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SEISMIC IMPACT ON LIFELINES IN THE GREAT LISBON AREA

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SUMMARY

In this work a study on the impact of earthquakes on the lifeline systems of the Great Lisbon Area, in Portugal, is described. This work was part of a major program, an initiative of the Portuguese Civil Protection Service, intending to develop a tool for the emergency planning support. It aimed at the development of a simulator for the damage estimation of different lifeline systems, working on a GIS, including highway and railroads, water systems, power systems, liquid and gas fuels systems. Specific papers on the analysis methodologies and results regarding the individual systems were submitted, with this paper aiming at giving an integrated and compared perspective of the overall behavior of the entire lifeline network, stressing some of the main conclusions and showing some interdependence between the performances of the several systems.

Among some of the analyzed issues, regarding the several systems, are:

- Comparison of the used input and its format: Magnitude, epicentral distance, peak ground acceleration, permanent ground displacement;
- Comparison of output characterization: Malfunction probability, percentage of damaged equipment, probability of different damage stages;
- Construction of the fragility curves for the different systems, with the description of the general methodologies and criteria;
- Comparison of the performance of the different systems and main common reasons for malfunctioning; the output of some analyzed scenarios is shown and the discussion on its reliability is analyzed.

INTRODUCTION

The existence of preparedness plans that articulately allow the assessment of the impact of earthquakes and the minimization of their consequences is one of the tasks of the civil protection services.

In Portugal, the great Lisbon area is probably the zone with greater seismic risk. It is located in a zone affected by the occurrence of large magnitude (>8) although distant earthquakes (as the southern part of

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the country), sits on a zone where medium magnitude (>6) earthquakes occur and is the largest town and the capital of Portugal, where larger economical values are at stake.

Aware of that risk, the Portuguese Civil Protection Service (SNPC), decided to launch a project for the assessment of the seismic risk in the region. Several Portuguese institutions carried out this study, that included tasks going from the characterization of the seismic motion, assessment of the behavior of the building stock, vital structures and lifelines as well as the impact it may have in the population according to the time of occurrence. The authors took care of the assessment of the seismic risk linked to the lifelines, which is summarized in this paper.

The lifelines under study incorporated: the transportation network, including highways, other major roads and railroads; the electrical power system; the gas and oil distribution networks and the water supply system. The area under study, displayed in figure 1, is a zone around the town of Lisbon with approximately 5000 km^2, that includes the major towns around the Portuguese capital and which accounts for more than 3 million residents, representing around one third of the Portuguese population.

Figure 1: Location of the great Lisbon area

The paper presents some methodologies and some undertaken steps for the construction of seismic vulnerability assessment models of the networks and presents some results obtained regarding damage simulation for some seismic scenarios.

The impact of earthquakes on 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 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 disruption, which increases with the economic development in the affected zone. In past earthquakes, although a clear quantification of the indirect damage has not been made, it is believed it often exceeds the direct damage.

In some lifelines, especially those that are spatially spread, damage essentially occurs due to rupture of the foundation, obstruction induced by liquefaction, fault movements or landslides. In the lifelines that include some single components that are structural systems, damage can either be due to 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 structural dynamic characteristics and on their capacity to withstand cyclic actions.

DESCRIPTION OF THE LIFELINES

All the information regarding the lifelines for the region under study was implemented in a GIS, which contains the geographic information related to the lifeline elements as well as the main characteristics that are relevant to assess their seismic performance.

The GIS is also used to define the soil characteristics, zones with landslide potential and the site dependent ground motion characteristics, for any magnitude and epicentral location defined by the user. It was implemented to work as a seismic simulator, where the effects of the site dependent ground motion on the different components of the networks are analyzed.

Transportation network

The two main transportation networks of the great Lisbon area are the road and the railroad networks. In the GIS were included all the highways of the region, as well as other main roads. All lines of the railroad system were considered, except for the Lisbon subway. Figure 2 displays such information, including all road and railroad segments as well as all the main bridges, viaducts and tunnels. The decision to analyze only the highways and main roads and all the railroads resulted in the identification, characterization and analysis of 521 bridges, viaducts and tunnels for the road network and 243 for the railroad system.

