Methodologies for the Analysis of the Seismic Vulnerability of an Industrial Complex

Mário Lopes
Instituto Superior Técnico, Lisbon, Portugal

Isabel Pais
National Authority for Civil Protection, Carnaxide, Portugal

Carlos Sousa Oliveira
Instituto Superior Técnico, Lisbon, Portugal

Francisco Mota de Sá
Instituto Superior Técnico, Lisbon, Portugal

SUMMARY:
Recent earthquakes that stroke developed countries have induced economic losses that public opinion considers unacceptable. A relevant part of these economic losses were due to damage in industrial facilities and lifelines, which triggered interest on the evaluation of the seismic vulnerability of these types of infrastructure.
This paper describes the first phase of the study of the Sines Industrial Complex, in Portugal. Due to its large dimension, the first approach will be based on the comparison between the seismic design criteria of the different facilities and equipments with the potential seismic demand. In a second phase, a more detailed analysis of some facilities will be made. The selection will be based on two criteria: (i) their potential seismic vulnerability; (ii) and their importance measured by the consequences should a disruption occur.
The possibility for reduction of damage by means of Early Warning Systems will also be analysed with major stakeholders.

***Keywords**: critical infrastructure, risk reduction, seismic vulnerability, early warning system*

1. INTRODUCTION

In Portugal the importance of the subject addressed in this paper, although identified a long time ago by the technical and scientific community (SPES, 2001; Lopes, 2002), has been recently strengthened by a Parliament Resolution on seismic risk reduction (nº 102/2010 of 11 August, on the "Adoption of seismic risk reduction measures") and new legislation on Critical Infrastructure Protection (CIP) concerning the transposition of the Directive 2008/114/CE on the designation and protection of European Critical Infrastructure also involving National Critical Infrastructure (Decree-Law nr. 62/2011 of 9 May). Also some relevant works produced in recent years (Sá, 2011) brought an important contribution to the development of the National Programme for CIP under way in Portugal as in other EU countries.

The main objective of this Programme is contributing to raise and strengthen to acceptable but sustainable levels the resilience of Critical Infrastructures (CI) by defining priorities for the reduction of risk and identified vulnerabilities (Pais et al., 2011). Several types of threats can affect CI (intentional and non intentional). In this paper, earthquake and tsunami risk and the actions caused in industrial CI are addressed.

Beyond the traditional concern about the safety of human life, is also important to safeguard the ability of these infrastructures to remain functional during and after the occurrence of an earthquake. And this can only be achieved by means of prevention, acting before the occurrence of seismic events. The importance of the identification and implementation of preventive measures becomes even more strengthened because, failing that, economic losses will be added to human and structural losses.

The Project REAKT (2011), "Strategies and Tools for Real-Time Earthquake Risk Reduction," which brings together a large international consortium and is European funded (FP7), gives substance to many of these concerns. The aims of the Project consist on the study of seismic risk mitigating instruments, based on early warning capabilities, allowing in a short time (seconds) the triggering of automatic mechanisms for risk reduction, very focused on CI and their key components, which may as well see their resiliency increased.

Given its strategic importance, which implies an increased attention to safety, the Sines industrial complex, represented by its major stakeholders, was selected to develop a feasibility study for the implementation of a Early Warning System, taking into account not only the elastic waves but also to a tsunami event. National participation in this project focuses on two main themes: (i) analysis of the main infrastructure of the industrial complex, assigning a seismic resistance to the main elements that compose them, for which vulnerability functions will be developed as well as proposals for vulnerability reduction, (ii) studies of the potential benefits of the application of a Early Warning System (EWS).

2. THE REAKT PROJECT AND THE SINES INDUSTRIAL COMPLEX CASE-STUDY

2.1. Framework of the Project

The need to better understand the consequences of an earthquake in the critical national infrastructure and services, both in its structural component and the key elements that compose them and ensure their operationality has been raising increasing interest within the scientific community and other related technical areas. The Portuguese participation in the Project REAKT is largely a result of this interest.

