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Early Warning Systems: Feasibility and End-Users' Point of View

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Abstract—From the user's point of view, Earthquake Early Warning Systems (EEWSs) have a number of applications that need to be viewed in detail for better utilisation of the "lead time" and the usefulness of the associated information. From the seismological point of view, the most important information is of two types: (1) the amount of lead time, the period from the moment the end-user receives the warning until the moment of arrival of larger S waves of significant importance or of exceeding a threshold value of a parameter characteristic of the seismic motion and (2) the reliability of the information transmitted. Missing events and false alarms may be critical or not to the type of "facilities/equipment" we are trying to protect, depending of the consequences. And to be more confident of the predictions, the lead time becomes shorter because the number of stations required increases. To check the level of possible lead time for the Portuguese industrial complex of Sines, we used the available procedures (front and on-site detection for SS and SP wave arrivals) and published the results obtained with the present configuration of the station network and with a hypothetical station configuration. Monte-Carlo simulation was used for the epicentre location within the most critical seismic source zones. The level of reliability and useful lead time ideal for different operators may be quite different, depending on the type of equipment under analysis. Therefore, the optimum balance between reliability and lead time may vary significantly between end-users, and some may even be interested in more than one option. In this article we study the effect of these problems on the industrial infrastructures, a group of installations where EEWSs may have a tremendous impact. Lead times, false and missing events are analysed from the end-users' viewpoint. We applied a simplified and preliminary cost-benefit analysis of using EEWSs at an industrial site and concluded that it is worth doing for more frequent events, likely to cause some damage, but refinement of the modelling parameters deserves to be continued.

1. Introduction and Seismological Context

Early warning systems are important to reduce the potential impact of earthquakes and tsunamis in terms of deaths, injuries, property damage and economic losses. Warning in urban and industrial areas allows for clean emergency shutdown of systems susceptible to damage, such as power stations, transportation and computer centres. Earthquake warning systems are currently operational in Mexico, Japan, Romania, Taiwan and Turkey. Systems are under development for seismic risk mitigation in California and Italy. While papers by Allen *et al*. (2009) and a collection of papers in Gasperini *et al*. (2007) and Wenzel and Zschau (2014) deal with the EEW subject, studies on issues emerging with the application of EEW where technological events may be triggered by earthquakes have been published by authors such as Krausmann *et al*. (2011) and Salzano *et al.* (2013).

The EU REAKT Project (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 the concerns discussed in this article. The aims of the project consist of 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 critical infrastructures (CI) and their key components, which may as well see their resiliency increased.

Within the EU REAKT Project, very different situations have been analysed to give a good overall view of what the various problems are that we may encounter in the applications of EEWSs (long bridges, schools, gas mains, harbours, hospitals, industrial facilities, etc.). At the Instituto Superior Tecnico (IST), University of Lisbon, we have been studying the effect of these problems on industrial infrastructures, a group of installations where the EEWS may have a tremendous impact. Lead times, false and missing events are analysed from the end-user's viewpoint.

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From the user's point of view, Earthquake Early Warning Systems (EEWSs) are important tools to provide information about the arrival of strong motions at a site with the maximum lead time, constrained to the minimum probability of being a false event and to a given ground motion (indicator) threshold. To achieve these objectives, we take into consideration the seismological estimates of the epicentral location and magnitude from the stations of the accelerometric network closer to the epicentral area. Knowledge of the rupture mechanism would also be of great importance, especially for large-magnitude events. Uncertainties exist in the estimations of these two quantities and depend very much on the number and location of stations identifying the wave passage. For the ground motion threshold, another uncertainty is added derived from the GMPE (ground motion prediction equation) for the zone under study. In this work, we will concentrate essentially on the lead time, and some attention is paid to the ground motion affecting end-user equipment and facilities.

The industrial complex of Sines (Portugal), with more than 30 km^2, is one of the largest in Europe, housing a significant number of critical infrastructures. Sines is located on the Atlantic Coast, about 180 km from various major seismogenic sources (the Gorringe Bank, Marquês de Pombal, Pereira de Sousa and San Vicente Faults) capable of generating earthquakes of 8.5 to 9 magnitude (Fig. 1). These sources will generate peak ground accelerations of about 0.3 to 0.50 g in stiff rock, with the possibility of 0.4 to 0.65 g in soft soils (EC8 2004).