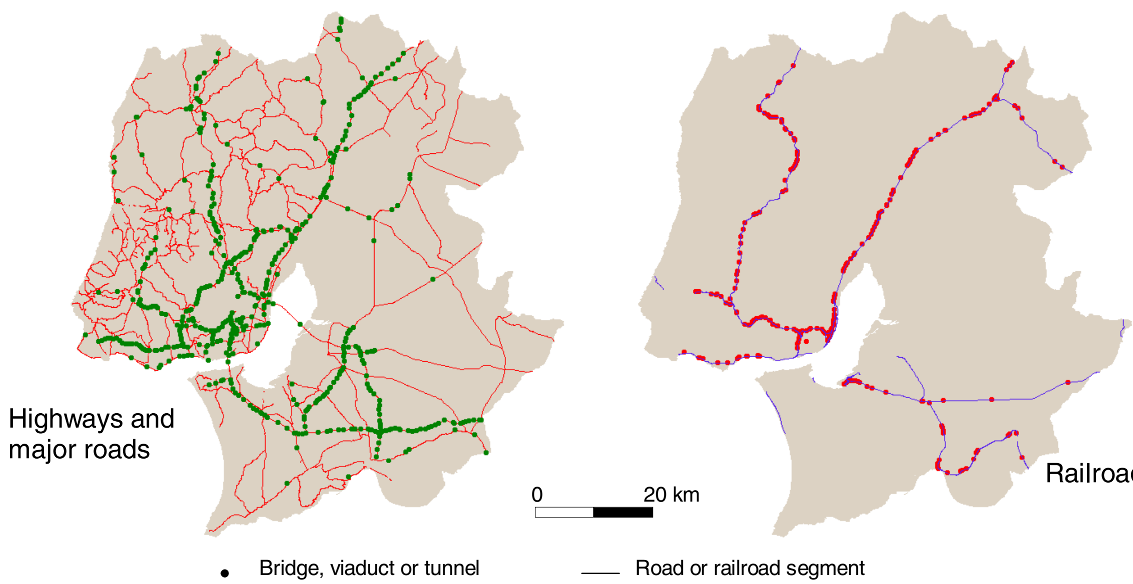

Figure 2: Road (Motorways and major roads) and Railroad networks

The GIS contains the information regarding the two lifeline networks defined by means of line sections 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.

Gas and Oil Networks

The gas network is composed of buried pipelines and compression stations called PRP and PRM (reducing and measuring stations), which may be found in different places of the network. The function of the compression stations is to reduce and measure the flow that is carried through the pipelines.

The natural gas system belonging to the great Lisbon area is shown in figure 3 (green, blue and pink lines).

The oil network (Figure 3 – red line) consists of buried pipelines, refineries (an important part of the oil system), pumping plants (allow to maintain the flow of oil in the pipelines) and tank farms (the facilities to store the fuel products).

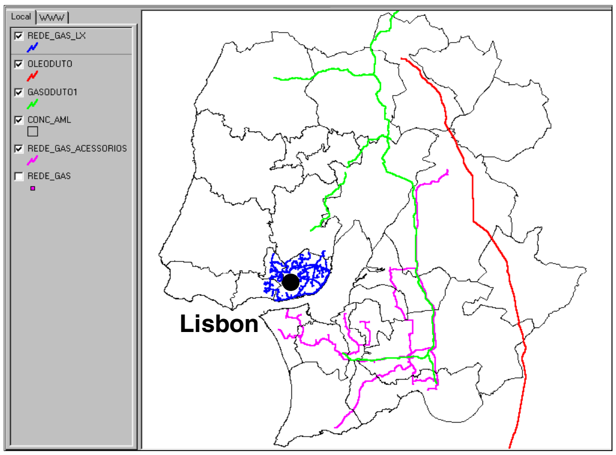

Figure 3: Gas and oil networks

The compression stations (gas system) and the refineries, pumping plants and tank farms (oil network) are vulnerable to PGA or PGD values, when located in areas that present liquefaction potential or when there is a tendency for the occurrence of land sliding or where is known the existence of active faults. Knowing that the tank farms are the components that determine the type of damage in the storage compounds of the oil networks, during this study the resulting damage of the occurrence of a certain seismic action in the oil networks is referred to the tanks. The buried pipelines, for gas and oil networks, present seismic vulnerability to PGV and to PGD values.

Water Supply System

The water supply system in the great Lisbon metropolitan area, north of Tagus River, is mostly run by EPAL, a semi-private company. The most relevant production figures are as follows:

- Average daily water consumption – 648.000 m^3 (1996)
- Maximum daily supply capacity (superficial and subterraneous sources) – 950.000 m^3 (1996)
- Average daily water consumption in Lisbon city – 164.400 m^3 (1996)

One of the most striking features of the water network is the high reliance on the so-called Castelo de Bode subsystem (superficial source in the Castelo de Bode dam), which accounts for 500.000 m^3/day of the total supply capacity. The water from Castelo de Bode dam is conveyed to Lisbon vicinity by a single water conveyance system.