As already mentioned, the objectives of the project are the study of instruments for seismic risk mitigation, i) based on direct analysis and reduction of seismic vulnerability of specific equipments and ii) based on the Early Warning capabilities, which allow, in a short time (seconds), triggering mechanisms for risk reduction, very focused on CIs and their key components, which may as well see their resiliency increased.

Portugal is part of the consortium, with partners such as IST (coordinator), and some stakeholders, including GALPENERGIA, REN and EDP. In one of the Project’s Work Packages practical applications to specific areas or type of infrastructures will be developed. Portugal proposed and was accepted, the study of the Sines industrial complex, as this complex concentrates about 10% of national infrastructure classified as critical in the 1st phase of PNPIC. The economic and strategic importance of the port of Sines in present times and projected for the future, also contributed to the choice of the area. It's a great opportunity to develop important stages of phase 2 of the National Programme for Critical Infrastructure Protection, joining and complementing scientific expertise with the technical expertise of the companies participating in the project’s work teams. Thus, the practical applications mentioned above may include the analysis of seismic vulnerability of porticos support piping, control buildings, buildings housing equipment, chimneys, power transformers and other equipment of some of the major industrial and port facilities of Sines.

2.1. Characterisation of the Sines Industrial Complex

The complex extends, facing the sea, approximately between Cape Sines and São Torpes Beach and to the interior, occupying an area of about 30 km^2, constituting a vast industrial platform called Sines Industrial and Logistics Zone (ZILS).

Here some of the most important national industries are located, especially in the energy and industrial sectors, highlighting the Sines Refinery (Galpenergia), the largest refinery in the country, the only terminal for Liquefied Natural Gas (LNG) and the Thermoelectric Power Plant of EDP. Repsol YPF (Petrochemicals) is also a sizeable company in the Complex.

The port, with excellent conditions and deep waters as a few in Europe, allows the mooring of deep draft tankers and container ships of great size.

This space (port + ZILS) comprises about 8-10% of the National Critical Infrastructures, which gives it an added importance in strategic terms for the functioning of the country therefore deserving special security concerns. Furthermore, it is a primary area of economic importance, now and projected into the future. An expansion process is taking place at the port of Sines.

In the Sines complex, there are three main industrial units, which correspond to the major stakeholders of the Project:

- Sines Refinery (Galpenergia) - (No.1 in Fig.1)

Occupying an area of 320 ha, with an installed capacity of 10 million ton / year, consists of 27 units built in three phases: the 1st dates back from 1975-77, which includes the iconic chimney of 240 m, the "Utilities", the 2nd phase of expansion dating from 1994, and 3rd in the last phase of construction which has just opened, in 2012.

It has 171 tanks, 95% of which from the 1st phase (cylindrical and spherical), a storage capacity of 3 million m^3 (half of crude oil), and many kilometres of piping, a unit of natural gas cogeneration (the largest in the country), which allows exporting energy. The refinery produces gasoline, diesel, LPG, fuel oil, jet fuel (aircraft), naphtha (which supplies the petrochemical industry Repsol for the production of polymers), among other products. A pipeline connects the refinery to Repsol YPF and Artland Petrochemicals.

Another large pipeline connects the refinery to the company CLC, SA (Fuel Logistics Company) in Aveiras, large centre storage and distribution of petroleum products in the country. The connection to the Oil Tanker Terminal is provided by an extensive belt of pipelines, where the supply of the refinery is made, as well as the transport of refined products, in the opposite direction, for export.

A railway line ensures the supply of jet fuel to Faro airport (transported by rail) produced by the Refinery. The gas consumed in the refinery (cogeneration) is supplied by REN Atlantic's pipeline.

