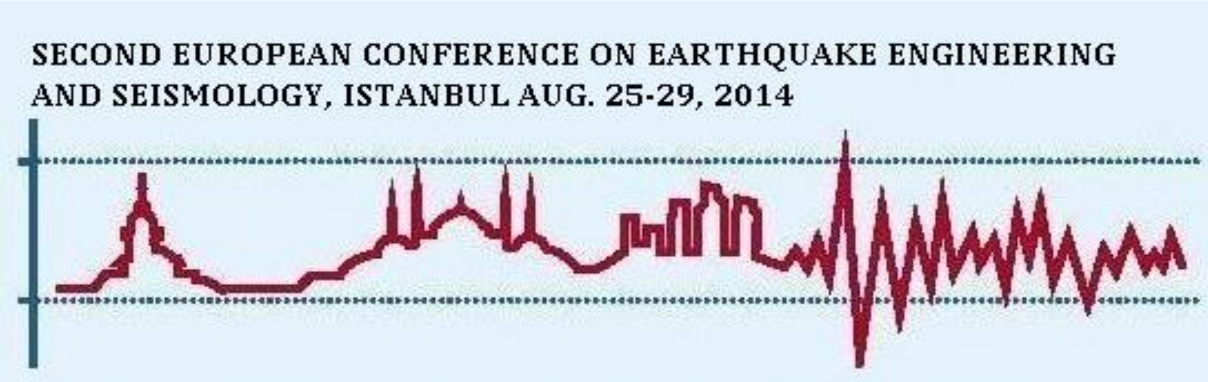

EVALUATION OF SEISMIC RISK OF INDUSTRIAL FACILITIES

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ABSTRACT

This paper describes part of a research project aiming at evaluating seismic risk at the Sines industrial complex in Portugal, including the detailed evaluation of the potential seismic performance of some important structures and equipments, and, where possible, to propose measures to reduce seismic vulnerability. The proposals for seismic risk reduction comprise three areas: (i) strengthening or other actions to reduce the vulnerability of specific structures or equipments, (ii) planning, in order to create redundancies in other zones of the country, and (iii) by means of early warning systems.
Two types of sets of accelerograms were considered for the purpose of nonlinear time history analysis: for near-field events, short duration accelerograms with high frequency contents and for far-field events, long duration accelerograms rich in low frequencies. Some results regarding the evaluation of seismic vulnerability of structures and equipments are presented and corrective actions are suggested.

INTRODUCTION

At the early stages of modern earthquake engineering the main concern was the protection of human life, and as a consequence less attention was paid to the lifelines and industrial facilities. Another reason for this was that, at the time, the importance of these facilities was much less than it is nowadays in developed societies. However the concern of these societies not only with the protection of human life, but also with the limitation of economic damage has been increasing, was felt clearly after the 1990´s earthquakes of Northridge (1995) and Kobe (1996), and is already a trend in code development for the main civil engineering structures (buildings and bridges). Damage control in lifelines and industry has also been increasing, especially after the 11th September 2001, which raised awareness for the need to protect critical infrastructures, first from terrorism, afterwards from all types of threats, including earthquakes and tsunamis.

This paper describes part of the portuguese contribution to the REAKT research project, aiming at evaluating seismic risk at the Sines industrial complex. This included the detailed evaluation of the potential seismic performance of some important structures and equipments, and, where possible, to propose measures to reduce seismic vulnerability. Figure 1 shows some of the facilities of the complex, including its deep-sea harbor.

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Figure 1 – Facilities of the Sines industrial complex

METHODOLOGY

Given the dimension of the Sines complex, and the available time and resources, it would completely impossible to make a detailed analysis of most facilities. Therefore it was decided to be make a general appraisal of the main facilities and a detailed analysis of a few chosen equipments and structures.

The first phase of the project comprised technical meetings with the main stakeholders and visits and inspections to the respective facilities. The choice of the equipments to be analysed was based on two criteria: the importance of the equipment/facility, measured by the impact of disruption on the facility, and its apparent seismic vulnerability. Figure 2 shows some structures/equipments that were analysed.

