Assessing scenario seismic risk of transportation networks

Análise de cenários sísmicos em redes de transporte

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Abstract

This study presents a methodology to evaluate the consequences of seismic events in the transportation systems, as well as in the surrounding industry. This methodology was applied to an industrial facility, whose production relies on the accessibility to strategic regions in the country, using the transportation network (roads and railway). The probability of activity disruption and the repair time were calculated for the facility and for the considered networks, thus enabling the estimation of the total losses that the company may sustain due to a number of seismic scenarios.

Resumo

O estudo apresenta uma metodologia que permite estimar, para determinados cenários sísmicos, o tempo de interrupção das redes de transporte devido aos eventuais danos sofridos nestas estruturas. Tipicamente, esta interrupção conduz a perdas económicas na indústria situada próxima da rede, as quais são também analisadas no presente estudo. A metodologia desenvolvida foi aplicada a uma indústria mineira no Alentejo, cuja produção e exportação se encontram dependentes da acessibilidade a regiões estratégicas através da autoestrada e da ferrovia. A probabilidade de disrupção e o tempo de reparação foram calculados para dois cenários sísmicos, não só para as redes consideradas mas também para a fábrica onde decorre a produção, permitindo assim estimar as perdas económicas indiretas devido à disrupção destas redes.

Keywords: Infrastructure / Seismic risk / Open-data / Portugal / Transportation network

Palavras-chave: Risco sísmico / Portugal / Redes de transporte / Cenários

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1 Introduction

The exponential growth in the global population, mainly concentrated in urban areas, has led to an increase of the so-called "mega cities" (*i.e.* settlements with a population above 10 million [1]), often located in hazard-prone areas (*e.g.* Mexico City, Tokyo, Los Angeles). These settlements frequently rely upon the interconnection and interaction between many networks. In the event of an earthquake, a failure of one of these systems may cause a cascading effect, leading to the failure of others. This interdependency has been indicated as one of the reasons for the increase in the global economic losses due to disasters in the last decade [2].

Mitigation and preparedness actions can have a paramount role in lowering the extension of the damages and improving the performance of the networks. Despite the extensive lifeline damage registered after the 2011 Christchurch earthquake, it is believed that the damage was significantly lower as a result of a seismic mitigation program undertaken by the Christchurch lifeline utilities years before the event. Figure 1 illustrates the contrast between the levels of damage registered in two electricity substations (located 500 meters apart), resulting from the fact that only the one on the right was seismically strengthened prior to the earthquake [3].

Figure 1 Substations belonging to the Christchurch's electricity network [3]

The assessment of the damage or disruption potential of these networks can support the creation of mitigation and preparedness programs, such as the one implemented in Christchurch. However, modelling these spatially distributed systems entails important technical aspects, usually not present in the seismic risk assessment of portfolio of buildings. Since networks are typically continuous systems, their modelling must consider the connectivity between the components of the network, as the performance of one element may affect the performance of others.

Within the various types of lifelines, transportation networks (*e.g.* roads, railways) are fundamental for the economic development of a given region. Moreover, these networks assume a pivotal role in the aftermath of a destructive event, not only in the response phase for the rescue operations and transportation of injured people, but also in the long-term, during the recovery and reconstruction efforts.

Over the last years, different methodologies have been developed for earthquake risk assessment of transportation systems, the majority of which can be grouped into three main categories. In the first level, the network is analysed in terms of pure connectivity. Example of his type of study is the work by Franchin *et al.* [4], where the percentage of population that cannot be hospitalized due to failure of the network is estimated. In the following level, the changes in the network' flow capacity due to the earthquake damage are taken into account, as well as the subsequent traffic changes. In Shinozuka *et al.* [5], the economic losses of an event are estimated as a function of the Driver's Delay, which measures the increase in total daily travel time for all travellers. The work of Miller [6] focused on post-earthquake conditions, and estimates the travel time increase using an iterative traffic assignment method, which intends to capture the changes in driver's choices based on the traffic situation. A broader systemic study, corresponding to a higher level of complexity, accounts also for economic factors, in order to estimate the total direct and indirect losses. It is the case of the study developed by Karaca [7], in which regional and national losses are evaluated as a result of an event occurring in the New Madrid Seismic Zone.