The water supply system most relevant components are those of water source (either superficial or subterraneous), water treatment plants, pumping units, conveyance systems, elevated (or superficial) tanks and the water distribution pipe network.

Electric Power System

The electrical network that supplies the great Lisbon area is interconnected with other zones of the country, with the power coming either from dams located in the northern part of the country, outside of the area under study, or from power plants, all but one also located outside the Lisbon area.

The electrical networks consist of modes and lines. The first are essentially the substations where the changes in voltage take place, the electric power is distributed by different lines and the control and protection equipment is located. Figure 4 shows a partial view of a substation, including a large power transformer and protection equipment. The lines of the transportation network (V> 60 KV) are aerial, supported by steel towers, and the lines of the distribution network (V≤ 60 KV) are usually aerial in rural areas and buried in urban areas.

Figure 4: Partial view of an electric power substation

METHODOLOGY OF ANALYSIS

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 because of the large return periods linked to the large magnitude earthquakes affecting the zone. This fact did not allow, in some situations, a direct use of the Hazus99 methodology and justified some adaptations necessary for a better representation of the Portuguese scenario.

For each network, slightly different procedures were used and described next.

Transportation networks

For the transportation networks, 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), 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.

The fragility curves were modeled as log-normal density probability 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:

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

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

To obtain the medians and dispersion coefficients for the definition of the fragility curves for the bridges and viaducts, an approach based on the Hazus99 methodology, but adapted to the Portuguese situation, was used and explained in more detail in another paper [3]. Typical reference fragility curves adopted in the study are presented in figure 5. Based on these curves and on corrective factors for each bridge class and even individual bridges, fragility curves were attributed to each individual bridge or viaduct.

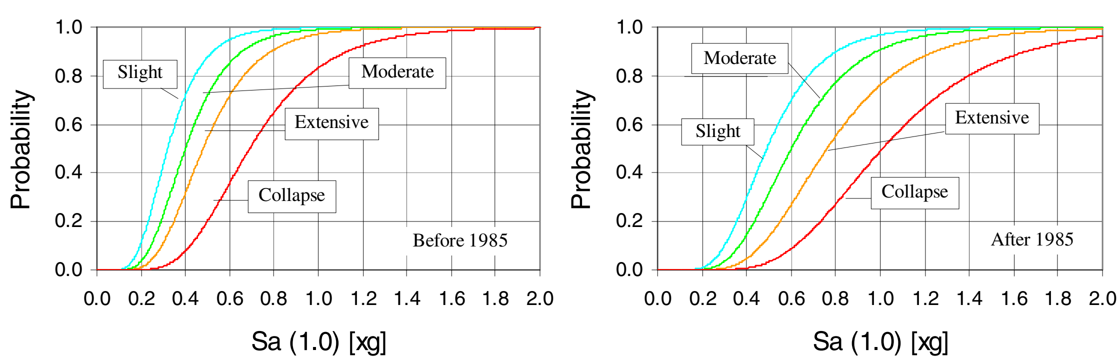

Figure 5: Reference fragility curves for bridge damage assessment.

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.

Gas and oil networks

For the seismic assessment to gas and oil systems the methodology proposed by Hazus99 was also applied, including small modifications [4]. This methodology takes into account separately, for all the network components, the effects of seismic wave propagation (quantified in terms of peak ground velocity, PGV or peak ground acceleration, PGA) and permanent ground deformation (PGD).

For the components, other than the buried pipelines, the damage functions or fragility curves were also modeled through lognormal distribution functions. A total of five damage stages for the compression stations were defined: none (ds_1), slight (ds_2), moderate (ds_3), extensive (ds_4), and complete (ds_5). Each of the fragility curves is defined by a median value of the ground motion (X_i), or ground failure, and an associated dispersion factor (β_i) according to equation 1, which was also used for the transportation networks. Similar expression is defined in the case of ground failure.

For the fragility curves definition it is important to classify the components: in this network all are classified as anchored, that means they were designed with special seismic requirements. Based on this classification, Hazus99 defines, for each damage stage, values for the median value of ground motion X_i and for an associated dispersion factor β_i.

In the gas systems the components are compression stations and for its characterization it is necessary to know if they were designed, or not, to resist to the seismic action (if they have anchored components or not). Regarding the oil networks the characterization of the refinery is done based on the existence, or not, of anchored components and on its capacity (small or medium/large). The Sines Refinery (Portugal), the only refinery existent in the studied network, corresponds to a medium/large refinery with anchored components. The pumping plant existent in Sines has anchored components, in accordance with the definition for this kind of components. For the tank farms, all located in Aveiras, the existence of seismic design in their components was verified and thus it was assumed that the referred tanks present anchored components.

