



## **EARTHQUAKE EARLY WARNING SYSTEM FOR PORTUGAL: FEASIBILITY AND PERSPECTIVE OF THE STAKEHOLDERS**

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### ***Abstract***

Several countries or regions have already implemented earthquake Early Warning Systems (EWS), namely Japan, Mexico and California. Others are being developed in other countries. In this paper the studies related to the technical feasibility and the possible interest of the main stakeholders of a large industrial complex in the south of Portugal are reported.

The zone studied was the Sines port and industrial complex. Sines is the only deep-sea port in Portugal, able to receive all cargo ships, with no limitations of type or size, and the industrial complex served by the port is the third largest zones of concentration of critical infrastructures in the country, after the two main towns of Lisbon and Porto.

Sines is approximately 150 km northeast of what is thought to have been the location of the epicentre of the Great Lisbon Earthquake of 1755. A first analysis performed 6 years ago with the accelerometric network existing in 2013, indicated that to produce a warning with a high level of reliability, the required number of stations would include all the stations in the southwest of the country, almost up to Sines. Thus the warning time would be no more than a few of seconds, too short. However, the situation could be changed easily if more stations were located in the southwest, near the corner of the Portuguese mainland closest to the likely epicentres.

It was also found that the requirements of the main stakeholders can be very different, reflecting the fact that the losses with false alarms are very different. For instances a shutting down of the refinery will produce millions of euros of losses, as restarting all systems would take a long time, while shutting down the LNG terminal can be done without the customers realizing it took place, thus forcing only to a little extra work with no major consequences. The system can also be used to provide sound alarms for the personnel in those facilities, allowing people, if previously trained, to move to more secure locations.

As a final conclusion, the implementation of such a system is not only feasible as it is a good investment, as large reductions of risk can be achieved with moderate investment. The possible extension of the system to other activities and areas would strongly increase the advantages of installing a EWS.

*Keywords: Earthquake; Warning; System; Feasibility; Stakeholders*



## 1. Introduction

Earthquake Early Warning System (EWS) are systems, that allow to issue a warning that an earthquake is about to strike a certain zone before ground motion is felt at that zone. Systems of these type were first developed in Japan to protect high speed trains from derailment but are today widely used in a wide range of applications aiming at reducing earthquake consequences. Other countries, such as Mexico, Romania, Taiwan and Turkey have developed such systems, which are also being develop in California and Italy. Several papers regarding these systems have been published, namely by Allen et al [1], Gasperini et al [2], and Wenzel and Zschau [3], with some others focusing on the application to industrial facilities, such as Krausmann [4] and Salzano [5].

EWS systems take advantage of strategically positioned seismic stations that detect seismic waves before they arrive to the locations where are the facilities/people that are intended to protect. EWS cannot avoid all consequences of earthquakes, but advanced warnings allow to take action in order to reduce part of the consequences. For instances, in the case of industrial facilities and lifelines, EWS allows to automatically cut-off power to many electromechanical and chemical equipment, shutdown pumps and close valves, stop transportation of hazardous materials, etc. before ground motions are felt. This type of actions has a strong potential to reduce the risk of fires and explosions, leakage of hazardous substances to the air and soil, thus strongly reducing the economic and environmental negative impact of earthquakes in industrial facilities and lifelines.

This paper, in the continuation of [6], presents the first studies on the feasibility of installing a EWS in Portugal, with emphasis on the protection of the Sines industrial complex. The needs of the stakeholders, measured mainly by two main parameters, the lead time and the reliability of the system, were compared with the ability to create a system that meets their needs. This study was realized in framework of the REAKT project “Strategies and Tools for Real-Time Earthquake Risk Reduction”, funded by the EU and the participation of almost all industrial stakeholders of Sines in the period 2011-2014.

Even though the Sines industrial complex was the case study, obviously such an EWS may have several other applications on other sectors of activities and other locations in Portugal and in Andalusia (southwest of Spain), as it is discussed later.

## 2. Sines: location and economic relevance

Sines is located on the western coast of Portugal 105 km north of the south-west corner of continental Europe and about 180 km of seismogenic sources capable of triggering 8.5 to 9 magnitude events, such as the Great Lisbon Earthquake of 1755. Figure 1 shows a map of southwest Portugal, identifying the location of Sines, the main faults in the area (white lines) and the epicenters of recorded earthquakes in the zone from 1961 to 2013 by IPMA (Portuguese seismological authority, from [7]).