2 Description of the methodology

The main goal of this methodology is to develop a procedure to calculate the seismic risk of a network and estimate the network downtime, or the time that it would be unusable. In the next sub-sections, the different steps of the process are described, based on the flowchart presented in Figure 2. The calculator utilizes a module developed using the programming language "Python" and the OpenQuake-engine [8], [9], an open-source software for seismic hazard and risk calculations, supported by the Global Earthquake Model initiative [www.globalquakemodel.org]. The methodology leverages upon some aspects of existing methodologies, in particular on the outcomes of the FP7 European project Syner-G [10], and publicly available exposure data from the OpenStreetMap initiative.

2.1 Using OpenStreetMap to build the exposure model

The first step of the methodology is to build the exposure model, containing not only the network geometry and location, but also information about the components of the network, grouped according to common structural characteristics.

The geometry of the networks was retrieved from openly available resources, namely the OpenStreetMap initiative (OSM) [www.openstreetmap.org]. It was assumed that the components that could affect most significantly the performance of the transportation system were the bridges. For this reason, only damage on this type of elements will be considered in the seismic risk calculations. It is also recognized herein that permanent ground deformation, landslides or phenomena of liquefaction can damage considerably the roads (*i.e.* pavements), but the consideration of these secondary hazards requires highly detailed geological data, which was not available. In the present study only the shortest path between each origin and destination was considered. Nevertheless, the methodology was developed in a flexible manner, meaning that other assets or points along the pavement can be included on the exposure model, as well as other alternative paths.

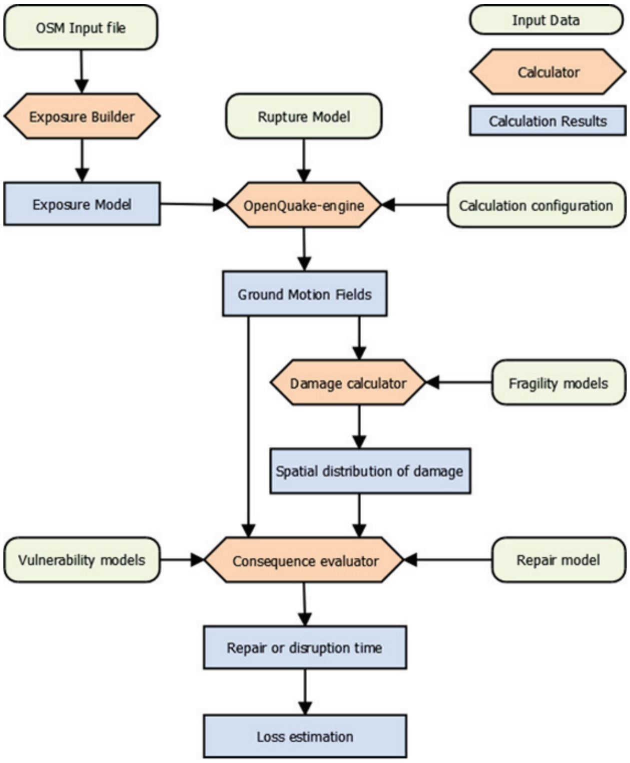


Figure 2 Methodology summary

2.2 Calculation of the ground motion input using the OpenQuake-engine

The second part of the methodology consists in the calculation of the ground motion fields for a number of specific scenario(s), using the locations from the exposure model previously created. This calculation was performed using the Scenario Hazard Calculator of the OpenQuake-engine [9]. For the ground motion fields generation it is necessary to establish a fault rupture model and define a number of parameters that will influence the calculations, such as the ground motion prediction equation(s) (GMPEs) to be employed (see Figure 2).