Figure 2 – Examples of analysed structures and equipments

The project started with the meetings and inspections of the facilities. There were 3 major stakeholders involved in the project since the phase of the proposal: the refinery (GALP), the thermal power plant (EDP) and the gas terminal (REN Atlântico). During the project all major industrial companies of the Sines complex joined the project: Repsol, Artlant, Carbogal, Euroresinas, Metalsines, CLT (manager of the petrol terminal and storage tanks), Administration of the Port of Sines, PSA (Port of Singapore Authority, that manages the container terminal), Portsines (manager of the port coal terminal), Águas de St André (manager of the water supply system) and AICEP Global

Parques, the general manager of the Sines complex outside the port area. There was at least one meeting and one inspection to each stakeholder facility, and several meetings and inspections to the facilities of the three major stakeholders.

INSPECTIONS AND INQUIRIES

The contact with each stakeholder started with a meeting in the respective facilities, where these were described in general, essentially from a functional point of view. Since some facilities are near the sea, during the inspections the tsunami risk was also considered, even though it was not part of the REAKT proposal. As a result of the inspections several weaknesses where identified. Figure 3 show some examples: a) power transformers: lack of anchorage, that allows horizontal displacements and possible damage in the connection to other equipments; b) and c) lack of transversal connections in pipes, allowing the pipes to fall from the supports or hit each other due to tranversal movements; d) water main near and paralell to the coast, exposed to tsunami wave; e) containers that can float to other facilities if there is a tsunami.

a) Transformers

b) Pipes

c) Water main paralell to the coast d) Containers (left) and other facilities behind

Figure 3 – Equipments with some vulnerabilities

Some of these weaknesses derive from a fact, that is thought to be common in Europe, that many industrial equipments are not designed, built and mounted with the concern of providing seismic resistance. This is due to two reasons: i) seismicity and seismic risk is not part of the curricula of university courses of mechanical and electrical engineering, and other engineering courses, and ii) lack of technical codes, (Lopes and Oliveira, 2001). The second reason is a consequence of the first one and both are related with the priorities at the early stages of modern earthquake engineering. At those times, several decades ago, the priority was the safeguard of the human life, therefore avoiding the collapse of civil engineering structures. Besides, the industry and the lifelines were less important than they are today, especially in developed societies. Therefore much more attention was paid to buildings, bridges and other structures, than to electromechanical and other equipments. However it was noticed in the meetings and inspections that more recent facilities were design and built according to more stringent requirements, including very demanding specifications for seismic design. A very clear example were the technical specifications for the Gas Terminal, built between 2001 and 2004, that prescribed a PGA=0.5g (Tractebel et al, 2001) for ultimate limit state design of the most important equipments, approximately the double of the value prescribed in the code in force at the time for current buildings. Another example was the Artland factory of pta (a plastic product used for several purposes), where the inspections revealed almost no weaknesses, which obviously does not mean they don´t exist as the inspections were not detailed and exhaustive, but indicates that are probably much less in number and importance than in older facilities. Therefore the main source of information and parameter used to the general assessment of facilities and equipments that were not analysed with detail (all but a few exceptions) were the general perception that resulted from the inspections, coupled with the date of design and construction obtained in the meetings and inquiries.

FRAGILITY ANALYSIS

The main structure analysed with detail was the chimney of the first phase of construction of the refinery and because the activity in the refinery will be disrupted without it. Other equipments and structures were analysed, such as the power transformers and specific buildings of some facilities. For the sake of compactness only the analyses of the chimney is described here.

The chimney is a reinforced concrete structure 234m high, and its structural cross-section, shown in figure 4, is a hollow circular section of variable exterior diameter (18m at the base and 6,3m at the top) and thickness (0,65m at the base and 0,20m at the top), with several openings and an inner layer of heat resistant bricks connected to the exterior reinforced concrete structure. The exterior layer of reinforcement extends troughout the height and the inner layer extends only on the lower 60m of the chimneys. It was designed in the decade of 1970, which included earthquake resistant design according to the first portuguese code of modern age that enforced seismic design (RSEP, 1961), which did not comprise Capacity Design and rules to enforce ductile behaviour.