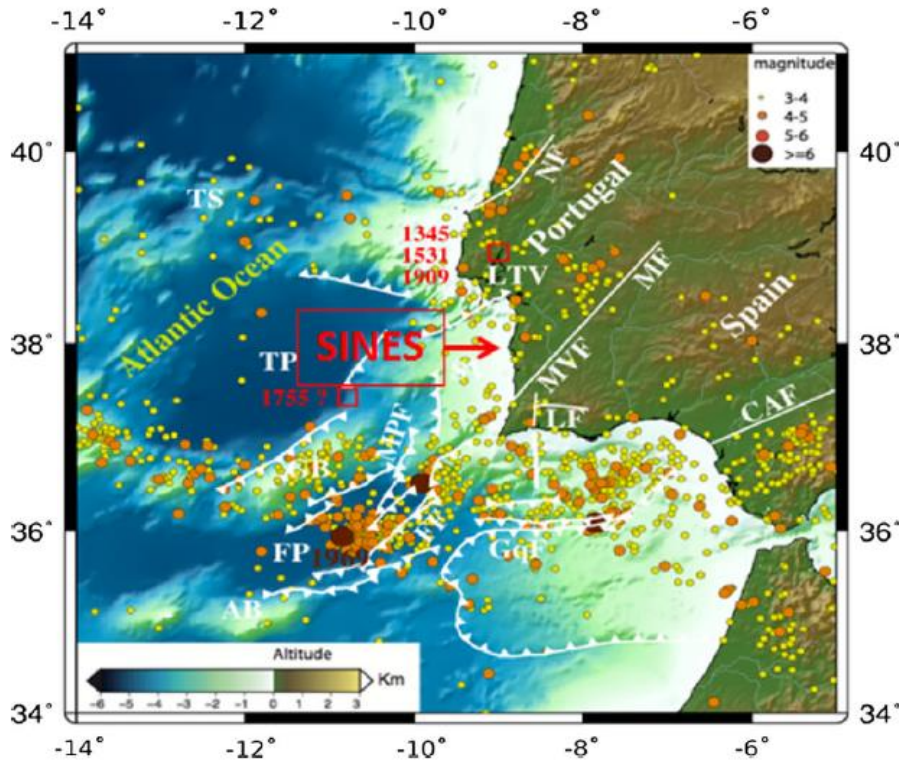


Fig. 1 – Location of Sines and instrumental seismicity

The Port of Sines is the only deep-sea water port in Portugal, capable of receiving cargo ships of any type and size. Initially it started with its oil and petrochemical terminal to supply the large refinery built at the same time in Sines. It can receive oil tankers of size much larger than the largest existing ones. Since it started to be built, in the decade 1960, the port has been expanded with specialized terminals for other types of cargo. Actually its container Terminal, managed by the Port of Singapore Authority (PSA) handles almost 2 million TEU per year. However, the port has space to enlarge the existing Terminal and built new ones, up to a total capacity of 8 to 10 million TEU per year. Besides a multi-purpose terminal, the port of Sines also comprises a new LNG Terminal, able to supply the entire country and able to be expanded if the demand increases. Besides its economic relevance, the gas Terminal is also of extreme strategic importance as it allows to diversify the sources of supply, rendering Portugal, and eventually Spain, less dependent of the gas received by pipeline from north Africa.

Sines is also in a strategic location, as it is near the crossing point of 40% of the world shipping routes, namely the Europe-Asia connections and Atlantic routes connecting Europe to Africa and the Americas. Figure 2 shows a map of world shipping routes. Sines is 370 km to the northwest of Gibraltar.