GMPEs (also known as attenuation relationships) provide an estimation of the ground shaking (for example, of the logarithmic spectral accelerations) and its associated uncertainty, at a given site. These equations have generally the following form:

$$\ln S_a(T) = \mu(M,R,T,\theta) + \sigma(M,T)\varepsilon(T) \tag{1}$$

which is based in the earthquake magnitude (M), source-to-site distance (R), period (T) and other parameters (θ) such as local site conditions and faulting mechanism [11]. The differences between the observed values and the median predictions, commonly refer to as the "residuals", are quantified by the second term of the equation. The error term in equation 1 can be split into two different components: the inter-event and intra-event variability of the GMPEs. The former is related to the variability of the median ground motion registered between earthquakes with the same magnitude and rupture, while the latter (intra-event) is related with the variation registered in the ground motion caused by an earthquake at sites at the same distance from the source and with the same local soil classification. Considering these two components as independent, the total standard deviation can be calculated using equation (2):

$$\sigma_{total} = \sqrt{\sigma_{inter}^2 + \sigma_{intra}^2} \qquad (2)$$

The Scenario Hazard Calculator of the OpenQuake-engine generates a number of ground motion fields by sampling both variability components from the GMPE [12]. In the calculation of each ground motion field, the OpenQuake-engine can take into consideration the spatial correlation of the intra-event residuals, using the Jayaram and Baker [13] model.

It is well established that site-specific conditions can have a great influence on the severity of the damages registered during an earthquake. Given the spatial distribution of lifelines, this characteristic assumes a major importance, since different geologic units most probably exist in the area of interest. In this study, the local effects were taken into account by using the $V_{S,30}$ map developed by Silva *et al.* [14].

2.3 Risk calculation: processing the hazard results

The final part of the methodology uses the results obtained in the hazard calculation to estimate the network' seismic risk. By using adequate fragility models, the damage levels for each node can be obtained, through the "Damage Calculator" module (see Figure 2). For each ground motion, the probability that one node is in a damage level corresponds to the vertical distance between consecutive damage state curves. Considering a specific path between an origin and destination, the probability of having a certain damage level (for example, collapse) between two points, with *n* nodes, corresponds to the probability of a series system, and can be calculated using equation (3) [15]:

$$P_f = 1 - \prod_{i=1}^{n} (1 - F_i) \qquad (3)$$

where F_i is the damage probability in node *i*. Having the damage probabilities, it is then possible to estimate the disruption or repair time for the network, by inputting repair curves in the "Consequence Evaluator" (see Figure 2).

3 Case study

The current section presents the case study of a Portuguese mining factory. The factory is located near Aljustrel, a mining village in the south of Portugal. The aim of the analysis is to determine, for two specific seismic scenarios, the damages and repair time of the factory, and the disruption time of the transportation networks used by the company: the highway network, which is used to import raw material from Lisbon or Spain to the factory; and the railway network, used to transfer the produced materials to the Sines port, for exportation. Based on these repair times, it is then possible to estimate the company losses.

3.1 Exposure and vulnerability models

To estimate the time that the factory will be unable to function due to earthquake damage, it is necessary to choose an adequate vulnerability function. The function adopted was retrieved from Araújo *et al*. [16], and relates the intensity measure with the factory downtime (Figure 3), for buildings with a *Portal Frame* structure, the prevailing structural system of industrial buildings in the country.