The Hazus99 methodology allows the user to select any seismic level, in particular the seismic design level considered adequate for the study area. To evaluate the probabilities associated to each damage stage, it is necessary to establish a certain seismic scenario. According to the reality of Portugal a peak ground acceleration of about 0.3g was chosen in this study and thus the medium values defined by Hazus99 were corrected taking into account the adopted modification.

The permanent ground deformations can be due to liquefaction phenomena, land-sliding and fault movements. Nevertheless, liquefaction is the occurrence that causes higher level of damage in the components of the gas and oil networks. Related to the soil's liquefaction two different phenomena exist: lateral spread and settlement. For the evaluation of the global probabilities of damage for each component it must be considered the probabilities associated to the occurrence of the most probable phenomena (lateral spread or settlement). The input variables are the seismic action and the classification of the component. To identify the seismic action it should be introduced the value of the probability of soil liquefaction occurrence (P_{LIQ}) and the values associated to the existence of permanent lateral spread (PGD_{LAT}) or settlement (PGD_{ASS}) due to the liquefaction. Based on the classification of the component, the medium value (X_{RFi}) and the standard deviation of the variable ln(x) (β_{Rfi}) associated to each damage stage and corresponding to the rupture of the component's foundation (RF), are defined:

i) Damage due to lateral spread

$$P[Ds \geq ds_i]_{LAT} = \Phi\left(\frac{\ln[PGD_{LAT}] - \ln[X_{RF_i}^{c}]}{\beta_{RF_i}}\right) p_{LIQ} \qquad i = 2,3,4 \text{ e } 5 \tag{2}$$

ii) Damage due to settlement

$$P[Ds \geq ds_i]_{ASS} = \Phi\left(\frac{\ln[PGD_{ASS}] - \ln[X_{RF_i}^{c}]}{\beta_{RF_i}}\right) p_{LIQ} \qquad i = 2,3,4 \text{ e } 5 \tag{3}$$

The probabilities of damage associated to the soil's liquefaction may be calculated through the following equation:

$$P\,[Ds \geq ds_i]_{LIQ} = MAX\,\{P\,[Ds \geq ds_i]_{LAT};\, P\,[Ds \geq ds_i]_{ASS}\} \tag{4}$$

The damage in the studied gas and oil ductile buried pipelines (repairs/ length – RR) are defined according to equation 5 for the dynamic soil effect, function of the PGV value, and quantified in terms of repairs per unit of length (repairs/km). The corresponding expression proposed in Hazus99 does not include the influence of the pipeline's diameter. To consider the influence of the different diameters, the factor K_ϕ was proposed [3]. Moreover, equation 5 is a simplification of the proposed in the Hazus99, for ductile pipelines.

$$RR_{PGV}[\text{repairs/km}] = 0.00003\, K_\phi PGV^{\,2.25} \tag{5}$$

The damage functions due to permanent ground deformations (PGD) are defined according to equation 6, where PROB stands for the probability of occurrence of the different phenomenon (liquefaction, $PROB_{LIQ}$; land sliding or geological fault, $PROB_{LANDS}$ and $PROB_{FAL}$).

$$RR_{PGD}[\text{repairs/km}] = 0.18\, PROB_{LIQ,\, LANDS \text{ or } FAL}\, PGD^{\,0.56} \tag{6}$$

In this methodology, it is assumed that damage resulting from the seismic waves propagation consist of about 80% of flows and 20% of ruptures, while the damage due to the soil's permanent deformations correspond to 20% of flows and 80% of ruptures. Thus, if no phenomenon associated to the soil's rupture occurs, the number of ruptures (ROT – ruptures/km) is obtained from equation 7. Otherwise equation 8 should be used.

$$ROT\,[\text{ruptures/km}] = 0.000006\, K_\phi PGV^{\,2.25} \tag{7}$$

$$ROT\,[\text{ruptures/km}] = 0.000006\, K_\phi PGV^{\,2.25} + 0.144\, PROB_{LIQ,\, LANDS \text{ or } FAL}\, PGD^{\,0.56} \tag{8}$$

Water supply system

Models for the prediction of earthquake damage in distribution pipes
With the exception of the buried pipes and aqueducts, the seismic vulnerability of the remaining components of the water system was depicted by means of slightly adapted Hazus99 fragility curves.

Distribution pipes, are made of cast-iron, ductile iron, reinforced concrete, asbestos cement, glass fiber and PEAD. The existent models for predicting earthquake physical damage in buried distribution pipes can roughly be divided into analytical models and empirical models.