Another source of seismic activity that affects the Sines area is related to the faults of the Lower Tagus Valley (LTV). Here the historical catalogue (Stucchi *et al.* 2012) does not show values $M > 6.5$.

The hazard values presented in Table 1 show that shaking levels above 0.12 g correspond to a return period of around 50 to 100 years. These values are within the values enforced by the code (RSA 1983; EC8 2004; EN1998-1 2011) for type C and D soils. Looking at the vulnerability of some industrial facilities presented in Sect. 3, we can observe that the PGA values that have a large probability of being exceeded in a relatively short time interval are large enough to create structural problems in various industrial components, especially if they were built prior to the modern codes of 1983 (RSA) or 2011 (EN 1998-1).

Several major industries and services are present in Sines, many of them critical infrastructures, interacting in a complex physical and functional dependency, prone to trigger chain reactions amplifying and propagating disastrous effects with great environmental impact. Within a 15-km distance lives a population of about 25,000 persons, with schools, health care equipment and many other important facilities.

In the present article, a first problem deals with the details and information to the end-users and the minimum amount of lead time required for several infrastructures existing in the Sines industrial complex are presented.

Automatic safety shutdown systems already exist in some plants based on the amplitude of incoming waves (SS On-Site System). We want to increase this information, adding the EWS Front detection (regional), which can provide around 10–20 s before the larger S-waves strike in Sines. These times are very important for initiating the shutdown of pumps, stopping transportation of hazardous materials, etc., and furthermore preventing or reducing cascading effects before they are triggered.

A second problem is establishing the triggering values, which depend essentially on the so-called fragility of the system (of one isolated element or composed by several elements connected in different ways). Given these fragilities, each end-user will be able to set his or her alarm or set of alarms according to the "best use". One may set a value different from the other depending on what one is trying to save. False alarms are also very important and may impair the whole system if the consequences are very costly as in the case of individual units that need a lot of time to be put into motion after the initiation of a stoppage.

Quantitative risk analysis (QRA) checks the safety of many of the Sines industrial facilities that are subjected to more frequent technological accidents. However, the earthquake hazard was not considered in the QRA.

The offshore seismic zones are also potentially tsunami sources with great impact along the Atlantic coast south of Lisbon, including Sines. A tsunami