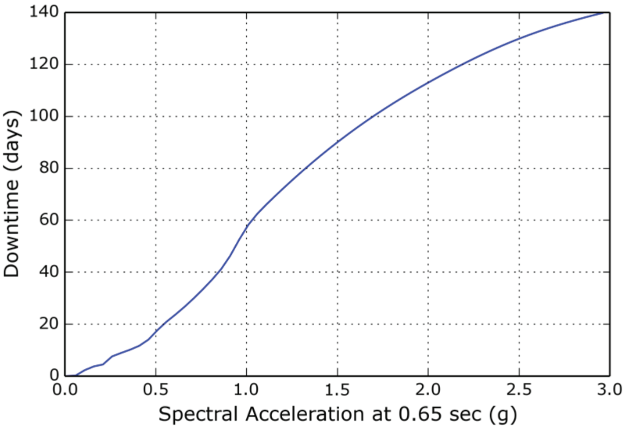
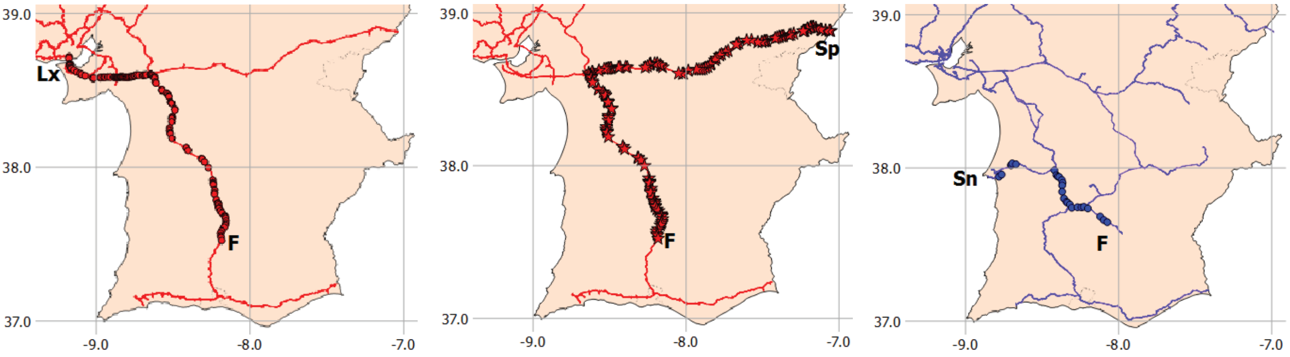


Figure 3 Downtime vulnerability function

The location and geometry of the networks (highway and railway) was extracted from publicly available data in a GIS vector format. By inputting the origin and destination coordinates, the shortest path between these points is calculated (using the Dijkstra algorithm), and the exposure model for each path is build (see Figure 4).

Since the available data did not specify the properties of the bridges (*e.g.* span length, material or structural type) and the development of specific fragility functions was out of the scope of this study, a decision was made to employ fragility functions from the existing literature, in particular the ones proposed by Azevedo *et al.* [17] for bridges located in the most severe seismic region of Portugal (see Figure 5). However, instead of using a dispersion of 0.4 for these fragility functions (value adopted in the referred study), a value of 0.6 was considered, following the recommendations found in Hazus [18] and the findings from Silva *et al.* [19].

This fragility function was applied differently depending on the type of asset. For the bridges and viaducts that belong to the highway, all of the damage states were considered. On the other hand, for the viaducts that intersect the highway, only the curves corresponding to extensive damage or collapse were considered, as lower levels of damage are not likely to affect the operability of the intersecting highway.



(a) (b) (c)

Figure 4 Relevant paths considered: (a) between Lisbon (Lx) and the factory (F), using the highway network; (b) between Spain (Sp) and the factory, using the highway network; (c) between the factory and the Sines port, using the railway network

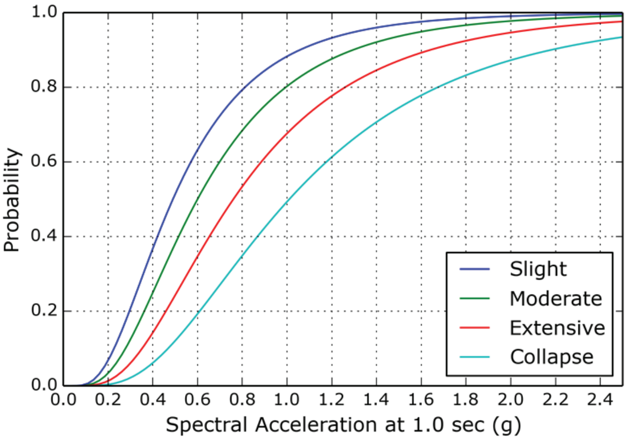


Figure 5 Fragility curves for Portuguese bridges [17]

3.2 Selection of seismic scenarios and ground motion prediction equations

In this study two seismic scenarios were selected, based on the seismicity of the region and on the study by Carvalho *et al.* [20]: the first corresponds to an offshore rupture with a 7.6 (M_w) magnitude, located in the "Marques de Pombal" fault, southwest of mainland Portugal (considered as a possible source for the 1755 Lisbon earthquake). The second scenario is composed by an onshore rupture, located in the Lower Tagus Valley, with a 5.7 (M_w) magnitude. The ground motion fields for the considered scenarios were generated using the Scenario Hazard Calculator of the OQ-engine [9].