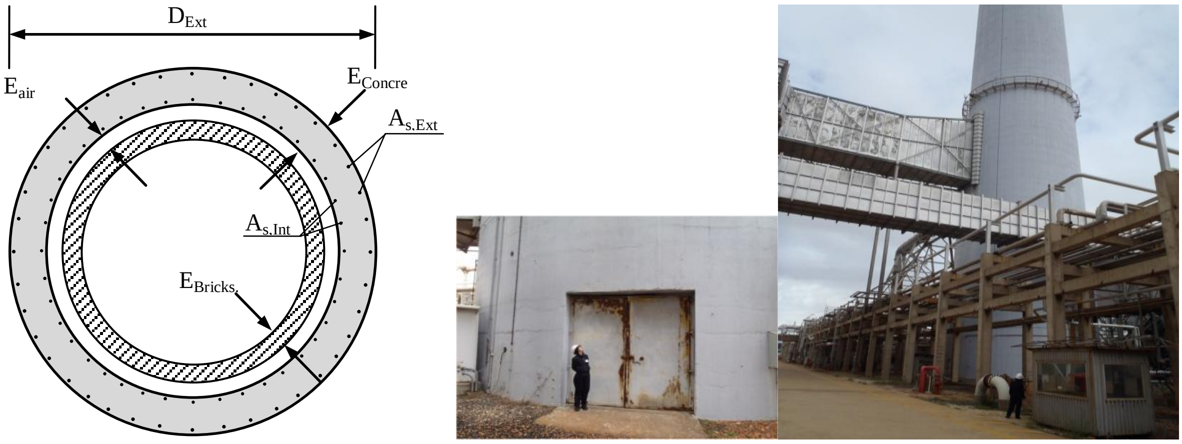
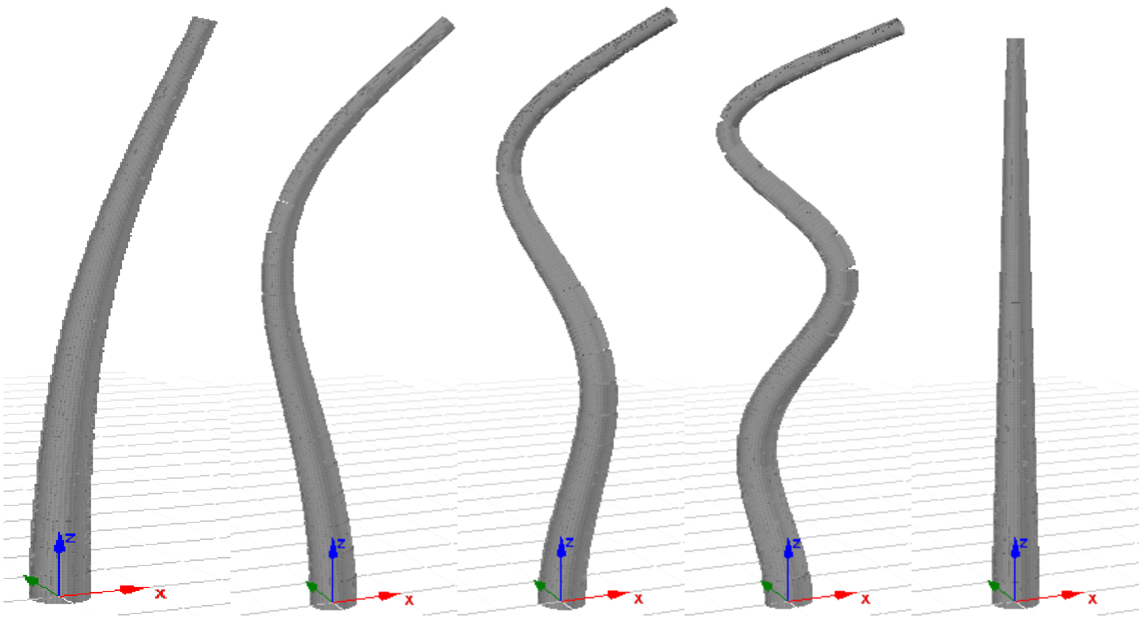


Figure 4 – Chimney cross-section and openings near the base

Most openings have very small dimensions and are not relevant for the analysis of the structure, but the three openings near the base have relevant dimensions, as shown in figure 4: the lowest one between levels 0 and 4m (above the soil) is 3m wide; the second, between levels 9 and 16m is 4,70m wide; the third one between levels 28 and 41m is 4,6m wide, the two last ones corresponds to angles of about 30º with center on the center of the cross section without openings.