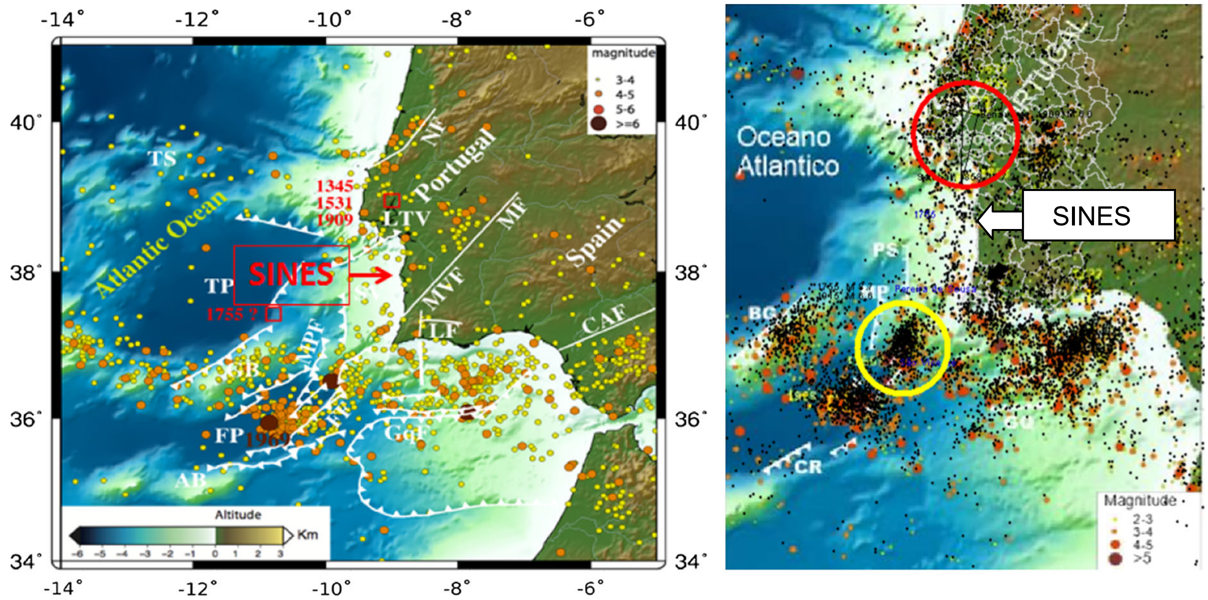

Figure 1

Location of Sines. **a** Instrumental seismicity (1961–2013, from the IPMA, *small brownish circles*); **b** historical seismicity up to 1970 and location of the main historical earthquakes of the Continental Portuguese territory and its adjacent margins. *GB-BG* Gorringe Bank, *TP* Tagus Plain, *TS* Tore Seamount, *FP* Ferradura Plain, *PS* Pereira do Sousa Fault, *FF* Ferradura Fault, *GqF* Guadalquivir Fault, *LTV* Lower Tagus Valley, *MPF* Marquês de Pombal Fault, *NF* Nazaré Fault, *MF* Messejana Fault, *MVF* Moura-Vidigueira Fault, *LF* Loulé Fault, *CAF* Cadiz-Alicante Fault, *CR* Coral Ridge (adapted from Pereira *et al*. 2014)

Table 1

Hazard values for Sines based on the historical catalogue and Atkinson and Boore (2006, 2011) attenuation law—$\Delta\sigma$ (stress drop) ~328 bar

PGA (g)–soil type D (EC8 2004)	0.03	0.06	0.12	0.20
μ (mean return period, years)	32	49	71	290
σ (SD, years)	96	116	142	405

early warning (TEW) for the Sines Complex, as well as for many other low coastal regions, is expected to be implemented in the near future. The subject of TEW is not addressed in this article.

2. Early Warning Developments

Stations that can incorporate the Early Warning Systems (EWSs) in Continental Portugal, at present date, belong to the networks in function. Many of them are not yet fully online. However, they already can be used to study the feasibility of an EWS, mainly to assess the possible "lead time" for the case that these stations come fully online. There are broadband seismological stations and strong motion 18–24-bit stations (Fig. 2). Two events are from the Lower Tagus Valley (LTV) region.

2.1. Epicentre in SW Iberia

Table 2 shows a group of several earthquakes recorded in 2007–2013, corresponding to the largest magnitudes of the last 8 years and to the ones recorded with the best equipment. These events were all M ~2–3, with most epicentres southwest of Continental Portugal, the most active area. Two larger events, $M \geq 5.5$, were also added. The arrival times of P and S waves to several stations were reported in the EMSC-CSEM (2014) catalogue.

For the purposes of studying early warning systems, information on the arrival times of P and S waves to different stations is useful. Data reported in Fig. 3 show the time difference (S–P) for those stations against the epicentral distance (obtained from Table 2). We plotted the S–P and S–P1 time differences at each station, where P1 is the arrival time at the station closer to the epicentre, station PFVI

