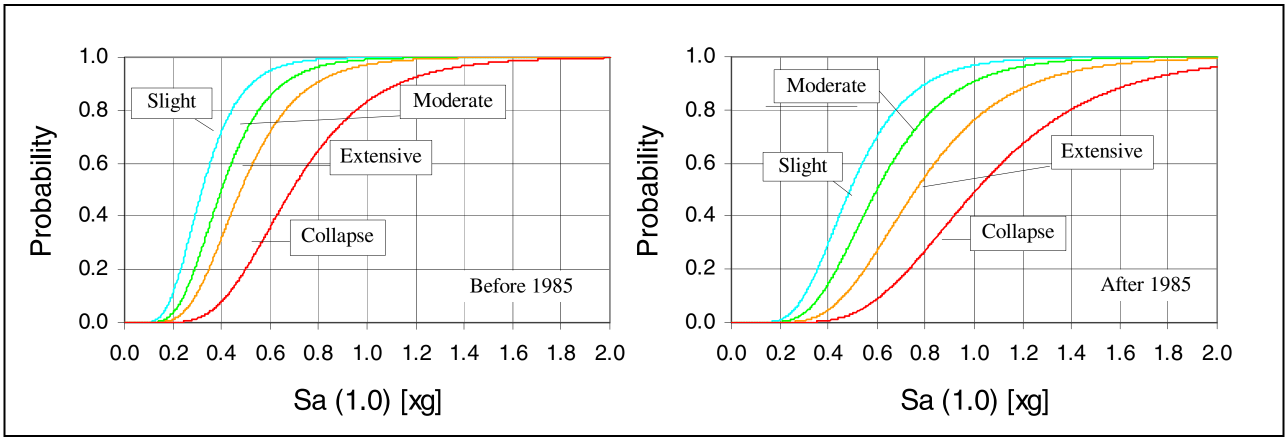

Figure 3: Reference fragility curves

Based on the reference fragility curves it is possible to define the fragility curves associated to each bridge class, introducing a set of corrective parameters, based on the expected seismic behavior of each class, which, for each damage stage, can be below or above average and thus be affected by a factor lower or greater than 1.0. For instance, when considering a recently built highway bridge with its seismic resistance guaranteed by the abutments and columns, it was considered that, given its characteristics, this type of structure has a behavior above average for low seismic action values, tending to the average for larger ones. This conclusion results from the fact that this type of structure is relatively well braced in the longitudinal direction and presents a favorable span/width ratio. Thus, in this case, the corrective values for the four stages were: 1.15, 1.10, 1.05 e 1.00.

Other corrective factors considered in the study were the angle of skewness (similar to those present in HAZUS99) and others to take into account any specific particularity of a given bridge (based on local observation or based on the design information).

Besides damage induced by vibratory movements, other phenomena may give rise to seismic action induced damage, namely foundation rupture. In HAZUS99 two types of foundation rupture are considered: due to liquefaction (assuming lateral spreading and settlement) or to landslide. In both cases the HAZUS99 methodology was adopted also because it was considered that there are not significant differences to the Californian situation.

RESULTS

Based on the developed earthquake simulator, several seismic scenarios were examined, among which two potentially critical for the Lisbon region.

The decision to analyze only the main roads and all the railroads resulted in the identification, characterization and analysis of 521 bridges and viaducts for the road network and 243 for the railroad system.

A macroscopic analysis of the results obtained for several examined scenarios shows that the damage simulation is in accordance with what could be beforehand expected. It can be observed that damage is logically linked to larger magnitudes, lower epicentral distances, occurrence of liquefaction, occurrence of landslides and greater vulnerability of bridges and viaducts.

Although generic and obviously expectable observations, it is important to mention that damage tends to concentrate in the epicentral zone, diminishing with the epicentral distance in a way apparently in agreement with what has been observed in previous earthquakes. Damage, both in road segments and bridges, is very much influenced by soil liquefaction, damage occurs preferentially in bridges that exhibit the more severe fragility curves and the typology of the foundation soils also has an influence in the bridge vulnerability, although the occurrence of liquefaction (directly dependent o the type of soil) is the most relevant parameter.

For each seismic scenario, each bridge was assigned, among the five possible damage levels (no damage, slight damage, moderate damage, extensive damage and collapse) the damage stage that, according to the obtained results, has a 50% probability of not being exceeded, which corresponds to the damage stage related to the median value of the observed damage.