A preliminary linear dynamic analysis yielded the vibration modes and frequencies shown in figure 5.



Modes 1 and 2 [T=3.73s] | Modes 3 e 4 [T=1.03**s**] | Modes 5 e 6 [T=0.46s] | Mode 7 [T=0.25s] | Mode 8 (vertical) [T=0.20s]

Figure 5 – Modes and frequencies

In the framework of the Work Package 5 of REAKT, a set of accelerograms, derived from European near field earthquakes was used by all partners (Iervolino et al, 2012). The respective average response spectrum is shown in figure 6. Given the fact that the first frequencies are clearly above the ones of highest accelerations in the response spectra, it is obvious that i) higher modes will likely dominate the response. Therefore it was decided to evaluate the seismic vulnerability by means of nonlinear incremental dynamic analysis. Besides Sines is in southern Portugal, a zone that is exposed to high magnitude far field events, such as the Great Lisbon earthquake of 1755, and therefore the seismic evaluation needs to take into account events of this type. For this purpose a set of semi-artificial, semi-natural accelerograms was used to represent this type of event, the respective average response spectra being shown in figure 7 Lopes et al, 2013). As it can be observed the zone of highest accelerations extends to higher periods, therefore for similar values of PGA this is likely to be the most severe type of event for the chimney.