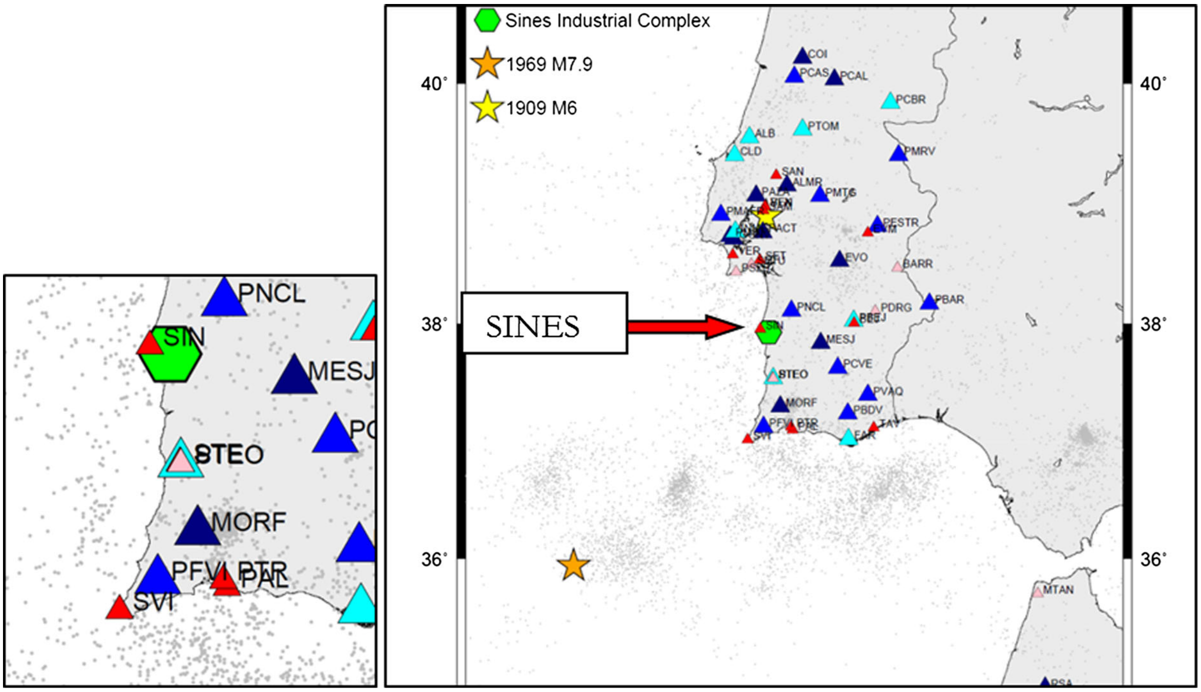

Figure 2

Seismological stations in Continental Portugal and a cloud of epicentres: *dark blue triangles* IPMA; *red triangles* SM, IST; *light blue triangles* SM-IPMA. *Left* detail of station locations SVI (San Vicente Cape) and PFVI (Vila do Bispo). (courtesy of Custódio, 2012, personal communication)

Table 2

Earthquakes considered in the current analysis

Date	Origin	Latitude (*N*)	Longitude (*W*)	H (km)	Epic location	Magnitude	Type
SW Iberia							
3 November 2014	03:39	39.95	11.25	30	309 km S Sagres	4.5	Mw
20 October 2014	02:05	39.96	9.45	20	65 km S Vicente	3.9	Ml
25 August 2013	07:16	36.58	11.57	31		3	Ml
15 August 2013	19:27	36.63	9.7	18	79 km Sagres	2.6	Ml
21 June 2013	18:40	36.66	7.86	10		3.8	Ml
7 May 2013	01:51	36.62	11.27	32	212 km W Sagres	2.9	Ml
19 April 2013	20:38	36.65	8.06	45	70 km S-Faro	3.1	Mb
15 April 2013	14:48	36.72	9.73	17	77 km Sagres	2.2	
19 March 2013	16:08	36.2	9.18	11	92 km Sagres	2.0	Ml
18 February 2013	13:26	36.63	9.67	18	102 km Lagos	2.9	Ml
3 May 2012	14:16	37.23	7.77	12	13 km Sao Brás Alport	3.8	Ml
22 July 2011	19:19	36.4	9.55	17	110 km Lagos	3.7	Ml
26 March 2011	07:36	37.36	8.37	15		4	Ml
31 March 2010	03:12	36.88	9.71	15	95 km Lagos	4.2	Ml
17 December 2009	01:37	36.46	9.95	10	134 km Lagos	5.5	Mw
12 February 2007	10:35	35.8	10.27	32	203 km Lagos	6.1	Mw
LTV							
1 August 2014	16:01	39.26	9.14	15	60 km N Lisbon	3.4	Ml
20 February 2014	02:27	38.35	8.88	2	46 km N Lisbon	3.7	Ml