Two scenarios were specially examined, for they represent the two main earthquake sources that can strike the great Lisbon area. The first, denominated "Tejo" corresponds to a 6.5 magnitude earthquake, with epicenter in the Tagus (Tejo) river valley, just in front of Lisbon and the second, denominated "Sines", with a magnitude 9 and epicenter off the Portuguese coast, near the town of Sines, at around 90 km from Lisbon.

"Tejo" scenario

In this scenario there was a significant volume of damage, both for the road and the railroad networks. Overall, 4% of the road bridges and viaducts and 10% of the railroad ones are classified as sustaining some kind of damage, with the collapsed ones and the ones suffering extensive damage being respectively 2% and 5% of the total. These values are in accordance with what could be expected for this type of occurrence. In the Northridge earthquake and for a zone with comparable size, only 1% of the bridges collapsed or had significant damage. The influence of liquefaction is quite visible and more in the road bridges than in the railroad ones. The bridges with extensive damage or collapsed are either located in a zone with liquefaction potential, in the southern margin of the river, or in the Lisbon area very close to the assumed epicenter, where, even without liquefaction, important damage can be observed due to the dynamic effects.

"Sines" scenario

The "Sines" scenario is the one that induces the greater volume of damage, both in the road and the railroad networks. In this scenario, 21% of the road bridges and 27% of the railroad ones are classified as suffering some damage, being the collapsed or with extensive damage respectively 18% and 14%. In this case the liquefaction influence is extremely large, being evident that in most of the cases collapse occurs for this reason. Most of the bridges with extensive damage or collapsed are located in the southern margin of the Tagus river, a zone with liquefaction potential and closer to the epicenter.

Ground motion and liquefaction

The distribution of peak ground acceleration values in the zone under study together with the zones where liquefaction occurs are depicted in figure 4, for both scenarios.

It can be seen that in the "Tejo" scenario a few zones in Lisbon, close to the epicenter, reach peak ground acceleration values around 0.5 g. Some extensive zones south of the Tagus river are subjected to acceleration values that range from 0.25 to 0.10 g.

The PGA values rapidly decrease to around 0.1g for the zones more distant from the epicenter, especially those situated in the northern part of the area under analysis, which exhibits better foundation soils. Liquefaction is bound to limited zones in the southern margin.

It the “Sines” scenario the distribution of peak ground acceleration values is more uniform, decreasing from south (where the epicenter is located at around 70 km) to north and ranging from about 0.4g to less than 0.1g. The zones south of the Tagus river are subjected to acceleration values that are larger than in the previous scenario, causing more liquefaction to occur in this zones. For a few zones in the northern margin the same situation occurs.

It is interesting to notice that the PGA distribution over the area under analysis is more uniform in the “Sines” scenario, which also shows larger average PGA values over the entire territory.

It should also be mentioned that liquefaction occurrence was mentioned both in the 1755 Lisbon earthquake, which, albeit some controversy, is believed to be somehow more similar to the “Sines scenario” and in the 1909 Benavente earthquake which was similar to the “Tagus” scenario, although with different epicenter location (further northeast, more distant from the town of Lisbon).