The definition of the GMPE(s) to be used in the analysis constitutes one fundamental step in the seismic assessment, as they can significantly influence the hazard estimations and, consequently, the risk results [21]. This selection needs to take into account different aspects related to the model, such as the tectonic environment, distance from the source and magnitude of the event(s). In the case of Portugal, this task is hampered by the lack of instrumental and historical records from which equations could be derived, or adequate data to validate the applicability of other models. The selection and applicability of GMPEs to Portugal is a complex issue, discussed in detail in Silva *et al*. [14]. The analysis of different sources ([22], [23]), together with the evaluation of other important parameters (the seismogenic environment, hazard disaggregation) indicate that the Atkinson and Boore (2006) [24] and Akkar and Bommer (2010) [25] GMPEs are among the most suitable ones to simulate the seismic hazard in Portugal [14].

3.3 Consequence and repair functions

After defining the exposure and input models, the ground shaking and the damage distribution in each point can be calculated. Having the damage states' probabilities, the repair time for each bridge can be estimated by multiplying these probabilities by the average repair time for each damage state.

In the present study two different loss indicators were considered: the repair time, which corresponds to the time needed to completely repair the structures; and the disruption time, which is how long the path will be unusable, meaning that the connectivity between the origin and destination is lost. The curves proposed by Shinozuka [26] were used, which estimate for each damage state the probability of repair of the bridge or viaduct as a function of the number of days after the earthquake, as shown in Figure 6.

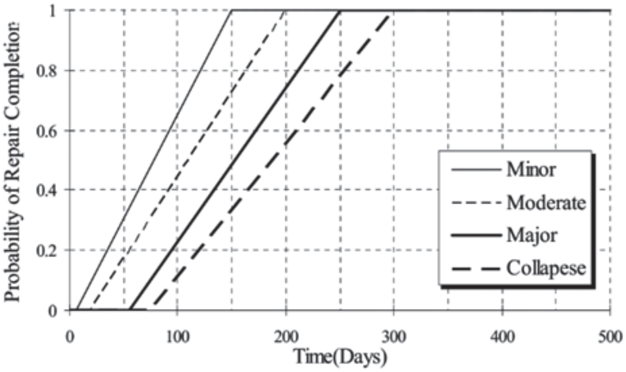


Figure 6 Probability distribution functions of repair completion date [26]

For the viaducts that cross the network, the "repair" time in case of collapse will correspond to the time needed to remove the debris, after which the network can be used without restrictions. Hence, it was considered that 10 days was on average a reasonable time for this operation. If the viaduct has extensive damage, it is necessary to determine whether it will be demolished or repaired, a process that usually requires some additional time. For this reason, in this case it was decided to adopt the same repair time as for bridges with extensive damage, as described in Table I.

Table I Repair times for bridges [26] and for viaducts (values in days)

Damage level	Bridges or viaducts	Viaducts that cross the network
Slight	80	–
Moderate	110	–
Extensive	150	150
Complete	180	10

4 Case study results

4.1 Damage level estimation

As explained in section 2.2, the Scenario Hazard Calculator of the OpenQuake-engine was used to compute the ground shaking in each point of the exposure model. Based on these values and on the fragility curves, the damage distribution was calculated (probability of having a certain damage level) using the "Damage Calculator". In Figure 7, the median collapse probabilities for each location are depicted.

The difference in the area of influence of the two scenarios is noticeable: the effects of the offshore scenario are widespread in the southern coastal part of the country, while the onshore scenario effects, which result from an event with a much lower magnitude, are concentrated in the region around Lisbon.

For the previously mentioned paths (Lisbon, Spain and Sines), the median collapse probabilities, obtained by equation (3), are listed in Table II. These values correspond to the probability that at least one element of the path collapses. For the onshore event only the values obtained for the path between Lisbon and the factory are presented, since the probabilities of collapse obtained for the other two paths are negligible.