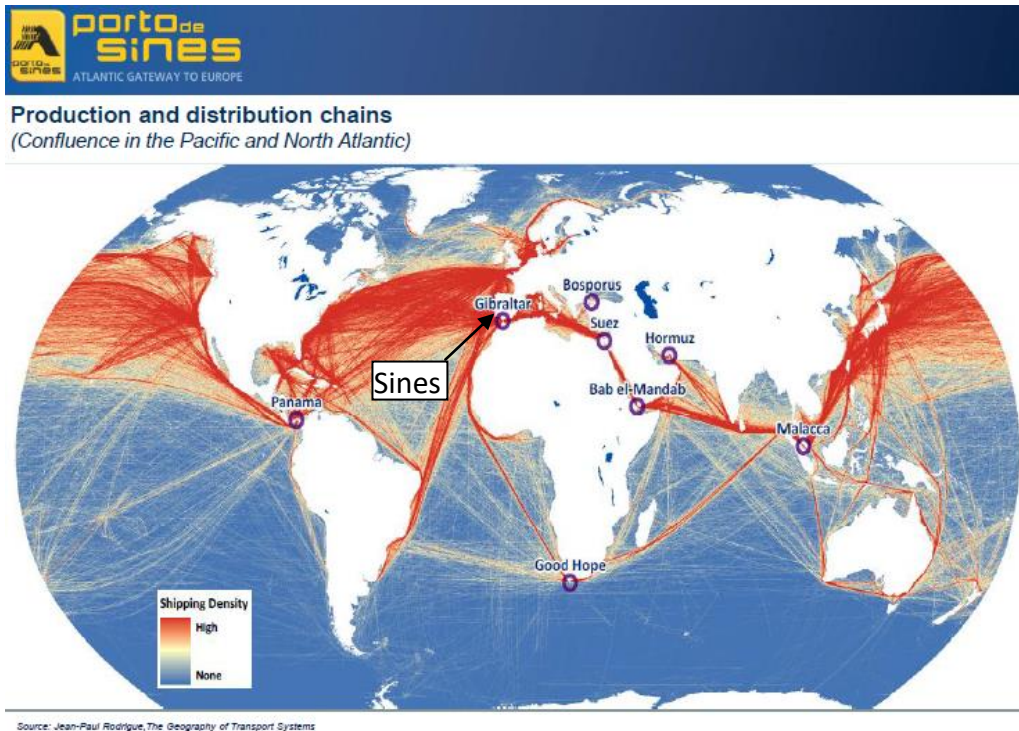


Fig. 2 – World shipping routes

The shipping connections to most world markets, together with the endless space in the vicinity of the port, that does not exist in the vicinity of other European ports with similar capacity to receive cargo ships of all types and sizes, has attracted industrial investment to Sines. Besides the large refinery (GALP) and a large thermal power plant (EDP Produção) that were built simultaneously or shortly after the port, several other industrial companies have built facilities in Sines. These include:

- REN Atlântico, gas Terminal
- REN Gasodutos, gas transportation network
- CLT, harbor storage facilities for petrochemical and oil products
- REPSOL, petrochemical facility
- REN, power transportation network
- Waters of Santo André, water supply and sewage network for the industrial complex and Sines
- Indorama (ex-Artland) – petrochemical facility
- MetalSines, factory of railway freight wagons
- Euroresinas, formaldehyde and resin producer
- Air Liquide.

Figure 3 shows a plan of the industrial complex and photos of some facilities.