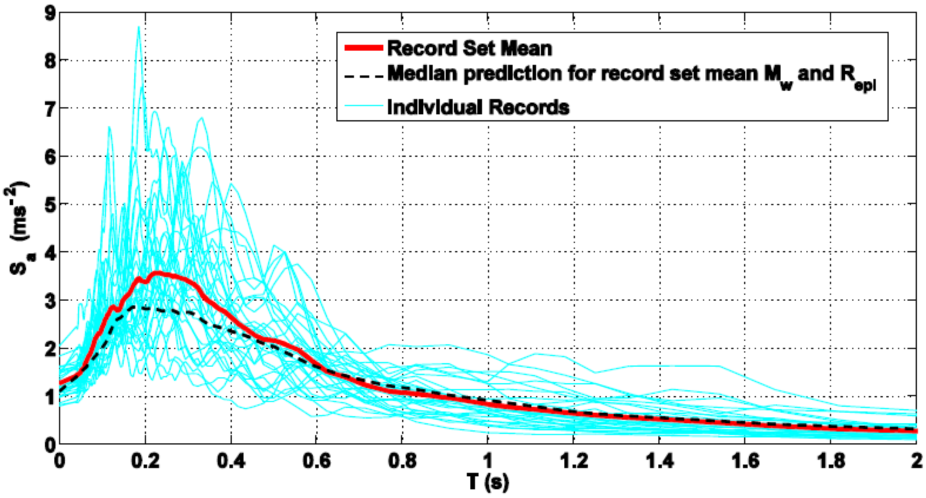


Figure 6 – Average response spectra for near field events

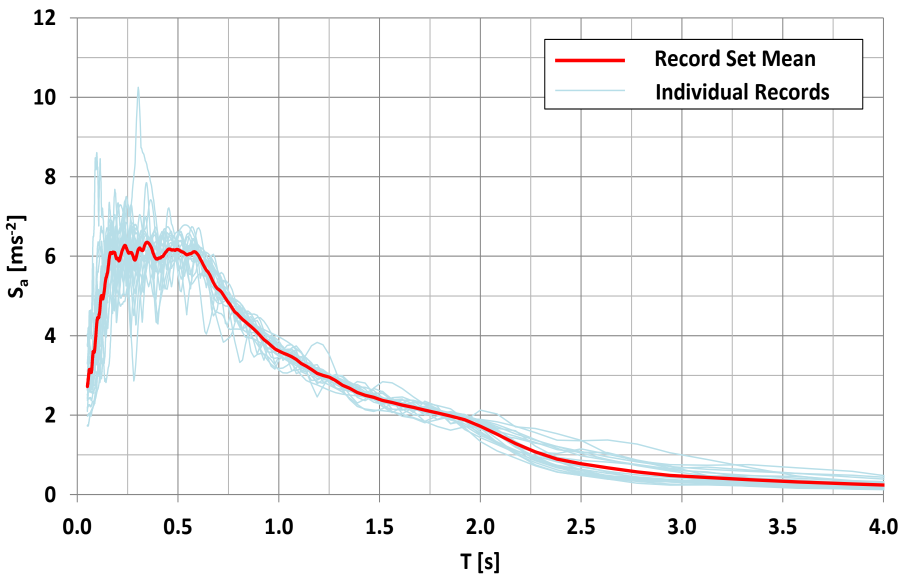


Figure 7 – Average response spectra for far field events

The structural model comprises 80 linear bars along the height, with different heights calibrated to have shorter length in the zones where plasticity develops. The program used was SeismoStruct (http://www.seismosoft.com/en/SeismoStruct.aspx), and Mander´s model (1988) was used to represent the uniaxial cyclic behaviour of concrete, while steel was modelled by Menegoto and Pinto´s model.

The seismic vulnerability is expressed through fragility curves which yield the probability that the structure undergoes the damage levels defined in table 1 quantified by the maximum strain in the structure during each accelerogram as a function of the PGA (peak ground acceleration) corresponding to the average response spectra of the accelerograms. For each value of the PGA the percentage of cases in each damage level was evaluated. The fragility functions are obtained by adjusting lognormal functions to the points that separate adjacent damage levels for different values of PGA. Figure 8 and 9 show the fragility curves for near and far field events.

Table 1 – Definition of damage levels

I -	No damage	$\varepsilon_s \leq 0.7\varepsilon_{sy}$
II -	Slight damage	$0.7\varepsilon_{sy} < \varepsilon_s \leq \varepsilon_{sy}$
III -	Moderate damage	$\varepsilon_{sy} < d \leq \varepsilon_{sy} + 0.25(\varepsilon_{su} - \varepsilon_{sy})$
IV -	Extensive damage	$\varepsilon_{sy} + 0.25(\varepsilon_{su} - \varepsilon_{sy}) < \varepsilon_s \leq \varepsilon_{su}$
V -	Very heavy damage	$\varepsilon_{cu} < \varepsilon_c$ or $\varepsilon_{su} \leq \varepsilon_s$

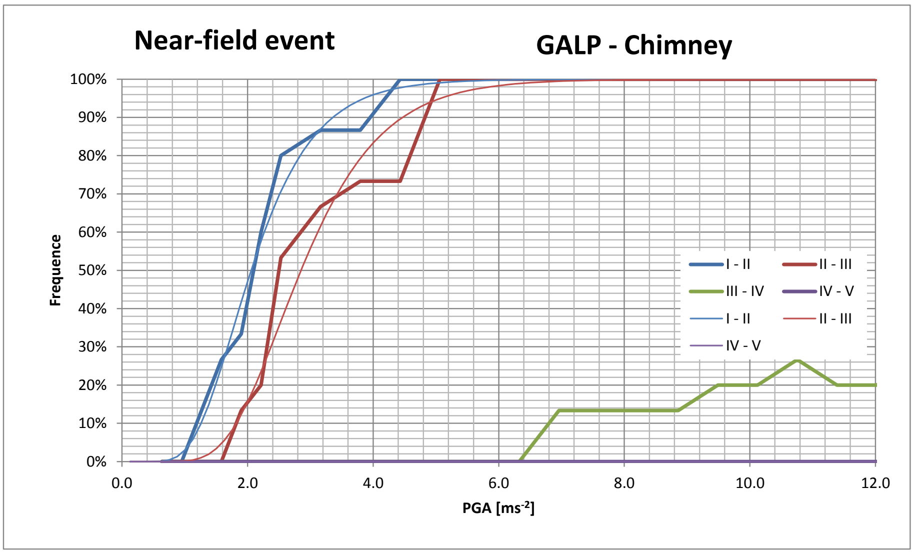


Figure 8 – Fragility functions for near field events (rich in high frequencies)