- Sines Thermoelectric Power Plant (EDP Production) - (No. 11 in Fig.1)

This is a coal thermoelectric plant, which is supplied by sea through the Multipurpose Terminal and transported to the plant by a covered conveyor belt 5 km.

The plant has four generators with an average power of 314 megawatt per unit, which launch in the 400 kV electricity transmission network of REN (groups 2-4) and 150kV (group 1). Its construction dates from 1985-1989.

It is noteworthy the boiler with a capacity of 950 tons of steam per hour, a height of 48 m (16-storey building) and is suspended by rods of steel frames. The turbines are also key elements are based on concrete slabs with springs, such as the coal mills. The cooling circuit of the condenser is opened on the coast and use seawater captured on the beach of São Torpes.

- Liquefied Natural Gas Terminal, LNG (REN Atlântico) - (No. 6 in Fig.1)

Began operating in January 2004. Supplies the country with 60% of total natural gas consumed. It carries out the reception process of the liquefied gas at temperatures of about -160°, gasification and storage of LNG. This is unloaded at the unloading dock (Jetty), whose load arms have a discharge capacity of $10000 m^3/h$, is conveyed in insulated pipelines, and pumped to 2 storage tanks, cylindrical, with 80 m diameter and a capacity of 120 000 m^3 each. A 3rd has been recently built and will soon become operational. They are located at an elevation of 15 m, based on slab over bedrock. Its construction took place between 2003 and 2011.

Vaporizers using water collected from the sea, pressurize bombs, condensers, several pipes with different types of support, among other equipment, comprise this strategic facility.

Once in a gaseous state, gas is released in the pipeline, passing first through a measurement station of the gas flow (GRMS).

Besides these three large industrial units, several others settled in the complex, taking advantage of conditions created by the proximity of the other infrastructure already in place. This is the case of Repsol YPF petrochemical and Artland, the Carbogal, Carbonos de Portugal, the Euroresinas, the Metalsines, the Recipneu, the Iberobetão, the COPISA, etc. (Fig. 1).

The Sines Industrial Complex also includes a cave dug into solid rock that stores propane, with seismic monitoring. Cave SIGÁS belongs to GALP (75%), BP (20%) and Repsol (5%).

The port is managed by the Port of Sines Administration (Administração do Porto de Sines, APS), has several terminals, almost all of them leased to different companies, such as the Oil Tanker Terminal (concession to CLT), which supplies the Refinery; the Petrochemical Terminal, which connects to Repsol; the Multipurpose Terminal (Portsines), where the coal is unloaded and supplies the Power Plant; hence a railway links the Multipurpose Terminal to Pego Coal Thermoelectric Power Plant (2 trains/day); the LNG Terminal (REN Atlântico), the Terminal XXI (PSA Sines) for containers connected by truck and railway to the rest of the country.

Figure 1 - Sines Industrial Complex - Main Infrastructures

The area of the complex (Fig. 2) is crossed by numerous pipelines of different types, sizes and carrying various products; has a huge number of deposits of different characteristics, cylindrical, spherical, on piles, on slabs, containing petroleum products, gas, chemicals, etc.; access roads; railway line that transports jet fuel to the South, to the Pego Coal Thermoelectric Power Plant and the containers unloaded at Terminal XXI; numerous sub-stations and transformer stations; water pipes coming from the dam Morgavel, built in 70 years to supply the complex, essential to the operation of the Refinery and the Power Plant; a wastewater treatment plant (Águas de Santo André) for treatment of effluents.

It is therefore a highly complex industrial zone, producing goods and services essential to the country and a living example of important interdependencies.

Figure 2 - Complex 3D image (highlights the representation of deposits

However, the area is less than 200 km of major seismogenic sources (Gorringe, Marquis of Pombal Fault, both at southwest of the southern coast, at Algarve) capable of generating high magnitude earthquakes. Its location near the coast, very shallow in many places, makes it vulnerable to tsunamis generated in the same areas of rupture of the oceanic crust. These tsunamis may have significant impact in areas of very low altitude where many of the complex facilities are located and of course across the harbour zone.