The analytical models generally consider only the seismic wave propagation effects and are based on the following assumptions:

- soil medium motion remains undisturbed by the presence of pipes;
- the relative motion between the pipe elements and the surrounding soil medium is negligible;
- the geotechnical characteristics are constant within the pipe segment;
- the pipe is sufficiently far away from the earthquake focus so that there is no attenuation along the pipe length.

The former assumptions led to the following damage equation in buried pipes with external radius R:

$$\varepsilon_{max} = \sqrt{\frac{v^2}{C^2} + R^2 \frac{a^2}{C^4}} \tag{9}$$

where C stands for the seismic wave velocity along the soil medium and *v* and *a* are, respectively, the peak ground velocity and acceleration. The ε_{max} variable represents the maximum strain in the pipe segment, which directly relates to physical damage estimates. The former equation disregards all types of permanent ground deformation effects, such as liquefaction, settlements, lateral spreads and landslides.

The empirical models for earthquake damage in buried pipes, such as those proposed by Isoyama [5] and Hazus99, are base on the post-earthquake damage assessment. These models generally relate the physical damage index R (number of breaks for km length) with a vibration severity variable (generally v, peak ground velocity). Isoyama proposes the following equation:

$$R(\alpha) = C_p C_d C_g R_0(v) \tag{10}$$

where $R_0(v)$ is a standard damage function for cast iron pipes, with a diameter within the 100 mm to 150 mm range, in an alluvial plain and without liquefaction. The C_p, C_d and C_g damage corrective factors modify damage taking into consideration that the diameter, the material and geotechnical-topographical conditions may be different from the standard conditions. These corrective factors were proposed by Isoyama based on the damage assessed for the Ashiya and Nishinomiya municipalities during the 1995 Kobe earthquake. Hazus99 proposes similar equations.

When comparing the former models (analytical and empirical) one of the most striking differences relates to the diameter effect. In fact, while the analytical model leads to increasing damage for larger pipes, the empirical models predict the opposite (the C_d factor decreases with the pipe diameter D). This remark and the lack of consideration of the permanent soil deformation effects led to the adoption of a modified Isoyama/Hazus99 model.

One of the limitations of any of the former physical damage models consists in the lack of information as to the operational effects of the earthquake. Kawakami [6] had predicted that there is a gradual decrease of functionality from 0.1 breaks/km to 1 breaks/km. For physical damage over 1 breaks/km the specific pipe in which it occurs is no longer usable within the water distribution network. These recommendations by Kawakami were considered in the interpretation of the simulator results.

Models for the prediction of earthquake damage in other components

As referred to previously, most of the water supply network components vulnerability was described through slightly adapted Hazus99 recommendations for unanchored components. The damage results were therefore assessed by the probability of occurrence of four increasing damage levels, DS2 to DS5, expressed in terms of one ground vibration severity index, generally PGA. Damage functions for pipelines were adapted from those prescribed for buried pipes through expert-based modification factors.

Electric power system

Such as for the Hazus99, lognormal functions were used to characterize the vulnerability of most components. Only for buried lines the damage stage was defined in a different manner, by the number of repairs per kilometer.

The Hazus99 values were used for the definition of the vulnerability functions of the less important equipments of the networks. However the fact that those values were calibrated from damage observed in past earthquakes in electrical facilities whose construction and assembly practices may be different from the ones of the Portuguese networks, led to different approaches in some cases.

For the most important equipments, as is the case of the power transformers, the median value of the vulnerability functions was directly evaluated considering the real external fixing conditions of the transformers, which may vary significantly. Figure 6 shows the case of a transformer that can be damaged if large displacements at the base take place.

A set of nonlinear dynamic analysis considering the transformers as one degree of freedom rigid bodies that can only move in the direction of the rails was performed to analyze the potential vulnerability of these equipments. Friction at the base was considered the only energy dissipation mechanism, since internal damping is reduced due to the type of construction of these machines. The results indicate that the frequency contents of the seismic action strongly influence the displacement of the transformers. This was considered in the simulator in an approximate manner by establishing a dependence between the median value of the vulnerability function and the epicentral distance. According to Hazus99 the peak ground acceleration is the only variable considered in the evaluation of the vulnerability of the transformers.

Figure 6: View of a transformer base fixing conditions

For other equipments, except buried lines, the median values used in Hazus99 were scaled assuming differences of vulnerability to the Portuguese reality similar to the ones observed for the power transformers.