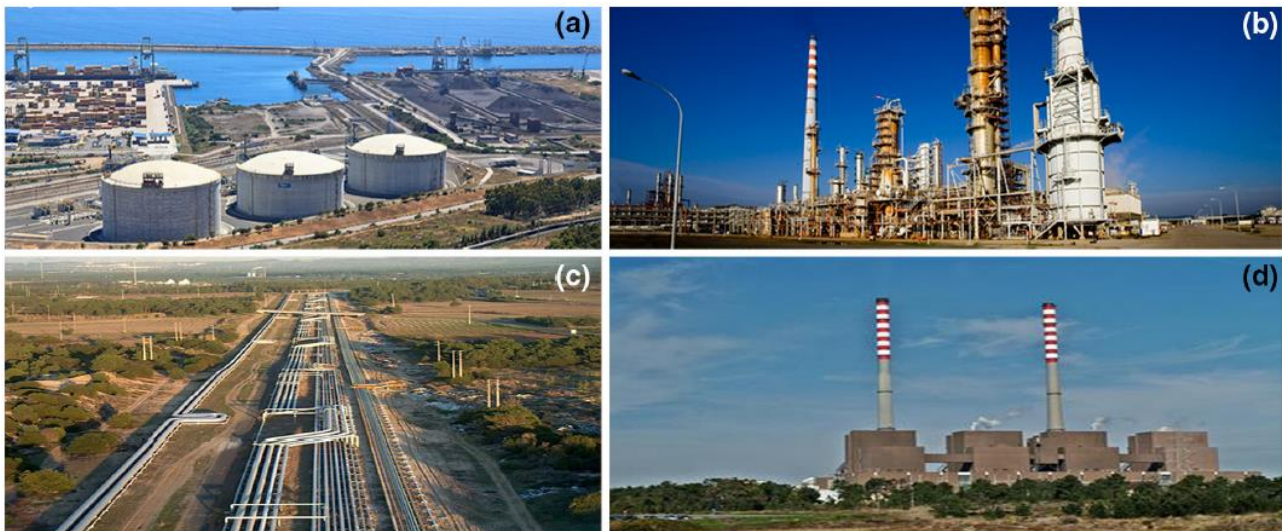
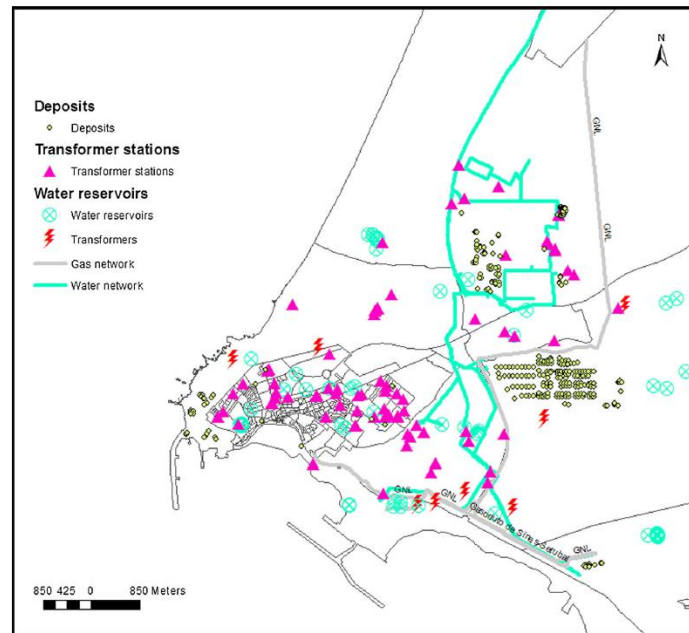


Fig. 3 – Sines industrial complex

An indicator of the importance of Sines for the Portuguese economy is the fact that it hosts about 10% of critical facilities in Portugal, only less than the two main towns/regions of Lisbon and Porto.

### 3. Seismological environmental

In Continental Portugal there are essentially two types of seismicity as a consequence of the collision of the two tectonic plates (Euro-Asiatic and African), which causes a compression field in two different zones [7]: (i) the Atlantic Ocean in the southern part of Iberia, running from SW of San Vicente Cape (extreme southwest point of Continental Portugal) to Gulf of Cadiz near the potential geological border of the contact plates, and (ii) the inland transition between the marginal zone and the stable Continental shelf of Iberia. The most pronounced of these sub-zones is the Lower Tagus Valley (LTV) where several strong historical earthquakes have taken place. The first zone can generate very large earthquakes (M8.5-9) at 100-200 km off



the coastal line and at a pace of 500 – 1000 years, whereas the LTV can generate inland events of (M6.3-7) every 100-200 years. Figure 4 shows the locations of these zones and Sines.

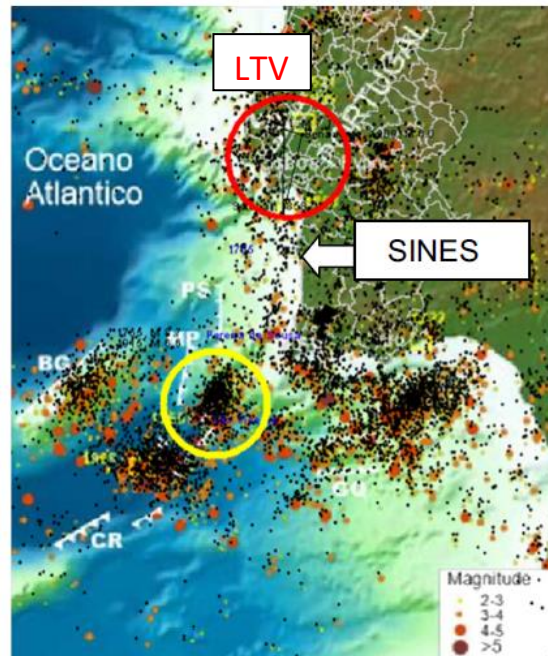


Figure 4 – Seismogenic zones and historical seismicity. Yellow circle (south of the mainland) - plate boundary. Red circle (north of Sines) – LTV [7]