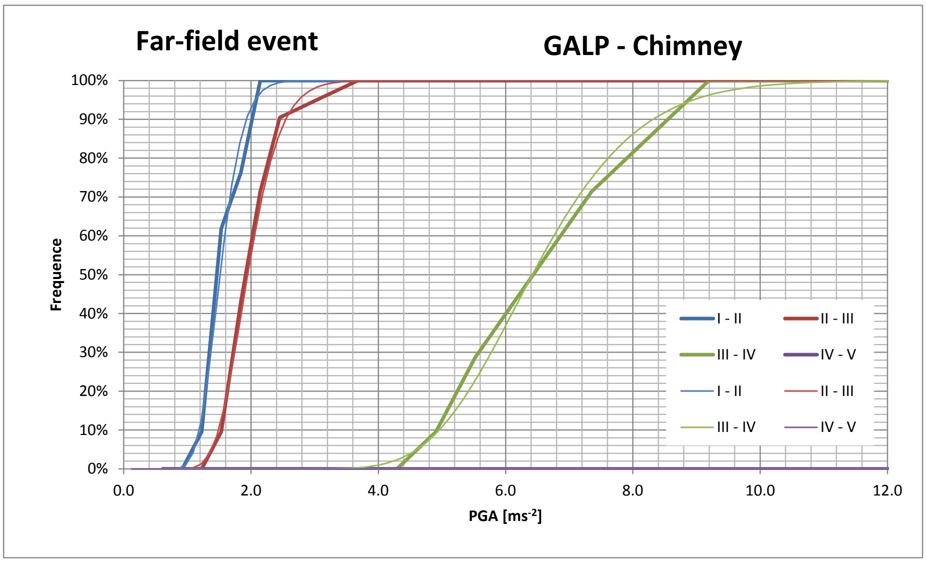


Figure 9 - Fragility functions for far field events (rich in low frequencies)

As expected the far field events lead, for the same values of PGA, to larger damage, showing the importance of the frequency contents in the assessment of seismic vulnerability of this type of structure. The results show that the likelihood of collapse is disregardable (if the quality of construction is reasonable, in order that the model is realistic), as the associated values of PGA are not plausible. This is good news. However according to the Portuguese National Annex (2009) of EC8 (2004) the PGA for far field events of high magnitude for the return period for the seismic action associated to the return period of 475 years and for the soil where the chimney is located, type C, the PGA is 2,13m/s^2, and at this situation the probability there is moderate damage is more than 50%. This type of damage may mean that the chimney needs to be repaired before the refinery can start operating normally. For this purpose it is also relevant to know where damage takes place. For this purpose figure 10 shows examples of the maximum curvatures along the height of the chimney and the curvatures at two different instants, for a situation of large incursions in the nonlinear range. As it can be observed plasticity spreads along a length of about 40m between levels 160 m to 200 m above ground, a zone of difficult access for repair.

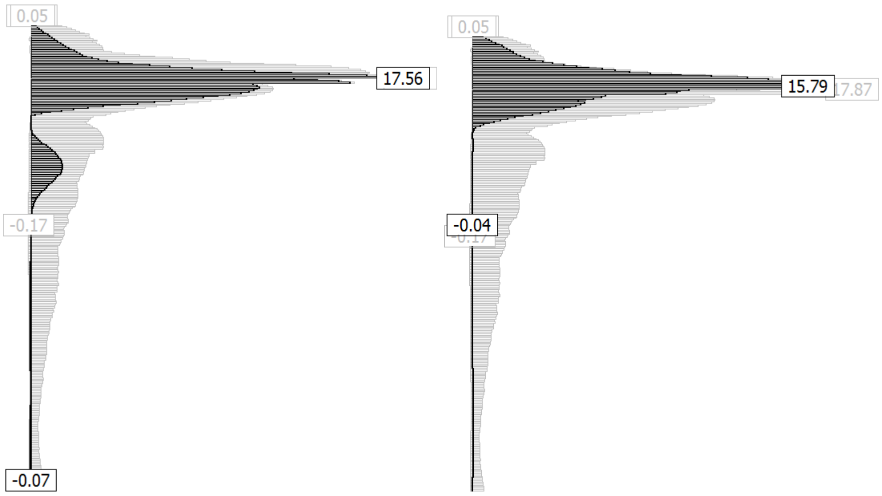


Figure 11 – Curvatures along the height at large deformations

RECOMMENDATIONS

It is expected that several suggestions to prevent damage or to repair structures can be offered to the stakeholders as a result of the REAKT project. For instances the following suggestions can be offered regarding the cases shown in figure 2. In the case of power transformers, the solution is simple and straightforward: to fix them to the foundation, for instances as shown in figure 11. In the case of the pipes, the first step is to assess if the potential transversal movements are large enough to cause damage, and if yes, to improve the transversal supports to prevent the movement, and if necessary to strengthen the support columns and foundations. The floatation of the containers cannot be avoided, but eventually it may be worth to try to prevent them from reaching other facilities. The problem of the water main can also be solved by burying it and/or creating redundancies (another water main in a different path) of similar capacity. In the three first cases the solutions are extremely cost effective, as the potential benefits are much higher than the respective costs.