RESULTS

Seismic scenarios under analysis

Several seismic scenarios were examined with the earthquake simulator available in the implemented GIS, intending to simulate different seismic occurrences that may be representative of the two main seismic sources that may affect the region under study.

The Portuguese seismic code foresees two types of seismic actions. The first is a medium magnitude earthquake at small epicentral distance and short duration, typically representing an earthquake in a fault in the Tagus Valley, near Lisbon. The second is a large magnitude earthquake at large epicentral distance and long duration, typically representing an earthquake with origin in the zone of confluence between the Euroasiatic and the African plates.

Two scenarios were specially examined, trying to represent these two main earthquake sources that can strike the great Lisbon area. The first, denominated “Tejo” corresponds to a 6.5 (or 7.0) magnitude earthquake, with epicenter in the Tagus (Tejo) river valley, just in front of Lisbon (or slightly northeast). The second, denominated “Sines”, has a magnitude 9 and epicenter off the Portuguese coast, near the town of Sines, at around 90 km from Lisbon. Figure 7 displays the peak ground acceleration distribution in the area, as well as the zones with liquefaction for the “Tejo” scenario.

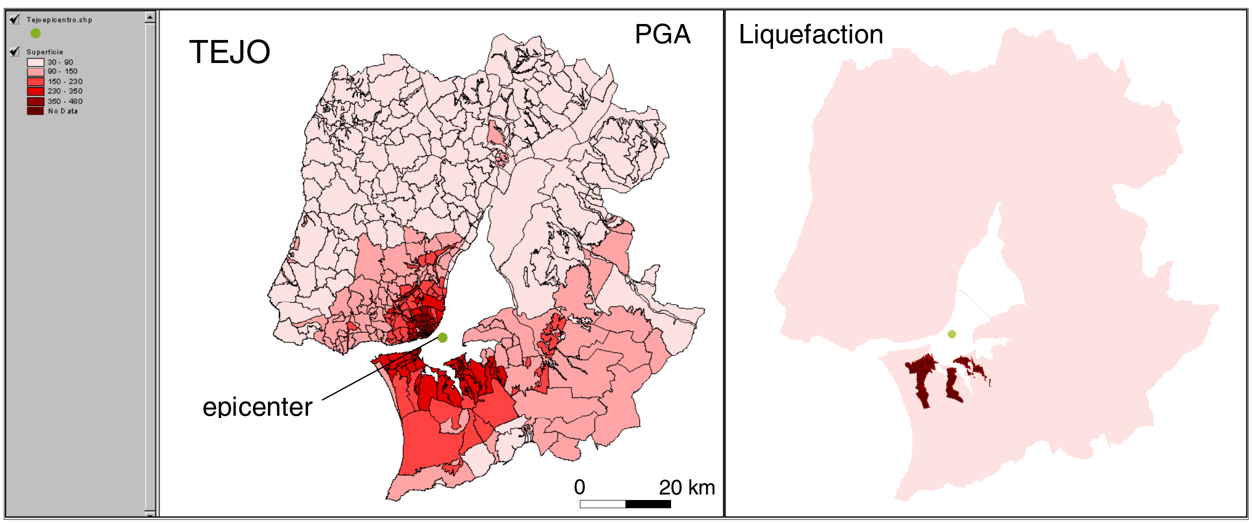

Figure 7: Peak ground accelerations and liquefaction occurrence (“Tejo” scenario)

A macroscopic analysis of the results obtained for other examined scenarios shows that the damage simulation is in accordance with what could be 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 networks.

Impact in the transportation networks

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, are 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 has a 50% probability of not being exceeded, which corresponds to the damage stage related to the median value of the observed damage.

“Tejo” scenario

In this scenario there was a significant volume of damage, both for the road and the railroad networks. In this scenario, 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.

Figure 8 displays the damage estimative 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.