Comparing the results obtained for the path between Lisbon and the factory for both events, it is noticeable that the onshore scenario leads to much higher probabilities of collapse, despite its lower magnitude. Although the offshore scenario seems to affect a higher number of components in this path, the levels of damage produced by this event are lower. On the other side, the onshore rupture produces very high damages, and although they are concentrated in one region, affecting only part of the path (closer to Lisbon), they are sufficient to increase in a determinant way the path collapse probability.

For safety reasons, highway structures are closed to traffic not only when a collapse occurs, but also in case of extensive damage

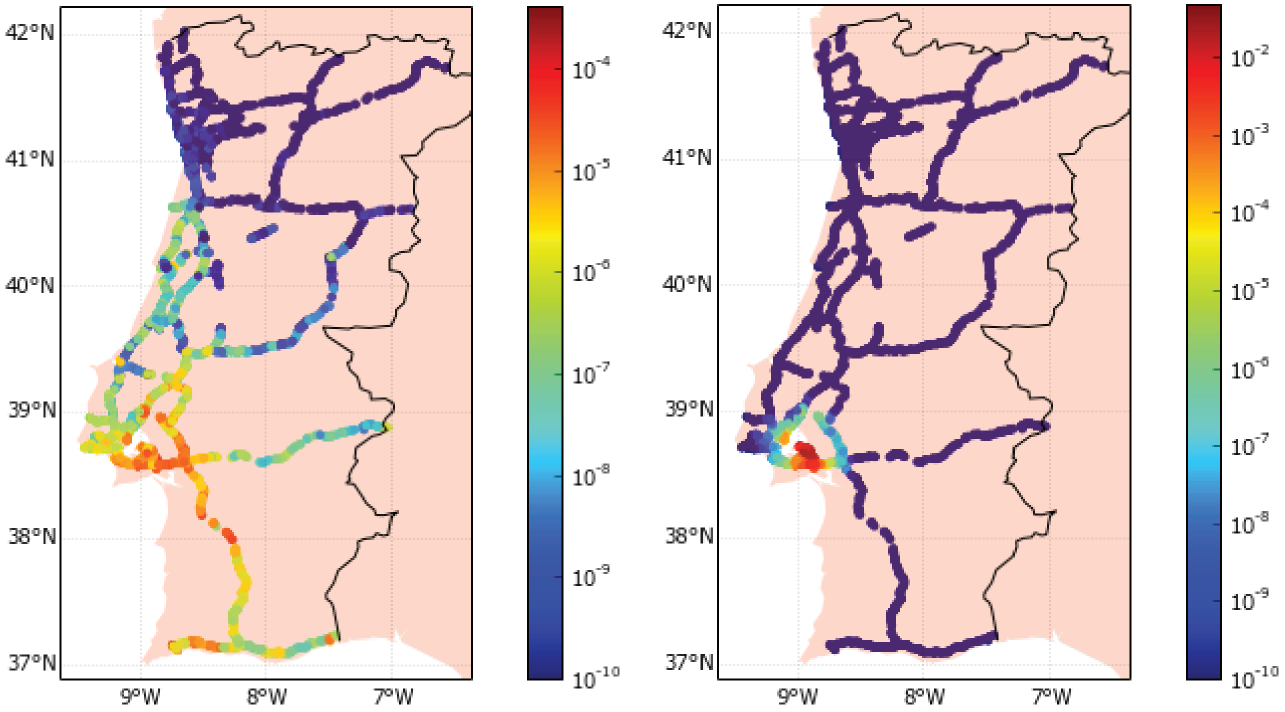


Figure 7 Median collapse probability of each asset of the highway network for the offshore (left) and onshore (right) scenario

in one or more bridges. Hence, to estimate the probability of the network being unusable after an event (disruption probability), both the probabilities of collapse and of extensive damage need to be considered. By calculating this value for a specific path, the probability of losing the connectivity between the origin and destination points is estimated. The median disruption values, presented in Table II, follow a similar pattern as the collapse probability.