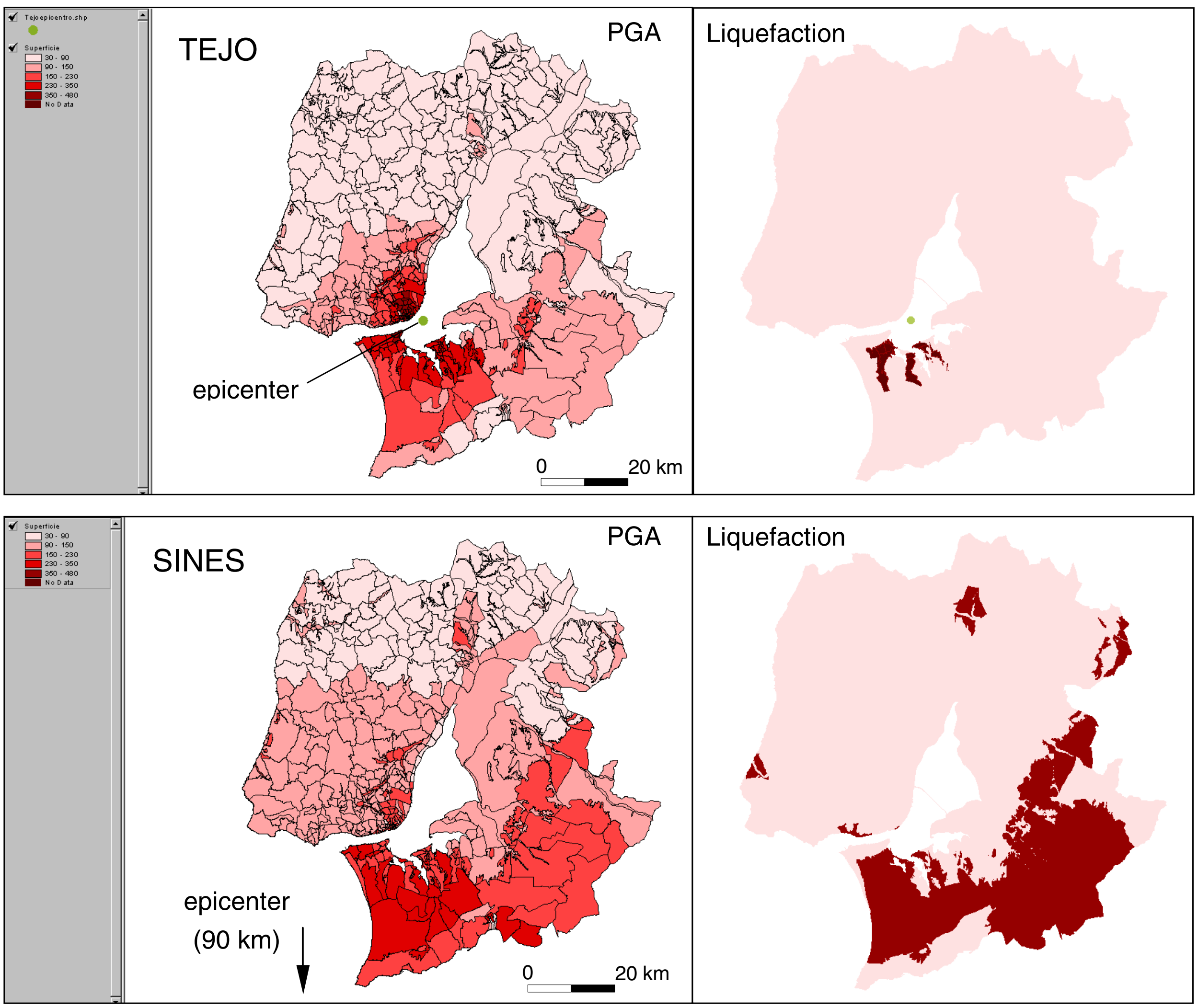

Figure 4 – Peak ground acceleration and liquefaction occurrence for the “Tejo” and “Sines” scenarios

Damage assessment
Figure 5 displays the damage assessment for both scenarios and for the bridges of both networks (road and railroad). It is easily verifiable that the "Sines" scenario is substantially more severe than the "Tejo" one, mainly due to the more pronounced influence of the liquefaction effects.