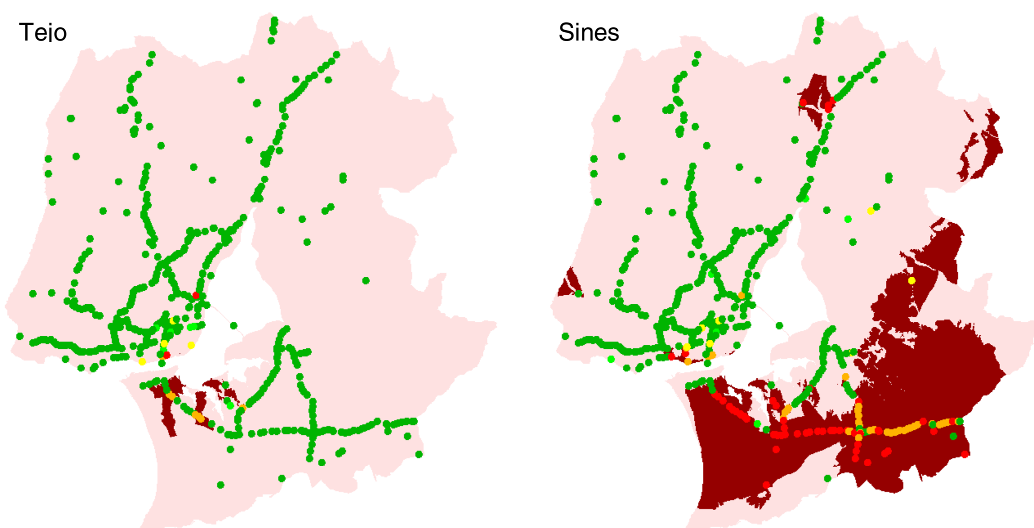

Figure 8: Global assessment of bridge damage for two seismic scenarios

Impact in the Gas and Oil networks

The results obtained for all the components of the gas and oil networks when subjected to the "Tejo" scenario are represented in the following two figures. Figure 9 shows the level of damage reached by the buried pipelines and the damage occurred in all the others components.

From Figure 9 one can say that damage in buried pipelines and all the other components are mainly influenced by soil liquefaction, which, for the "Tejo" scenario, occurs in the southern margin of the Tagus river. In fact, even the components close to the assumed epicenter, nearby the Lisbon area, have no damage due to the dynamic effects of the seismic action.

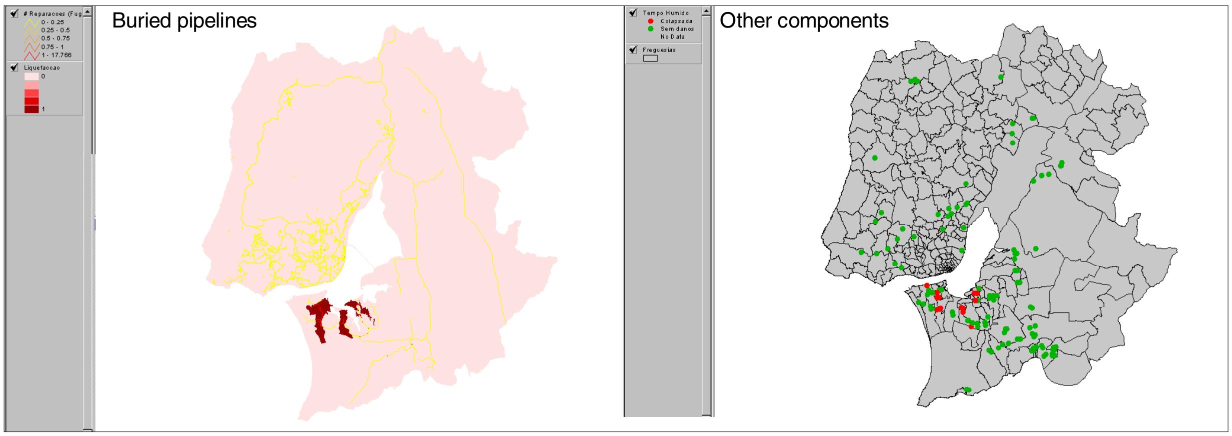

Figure 9: Damage in buried pipelines and other components ("Tejo" scenario)

Impact in the water supply system

The simulator allowed for an indeterminate number of earthquake scenarios. The present results correspond to the "Tejo" scenario, but with the epicenter slightly northeast, within the Northern Vila-Franca-de-Xira fault, with a magnitude equal to 7.0.

Figure 10 depicts the damage indicator for buried pipes, aqueducts and pipelines for such scenario, highlighted in red for components with R value within the 0.1-1 range, reduced functionality.

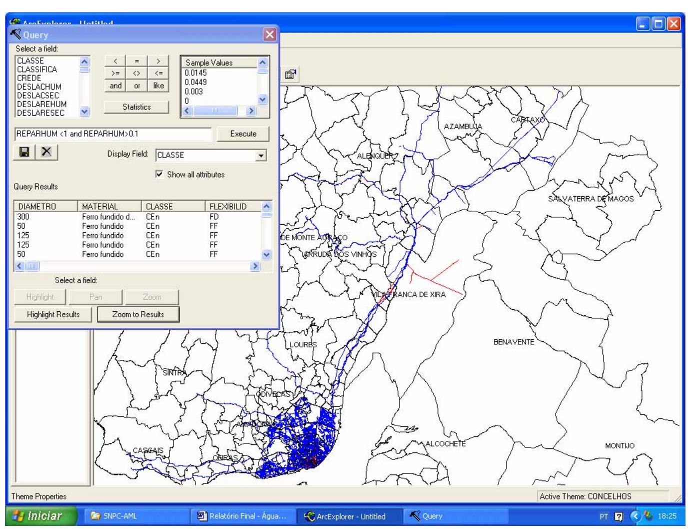

Figure 10: Damage indicator (breaks/km) for buried pipes, aqueducts and pipelines