Table II Collapse and disruption probability for the considered paths

Scenario	Path	Median collapse prob.	Collapse st. dev.	Median disruption prob.	Disruption st. dev.
Offshore	Lisbon	0.117	0.115	0.318	0.172
	Spain	0.064	0.083	0.196	0.141
	Sines	0.019	0.055	0.066	0.105
Onshore	Lisbon	0.448	0.235	0.748	0.203

4.2 Repair and disruption time estimation

The factory repair time can be calculated by directly applying its vulnerability function (Figure 3) to the ground shaking values. The median values obtained are listed in Table III. Considering its location, it is not expectable that the factory suffers direct damage in the onshore event, since the rupture affects mainly the region around Lisbon. On the other hand, it might register some damage and will probably need to be repaired if a rupture similar to the offshore scenario occurs.

Table III Repair time for the factory, for the different scenarios (values in days)

Scenario	Median time	Standard deviation
Offshore	0.952	2.394
Onshore	0.021	0.039

The repair time for each path corresponds to the sum of the products between the repair time for each damage state and the corresponding probability of such damage state for each point of the path (see section 3.3). By considering only the collapse and extensive damage probabilities, the disruption time for each path was also estimated, which corresponds to the time that the network will be unusable (time needed to repair or to rebuild structures with extensive damage or that collapsed). The median repair and disruption time for each path are presented in Table IV.

Table IV Repair and disruption time for the considered paths (values in days)

Scenario	Path	Median repair time	Repair time st. dev.	Median disruption time	Disruption time st. dev.
Offshore	Lisbon	73.55	54.63	44.57	36.87
	Spain	48.38	38.26	26.44	23.91
	Sines	15.43	22.90	8.15	14.24
Onshore	Lisbon	175.09	125.93	125.92	103.25

These values were calculated considering that the bridges are repaired one at the time. To have more realistic results, it is necessary to have information regarding how many construction companies or teams would be able to work in the repair operations, and then divide the repair or disruption time by the number of teams.

In Table V , the disruption time of the critical path is compared with the repair time of the factory. It is relevant to note that there is a redundancy in the path for importation of raw materials (Lisbon and Spain). Thus, if one path is not available, the other can be used. Considering that the factory depends on both importations and exportations to work properly, the critical path for the factory will be the one with the higher repair time.

Table V Comparison between the repair time of the factory and the disruption time of the critical path (values in days)

Scenario	Repair time of the factory	Disruption time of the critical path
Offshore	0.952	26.44
Onshore	0.021	0

In this specific case study, the disruption time of the critical path for an offshore scenario is higher than the repair time for the factory itself. This indicates that the factory may register greater losses due to its dependency on the transportation network, and not necessarily from damages directly in its structure. In the onshore scenario, the factory is practically unaffected and its networks' dependency is not determinant, as a result of the existence of two alternative paths for importation of raw material (Lisbon and Spain). However, if the factory imported material only from Lisbon, the critical path would have a disruption time of 125.92 days, which would represent a significant loss for the company.

5 Conclusions

The present study focuses on the seismic assessment of transportation lifelines, proposing a methodology to evaluate the consequences of an event in transportation networks, but also analysing how the interruption of these networks would affect its users and the economic losses that its disruption would imply for specific users.

The consequences of two earthquake ruptures were analysed for a specific case study, a Portuguese mining factory whose production and exportation depends on the highway and railway network.

The two scenarios produced distinct consequences for the factory. For the offshore scenario, the disruption time of the critical path was higher than the factory's repair time. This shows that, although the factory does not suffer extensive damage, its losses may be high as a result of its dependency on the network. On the other hand, in the onshore scenario, this dependency is not critical, due to the existence of two alternative paths for importation of raw material (Lisbon or Spain). However, if the importations were done using the Lisbon path exclusively, the company would most probably have a long interruption in the supply of raw material, leading to significant losses for the company.

These results indicate that, in certain cases, the company may not suffer direct damage to its structure, but may be unable to prevent economic losses, as a result of its reliance on the transportation network. It also highlights the importance of having alternative paths for material supply and for exportation, as this can increase the earthquake resilience of the factory.

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