In relation to EWS we have to tackle these two situations in a different way. For the first case, with epicenter in the south, all territorial area of continental Portugal and southern Spain can benefit from EWS. However with the stations of the Portuguese Seismological Network in 2014, the lead time for Sines, considering a number of stations to allow an high level of reliability, would be too low, close to zero. This was due to the fact that, as there are few stations in the zone closest to the epicenter (the southwest corner of the Portuguese mainland), it would be necessary to use data of stations located in a large area, almost up to an epicentral distance similar to the one of Sines. Some improvements on the Network have taken place since 2014, but not enough to change qualitatively the situation. However with further increases of the number of stations located near the southwest corner of the Portuguese mainland it will be possible to increase considerably the lead time, as information from the necessary number of stations can be received much faster. Some studies have already pointed out this possibility [8,9].

For the LTV, the situation is much more difficult to handle, essentially due to the short distances from the fault sources to major towns such as Lisbon. Depending on the relative location of stations to the fault rupture, a few seconds (clearly less than 6 sec) might be gained for the city of Lisbon. For Sines, the lead time may be a little larger, but not above 8 sec.

The situation in the Plate Boundary can be updated if “ocean bottom seismometers - OBS” can be added to the network, identifying earlier and more precisely the impending earthquake. Even not using this possibility, the design of inland stations network can be improved, assuring a better coverage of the territory and consequently a more reliable system.



#### 4. Perspective of the stakeholders

The potential usefulness of an EWS was object of an inquiry to the stakeholders, as well as several discussions with most of them. They were asked what would be the usefulness of a 12 sec and of a 25 sec warning before an earthquake strikes and what would be the impact of a false alarm.

Their needs and requirements vary substantially. In the analysis of this issue, the most important variables to characterize the stakeholders interest are: i) lead time (period of time from the moment a warning is issued and the arrival of the most destructive waves, usually the S waves, ii) the reliability of the warnings, this is the probability of missing events or false alarms, and iii) the threshold value above which action should be taken. It was found that different stakeholders have different interests and needs, therefore these variables change between facilities but also between different equipment in the same facility. In some facilities the cost of a false alarm, is tremendous, for other facilities it is not even a major problem, it represents only added work in the facility with no consequences in the supply. 83% of stakeholders considered that with a 12 sec lead time it is possible to trigger several automatic actions with ability to reduce damage significantly, but also considered that it was not enough to avoid many other negative consequences. Some examples are as follows:

- Refinery: false alarms are extremely costly, as 3 days are necessary to put the whole facility back in operation after shutdown. However, true alarms are very beneficial, as would allow to strongly reduce the risk of fire and explosions, as well as to allow the personnel to move away from more dangerous locations. So the refinery would benefit strongly from an EWS, as long as the level of reliability is high.
- Electric power plant: the angular speed of the turbines can be reduced in seconds, but it takes hours to bring them to normal service conditions. Therefore, false alarms are extremely costly. A true alarm is very beneficial, even though less than in the case of the refinery.
- Gas Terminal: if a 12 sec warning is received, valves cannot be closed completely (that would require 2 minutes) and stop the flow of gas in the pipes, but they may close partially, reducing the flow and therefore the internal pressure in the pipes. Since the internal pressure is the best indicator of the probability of leakage, the 12 sec warning has the potential to reduce significantly the number of leakages that may occur. If a false alarm occurs, and, for instances, half an hour later the whole system is initiated again, final clients will not notice anything, as the gas in the transportation network and other deposits will be enough to supply the whole country. Larger interruptions periodically take place for current maintenance works without affecting final customers. Therefore, the main consequence of a false alarm is a temporary extra work for the Terminal personnel.
- Gas transportation and distribution network: the situation is very similar to the one of the LNG Terminal, for the same reasons.
- Electric transportation and distribution networks: it is very advantageous to shutdown the substations a few seconds prior to the earthquake. This will contribute to de-energize many equipments in many industrial facilities, reducing the risk of fires, explosions and direct damage to those equipments. However, a false alarm would be extremely costly for the same reason, as it would lead to a sudden stop in production, which would take a long time to recover in many industrial facilities. So, as for the refinery, an EWS could be very beneficial as long as warnings are very reliable, this is, the probability of false alarms is very small.