Damage is mostly concentrated in the vicinity of the epicentre, particularly in some pipelines and other water conveyance components near the city of Vila Franca de Xira. Some damage is also expected in the water distribution network in Lisbon city, mostly due to permanent ground deformation effects in worst soil conditions in downtown Lisbon.

For spatially discrete components, damage is described by the probability of occurrence of each of the four damage stages (DS2 to DS5). These results can be better understood by defining an individual damage indicator, which describes the most likely damage stage (from 0 to 5), computed as the weighed average of these damage stages probabilities. Figure 11 depicts the results of this individual damage indicator for all discrete components, highlighted in red for components with values in excess of 2.

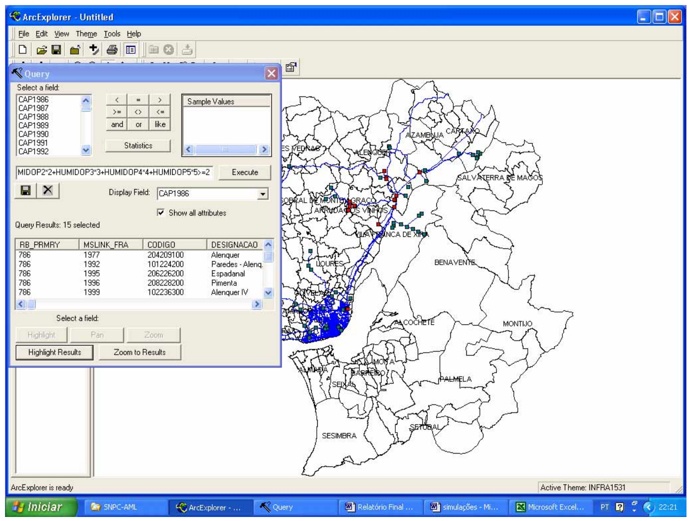

Figure 11: Individual damage indicator for discrete components

The highlighted components are mostly in the epicenter region, with the exception of a water reservoir in the city of Lisbon. One water treatment plant and one pumping station (and adjoining tank) present an individual damage indicator of nearly 5, indicating that these near-epicenter components should collapse.

Impact in the Electric power system

A damage scenario was evaluated for a case in which, in all the zone of the study, accelerations equal the ones defined in the Portuguese code of actions for a far distance earthquake. Obviously, this is not a real scenario, but it is thought that in average terms it may be a representation of a far distance earthquake of large magnitude. However in terms of economic consequences for the community as a whole the most relevant output of the study is the duration of the interruption of the energy supply and the number of affected people. The Hazus99 methodology was considered inadequate for this scenario since it assumes that there are enough human and material resources to repair simultaneously all the damaged equipments. The analysis was done considering the available resources and led to the conclusion that the recuperation of the networks could last for a few weeks.

CONCLUSIONS

The proposed methodology to evaluate the behavior of the lifeline 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.

The methodology adopted in this work and proposed by Hazus99, to predict the damages in all components of the gas and oil networks resulting from seismic actions, allows the assessment and evaluation of each one of the components of the system. The global evaluation of the gas and oil networks can be easily done based on a GIS. With this procedure it can be obtained the state of the damage corresponding to a certain component and the global damage of the system, for certain seismic scenario. For this networks the results for the “Tejo” scenario are presented.

The results obtained show that the permanent ground deformations, in particular the effects of liquefaction phenomena, are systematically the cause of the most severe observed damages.

For the spatially distributed systems (typically those with buried pipes) the simulator results clearly indicate that, when existent, permanent ground deformation effects lead to damage indicators clearly in excess of those due to the seismic wave propagation effects.

Most of the discrete components (such as bridges, viaducts, water treatment plants, pumping stations and wells) were described according to Hazus99 recommendations that were initially developed for the United States. There is, therefore, a lack of European models calibrated with data characteristic of European typical solution in terms of the discrete components.

The simulator disregarded the functional interaction between different lifelines, such as water and electrical power supply lifelines. A more refined approach would greatly improve the post-earthquake functional damage estimates, as well as the corresponding recovery time and associated costs.

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