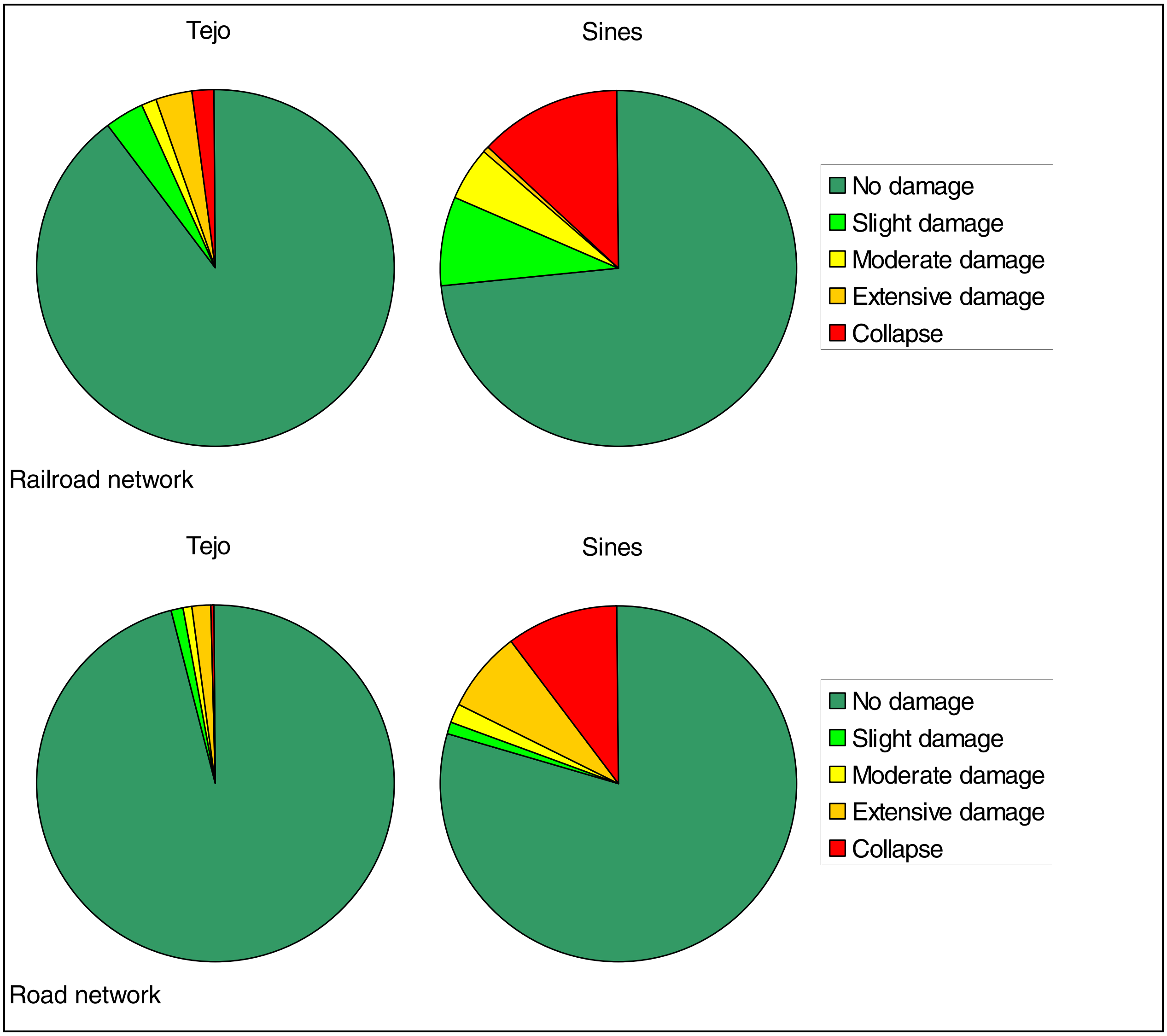

Figure 5: Global assessment of bridge damage for two seismic scenarios

Sensitivity analysis
To verify the sensitivity of the global damage assessment to possible imprecision in the evaluation of the fragility curves for the bridges, a factor reducing the resisting characteristics was taken into account. It was considered that the factor could vary between 1.0, corresponding to assuming that the resisting capacity was correctly estimated, and 0.2, corresponding to a drastic reduction of the resistance to 20% of the estimative made based on the general criterion. The consideration of this factor is linked with possible systematic deficiencies in the design or construction procedures not accountable with the adopted assessment.

The results of this sensitivity analysis, some of them displayed in figure 6, show that the consideration of reducing factors implies a general aggravation of the damage stage of the different structures. The lower the reducing factor is the lower is the number of structures without any damage and the larger is the number of structures with in the most severe damage classes. The variation is negligible for a reduction factor equal to 0.8 and only has some significance for reduction factors lower than 0.5, which shows that the model leads to expected damage values which are not very sensitive to small variations in the properties of the adopted fragility curves.