- Harbour facilities: most equipments and systems are not strongly affected by false alarms, but strongly benefit from a few seconds warning before ground shaking. For instances the pipes used to transfer petrol or other liquids to and from vessels: even if the lead time is not enough to completely close valves, the reduction of flow and internal pressure may strongly reduce damage. To avoid water hammer phenomena, synchronization of equipment on board and on quay is necessary.
- Communication systems: false alarms are not very important, but a few seconds of alarm before strong ground motion hit, can be used to transmit “orders” to all control systems prior to the impact of strong ground motion. Therefore, the EWS, even without high reliability, is very useful.
- The labor force: false alarms have little direct negative effects in most cases, but they may have a very negative indirect effect, which is to undermine confidence in the EWS. True alarms may be very beneficial, as the lead time may be enough for many workers to move away from unsafe locations, as well as activate fire brigades. This may be relevant for instances for the automatic opening of head quarter doors for exit of fire fighting vehicles, avoiding the possibility that deformations imposed by the earthquake jams the doors while closed.

It can be concluded from the above that stakeholders’ needs may vary. However, if possible, the EWS should aim at an high level of reliability for the sake of credibility and to serve most stakeholders. However, in some cases, it may be worth to analyse the possibility of issuing warnings of less reliability for some stakeholders if that allows to increase the lead time. It may even be possible that some stakeholders may be interested in more than one hypothesis, depending of the equipments they manage.

## 5. Lead time and reliability

In the last five years many advancements in scientific and technical terms took place, bringing various advances to the EWS (for shaking) of great interest for society in general and for critical facilities in particular. These advances deal with investments in analytical models better calibrated with the accumulated information from earthquakes which are occurring at their natural pace, with the use of alternative instrumentation and design networks, and with commercial industry starting their activities in the field. More countries and regions are testing EWS systems, new algorithms, including the new AI technologies, are being developed aiming at increasing the lead times for alarms and reliability in the whole system. Essentially there are two types of EWS situations under analysis: (i) “on-site”, which uses only the time gained by a station or stations located on the site under analysis; (ii) “regional” which will take advantage of having stations identifying the type of earthquake that was triggered, located at shorter distance to the epicenter when compared to the distance epicenter-site.

Portugal, in spite of having good conditions for the implementation of EWS with great benefits to the population and critical facilities, did not progress much because emphasis in “tsunami early warning”, has gained a good deal of sympathy. Only in very recent times, the possibility of using OBS or coverage of bottom ocean, created a new wave of interest in these topic.

As mentioned in Section 4 a major issue we face in relation to EWS in Portugal, and of course elsewhere, besides the lead time available is the reliability of the predictions. Depending on the objectives of the EWS, it might be of great importance to have a system with reduced probability of missing events and false alarms. To achieve that purpose we have to check in first place how the existing system (run by IPMA) considering 10 stations in zones closer to the epicentre than Sines but not designed especially for EWS has been performing in the last couple of years, using only low magnitude events (M3-4). Then, a few stations should be added to complete the network in two different locations: near the south corner of Portugal to yield larger lead times for the southern seismicity and around LTV to increase the leading times for epicentres in this region. The south scenario is more relevant to Sines, as the magnitudes of possible earthquakes in this zone can be higher than in LTV, and Sines is in the middle. Therefore, for the south seismic source, to have the high level of reliability that most Sines stakeholders require, a number of stations larger than the existing ones in the southwest of the country are required. If that is done, it is estimated that lead times between 12





sec and 25 sec are possible for Sines. The maximum theoretical lead time that can be achieved for an event with epicentre 200 km away from Sines, is shown in Figure 5, for the case of a station located on the San Vicent Cape for both “regional” and “on-site” situations. If the OBS stations can be used in the near future this action would increase the times and the reliability of the system for the southern seismicity.

It is very difficult to estimate a cost (i) for these new stations some of which might be of high quality (“broad-band” and “continuous GPS”), (ii) to implement the software for the entire system (acquisition, transmission, treatment, decision-making and back transmission of alarm to selected stakeholders, a number of industrial and economic clusters or the population at large) and (iii) the maintenance of the system working (24h/7days a week). Several hundred thousand euros are needed initially, and probably a few hundred thousand every year for maintenance, mainly costs with specialised personnel.