Figure 11 – Power transformer prevented from sliding

The case of the refinery chimney is clearly different from the previous ones, not only because it is a different type of structure but also because it was studied with detail. Essentially there are two major options to reduce earthquake consequences associated to damage on the chimney: strengthen before an earthquake happens or repair and strengthened after a damaging earthquake occurs. The options cannot be equated as for new construction: in this situation the added cost of ensuring an appropriate seismic performance, as compared with the current situation, would be very low and in that situation (new construction) would certainly be the best course of action. However, as the structure is already built and in service, the cost of strengthening to reduce damage is higher. It is therefore worth doing a cost-benefit analysis, at least qualitatively.

The expected type of damage is not susceptible of causing loss of live, and therefore it is essentially economic damage that is at stake, and can be equated as follows: during the period of repairs the refinery will be out of service, as the chimney provides an indispensable service for the operation of the refinery. Therefore indirect effects, in this case the disruption of all refinery operations, can be much more important than the direct cost of repairing the damage in the chimney. Therefore it is reasonable to assess damage by considering it essentially a function of the repair time. What are the economic consequences of disrupting production? For the company managing the refinery it is essentially the possible loss of revenue during that period due to the fact that the chimney is out of service. In the analysis of this situation it must be considered that the refinery may be partially or totally out of service due to damage in other equipments or structures. But, much more important than loss of revenue, it may be the impact on the whole portuguese economy due to the shortage of supply of gasoline, diesel, jet fuel and other products of the refinery, if it happens. This depends on the dimension of the country strategic reserves of these products, which is thought to be of a few months. Therefore if the repair time is minimized, and it is ensured that it will be likely it is below the time the reserves last, the economic impact is essentially the cost of repair and loss of revenue for the company that manages the refinery. Since this value is probably not too different from the cost of repairing the chimney before the earthquake, the option of repairing and strengthening after the earthquake may be a reasonable one. Therefore preparedness to organize the reparation of the chimney as quickly as possible after a damaging earthquake occurs may be the best option. For this purpose, knowing à priori the zones more likely to be damaged may be useful to establish priorities for the inspection work after the earthquake and prepare à priori the repair work and solutions for its quick execution.

SUMMARY AND CONCLUSIONS

The methodology for a preliminary evaluation of seismic risk in the large Sines industrial complex, in southern Portugal, with very short financial and human resources, is described. It comprises three main taks: i) meetings with the stakeholders and guided visual inspections to the respective facilities, ii) an inquiry on the main characteristics of the facilities, in particular the date of construction, which can be related with the codes in force at the time of design and construction and other technical

requirements, and iii) detailed analysis of the seismic vulnerability of selected equipments and structures, based on their importance and possible vulnerability.
Several possible vulnerabilities where identified based on inspections and qualitative assessment, and low cost actions to reduce those vulnerabilities where offered. That was the case of power transformers, water main and several pipes.
The detailed vulnerability evaluation of a very important structure, the 234 m tall refinery chimney by means of incremental dynamic analysis was described and the main results shown. Two types of seismic events, with different frequency contents were considered: near field events, rich in high frequencies, and far-field events with low frequency contents. The results show that the seismic behaviour of the chimney is sensitive to the frequency contents and that given its flexibility it is more sensitive to far fields events. The results showed that collapse of the chimney is virtually impossible for plausible seismic actions in Sines, as long as the quality of construction was reasonable and there are no weaknesses not considered in the structural model. However for the EC8 seismic action corresponding to the 475 year period, moderate damage (cracking and damage to the heat resistant brick layer) would occur and could hinder the ability of the chimney to continue in service. Possible courses of action to minimize the effects of this situation were discussed and a suggestion offered.

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