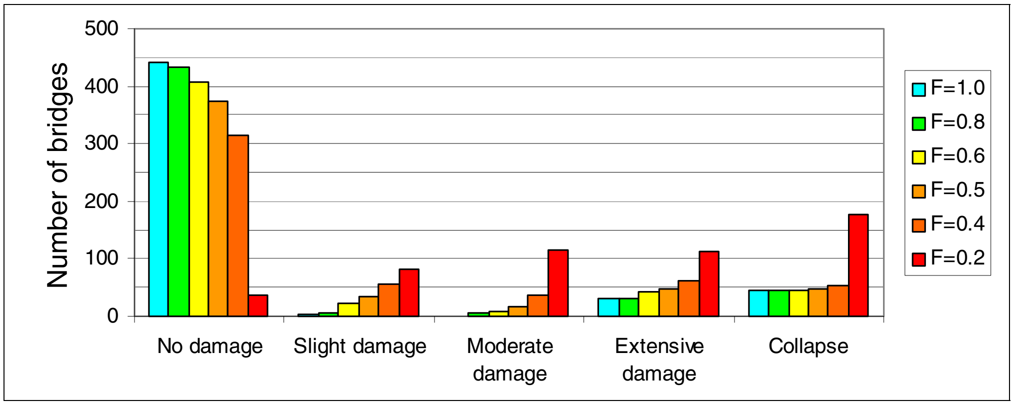

Figure 6: Observed damage as a function of the reduction factor (F) for the resisting capacity

Also important is to analyze the sensitivity of the observed damage to the magnitude of the events.

It should be said beforehand that a magnitude 9.0 for the "Sines" scenario is already an upper bound of credible magnitude for this very large magnitude event, and although the genesis of the 1755 Lisbon earthquake is not fully understood, this scenario tends to simulate what is believed to have happened at that time.

In what regards the "Tejo" scenario, it tends to simulate an event occurring in local faults which have also have caused earthquakes in the past. Although it is not credible that very large magnitude earthquakes may occur in such faults, the "Tejo" scenario was also examined for magnitudes ranging from 6.5 to 8.0.

Te results of such analysis are displayed in figure 7, which shows the percentage of bridges in each damage class for the different magnitudes.

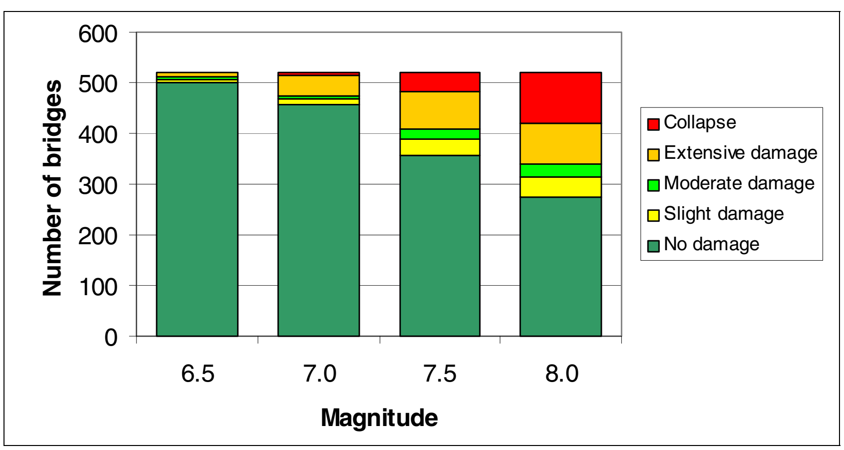

Figure 7: Observed damage as a function of the magnitude for the "Tejo" scenario

It can be seen that, with the increase in magnitude, there is a significant decrease in the number of bridges without damage, especially for magnitudes 7.5 and 8.0. All damage classes exhibit larger number of bridges with the increase in magnitude, especially in what concerns the collapsed or severely damaged bridges in the case of magnitudes 7.5 and 8.0.

CONCLUSIONS

The proposed methodology to evaluate the behavior of transportation network elements seems to be adequate for a global damage assessment and allows the analysis of the impact of different seismic scenarios, namely in terms of epicentral location and magnitude.

The estimates obtained for some of the most severe scenarios show damage patterns similar to some verified in comparable seismic zones. The reliability of the results depends on the fragility curves adopted for the different types of bridges and viaducts, but seems to be even more dependent on a correct characterization of the liquefaction occurrence.

REFERENCES

[1] Applied Technology Council - ATC13 - Earthquake Damage Evaluation Data for California, 1985.

[2] Federal Emergency Management Agency and National Institute of Building Sciences - Earthquake Loss Estimation Methodology HAZUS99 - Technical Manual, 1999.

[3] RSA – Regulamento de Segurança e Acções para Estruturas de Edifícios e Pontes (in Portuguese), Imprensa Nacional Casa da Moeda, 1984.