The problem of benefits gained for having lead times contrasting to the present situation without any lead time, is very difficult to estimate accurately, first of all because these gains are stakeholders-specific, and because little experience has been gathered so far to proportionate detailed information. Also the probabilities of events are difficult to measure well. In a study recently published [10] the authors present a group of examples (hospital shut down, fast train braking, school procedures like “Drop, Cover and Hold”, were contemplated) and the benefit ratio was clearly above 4. It is thought that if lifelines and industrial facilities are also included, this ratio may increase significantly. Anyway, a qualitative cost-benefit analysis may be enough to decide if it is worth to invest in a EWS as long as the potential benefits in avoiding economic losses and in reducing the number of victims, multiplied by the probability of occurrence, are far more, say one order of magnitude (10 times) or more, than the likely accumulated cost of the system. This would eventually lead to a situation in which all the uncertainties would not be enough to change the qualitative conclusion.

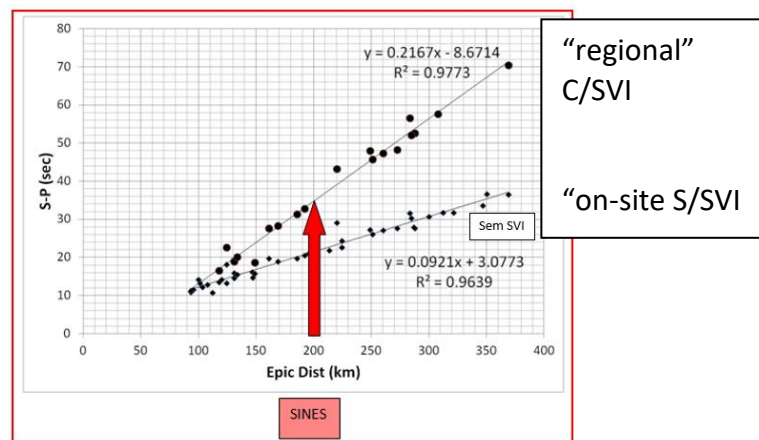


Fig. 5 – Time differences between S and P waves for “on-site-without/SVI” and “regional” using only San Vicente station (SVI), and for earthquakes at 100 km SW of SVI [6]

## 6. Recommendations

Even considering only the qualitative cost-benefit analysis of implementing and maintaining an earthquake EWS to protect the Sines industrial complex for a scenario of a seismic event similar to the one of 1755, with epicenter southwest of the Portuguese mainland, it seems obvious that it is worth for Portugal to develop such a system even though all partners should be aware of liability problems associate with these predictions [11]. The few seconds proportionated by the EWS are of great importance as referred by [12]. Other benefits not discussed in this paper, strongly increase the potential benefits of an EWS: these are the benefits of the system for other areas of economic activity, other zones in the country, mainly the Lisbon region, and the ones associated to inform directly the population. Other areas of activity regard for instances the



transportation system all over the zones potentially affected. With this regard it is useful to remember the original motivation to develop the EWS in Japan: to reduce the speed of high speed trains. In southwest Portugal, in certain zones of the rail network, trains circulate at 220 km/h, and the reduction of their speed is another advantage of the EWS. And numerous other applications of the EWS exist, namely in all the industrial facilities of the Lisbon region and south of Portugal, in the lifelines, for instances in the gas network in the Lisbon region, in the activation of fire brigades throughout the potentially affected zones, in warning workers to move to secure locations in civil construction sites and other activities, warning drivers to slow down to avoid accidents, etc. Of course training of the personnel in the enterprises that will receive the early warning as well as the population, is necessary for people to be prepared to act in the most efficient way when the warning is received. Otherwise many people will not know what to do, or worse, they may react in the wrong manner, for instances unprepared drivers could brake abruptly and induce more car accidents than the ones the earthquake would.

Therefore, it is strongly recommended:

- i) that the authorities implement the EWS for a seismic scenario similar to the one of the 1755 earthquake not only to reduce earthquake risks in Sines but also for all economic activities in the most affected areas, as well as to reduce risks by informing the population directly, using radio, mobile phones, sirens, television, and other available means.
- ii) Promotes periodic exercises and information campaigns for people and companies to be prepared to take advantage of the EWS when a strong earthquake strikes again.

## 7. Acknowledgements

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