2.2. Qualitative identification of potential vulnerabilities

The first phase to identify vulnerabilities includes technical meetings, visits and inspections to the facilities concerned. It is not possible within the REAKT Project to visit all industrial facilities and infrastructures of Sines. So, it was necessary to be selective, by visiting the companies of the stakeholders and the terminals of the port of Sines. However, the scope of REAKT has been extended to the tsunami risk, because Sines can be affected by an earthquake scenario similar to the one occurred in 1755, this is, a high magnitude earthquake with its epicentre in the sea, bound to generate tsunamis, because the type of movement between the plates can change the bathymetry.

Obviously one must recognize that certain infrastructures such as port terminals will necessarily be affected in the event of a tsunami. It is not possible to prevent a tsunami dragging containers or other materials stored at the port, damaging the buildings contents near sea level and affecting port facilities. But certain precautionary measures may, in some cases, be taken to reduce some of the consequences of the tsunami effects.

The tsunami may also affect other equipment located in flood zones. In this respect it should be noted that flood areas can reach places situated much higher than the wave height itself, as it has wavelengths of several kilometres and the front of the wave will be pushed by the huge amount of water coming from behind. Take the case of the tsunami triggered by the Japan earthquake in March 2011, where the water reached levels much higher than the 14 m height tsunami wave.

Among the equipment potentially bound to be affected by the tsunami due to the low elevation where they stand, there are water pumping facilities, and pipelines carrying oil, liquefied gas and other fluids between the industrial and port facilities.

For the direct effect of an earthquake, associated to the vibration of the soil, it is believed that several electromechanical equipments may present significant vulnerabilities, due to the lack of applicable technical legislation. This is a problem in many countries of the world. In the early days of modern earthquake engineering in the first half of the twentieth century, the primary concern was, of course, the safeguarding of human life. This priority, coupled with the fact that in those times the dependencies of the society and economy in relation to infrastructure networks was much smaller than today. So it meant that attention was focused on constructions built by civil engineers, particularly buildings and bridges.

As a result, much less attention was paid to electrical and mechanical equipment in industry and infrastructure networks, so that even today in many countries, the engineering courses in these areas do not include the issue of seismic resistance of equipment. Associated with this issue in many countries there are gaps in technical legislation associated with these equipments, which in Europe is largely missing with respect to the seismic problem. As a result of these omissions of many decades, professionals responsible for design, manufacture and assembly of these equipments often are not concerned with the issue, due to lack of information. And in general the situation is more serious in older equipment. The visits and inspections which have been made confirmed this perception and identified specific cases, but they induce a greater focus on older equipments. For example it is expected that the vulnerability of the most recent areas of the refinery is less than the vulnerability of the oldest parts.

Another example is shown on REN Atlântico facilities, the natural gas terminal, built during the last decade. The seismic design actions were the object of a specific study, that recommended to considerer a value of PGA=0,5g for Ultimate Limit State design. This is reflected, at least apparently, in the structural conception and robustness of structural elements. For instance, the natural gas deposits and the braced steel structure, shown in figures 3 and 4, are an example.

Figure 3 - Natural gas deposits

Figure 4 - Steel structure braced for horizontal actions (in blue)

Another phase will follow in which the seismic vulnerability of the most important and/or apparently most vulnerable equipment will be analyzed in more detail.

For instance, the chimney of the refinery, 234m tall, as shown in Figure 5, will be analysed due to its importance, by means of NLTH (nonlinear time history) analysis, even though due to its low frequency, it is expected to be on the constant displacement branch of the response spectra and not to be very vulnerable. The seismic action will be modelled by a set of accelerograms, that will be scaled in order to evaluate the level of the seismic action that leads to rupture.

Figure 5 - Tall chimney

The power transformers, a critical equipment for all facilities, may be i) clamped to the foundation, in which case damage will only occur due to movement after rupture of the connection to the foundation, or ii) supported on wheels, in which case damage may take place essentially due to excessive horizontal displacement in relation to adjacent equipments.

Figure **6** shows one of these transformers. In this second case, of more concern, the transformers can be modelled as one degree of freedom systems with no damping (due to their internal constitution there are almost no moveable parts in the interior) but with a friction force at the base that is always opposed to the horizontal movement. Since damage is triggered by relative displacements to adjacent equipments, the seismic performance depends on the maximum horizontal displacement of the transformers. This will be evaluated by means of the numerical (time step) integration of the dynamic equation of movement (NLTH analysis).

Figure 6 - Power transformer supported on wheels

2.3. Prevention and Risk Reduction

Obviously, the characterization of the problems is important, but alone will have little use, because in the end, the objective is seeking the reduction of risk and not just risk assessment. Risk reduction must be done before earthquakes occur mainly because, in addition to actions previously prepared and planned, little can be done afterwards. In this context, this project includes the following main ways of reducing the risk: (i) proposals for action to eliminate the vulnerabilities identified where economically justified, which may involve some kind of cost / benefit analysis, at least qualitative, quantitative, if possible; (ii) in the planning, for example by creating redundancy elsewhere in the country, and (iii) using early warning systems (EWS), which is, as mentioned, an explicit aim of REAKT.

These systems consist of the installation of accelerometers at critical points of the territory, particularly in the area southwest of the Algarve, closer to the epicentres of more concern, with the ability to make early detection of seismic waves, through its location, closest to the epicentre than to the facilities to protect. So it may be possible to predict, within a few seconds before, the arrival of seismic waves at Sines and other parts of the territory (Lisbon, etc.) and take advantage of these seconds to activate automatic (without human intervention) mechanisms to turn off the power, stop machines, shut down pipes, etc. with the potential to reduce damage. The potential benefit of such a system will be discussed with the stakeholders, both qualitatively and quantitatively. These analyses will allow assessing its potential interest, by comparing the benefits with the costs of implementing and maintaining the early warning systems.

3. FINAL REMARKS

The first phase of the analysis of the potential seismic vulnerability of the Sines industrial complex was described, as well as some types of analysis that will be performed on some facilities and equipments. These will aim at assessing seismic vulnerability as well as to identify weak points leading to recommendations for the reduction of risk.

The feasibility of implementation a EWS to the Sines industrial complex, in order to reduce the damage caused by a seismic event in the industrial units covered by this project will be performed. This will be crucial to assess the usefulness of implementing such a system and to assess if it can be considered as a risk reduction solution to be applied.

If it is concluded the system is feasible and economically justifiable, the next step will be to create the necessary conditions for the installation of a EWS.

REFERENCES

Lopes, M. and Oliveira C.S. (2002). Seismic Risk and the Industrial Park (in portuguese),*Journal of the Portuguese Industrial Association).* **Nº 5/6, May-June 2002**, 34-38.

Pais, I., Sá F.M., Lopes, M. and Oliveira C.S. (2011). Critical Infrastructures: Proposals to Reduce Seismic Risk (in portuguese), *Journal of Civil Emergency Planning.* **Nº 23,** 16-21.

Sá, F.M. (2011) National Programme for the Reduction of Seismic Risk in Critical Infrastructure, *Report elaborated for the National Council for Civil Emergency Planning in the scope of the National Programme for Critical Infrastructure Protection.* Fuzzy, Engenharia de Sistemas e Decisão, Lda., 193 pages.

SPES (2001), Portuguese Society for Earthquake Engineering (2001). Reducing the Seismic Vulnerability of the Building Stock. *Edited by SPES and GECoRPA, Portuguese Association of Companies for Preservation and Restoration of the Architectural Heritage*, 149 pages.

REAKT (2011) http://www.reaktproject.eu/