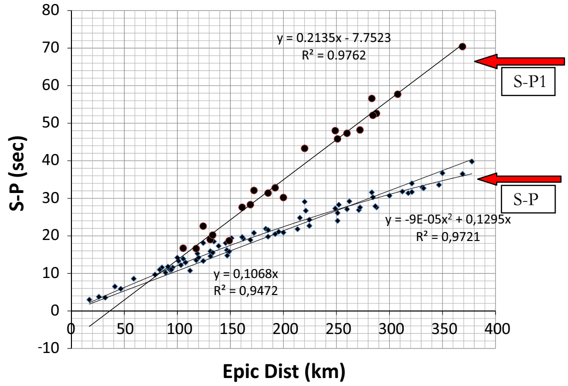

Figure 3
Lead time in seconds for epicentres located SW of Continental Portugal (Sines is around 100 km from the southernmost location of Continental Portugal where station PFVI is located). From P and S arrival times at different stations we obtain $V_P = 7.86$ km/s and $V_S = 4.53$ km/s

(Fig. 2) of IPMA (2014), located at the SW corner of Continental Portugal.

It is clear that if we only consider these times without any time for data treatment and transmission, with the S–P1 we would increase the lead time in relation to one calculated from the on-site (S–P) measurement of 12 s for sites 200 km away from the epicentre (Sines) and 21 s for sites at 270 km (Lisbon). This corresponds to the time difference between the two lines of Fig. 3.

The total lead time without any delay time (the top line in Fig. 3) is about 35 s for Sines if the detection of P waves is made in PFVI. (If using the San Vicente Cape station, SVI, which is not yet online, at the most southwest point, the gains would be even slightly larger.)

According to recent studies developed by Carranza *et al.* (2013), based on the existing IPMA seismographic stations (2014), the lead times (already extracting the data treatment and transmission) for Sines for an event with an epicentre at about 289 km based on 5, 8 and 10 stations are 25 s, 16 s and 12 s, respectively (Table 2). Data treatments comprise the automatic analysis of the accelerograms near the seismic source, leading to an estimation of the magnitude and epicentral location, allowing the estimation of ground motion amplitude at any site of interest. The decision to issue a warning will then be automatically made by means of comparing the estimated values of a ground motion indicator with the threshold values of that indicator to be defined as a function of the stakeholder's needs.

However, the above-mentioned lead times present large differences that may be reduced by optimising the location of the different stations by means of concentrating a large number of stations closer to the potential epicentre. With the current network configuration, a minimum number of ten stations needed to trigger the alert would mean that Portimão (10 km east of Lagos) would be within the blind zone that could not be alerted. Only 5 s would be available at Faro, 21 s at Lisbon and 46 s at the farthest city, Seville (Spain).

The numbers presented in Fig. 3 and Table 3 are not totally in agreement with each other because Fig. 3 was made with various epicentre locations closer to the Continental corner than the epicentres considered in Table 3. Nevertheless, the values are similar in tendency. The more stations that are used in the computation, the higher the reliability of the estimation, but of course the smaller the lead time. Perhaps, if the stations were organised in an L-shaped array along the west and south coast lines, the gains might be higher.

The results obtained for Lisbon by Pazos *et al.* (2014) and Romeu *et al.* (2014), using six existing stations and different software, are more conservative, arriving at a lead time from 20 to 43 s for two epicentre locations, 100 and 200 km SW of the PFVI Station, or from the Gulf of Cadiz, respectively. However, Sines is almost in the "blind zone" for the SW San Vicente Cape seismic source (Fig. 4).

Table 3

Lead time in seconds for an epicentre located SW of Continent Portugal (289 km from Sines) (courtesy of Carranza et al. 2013)

	R/km	Lead time 1 Station	Lead time 5 Stations	Lead time S Stations	Lead time 10 Stations
Portimao	221	22	9	0	−5
Faro	261	32	18	10	5
Sines	289	38	25	16	12
Lisboa	327	47	34	25	21
Huelva	350	53	40	31	26
Evora	370	58	44	36	31
Cadiz	388	62	49	40	35
Tanger	429	72	58	50	45
Sevilla	435	73	60	51	46
Badajoz	451	77	54	55	50

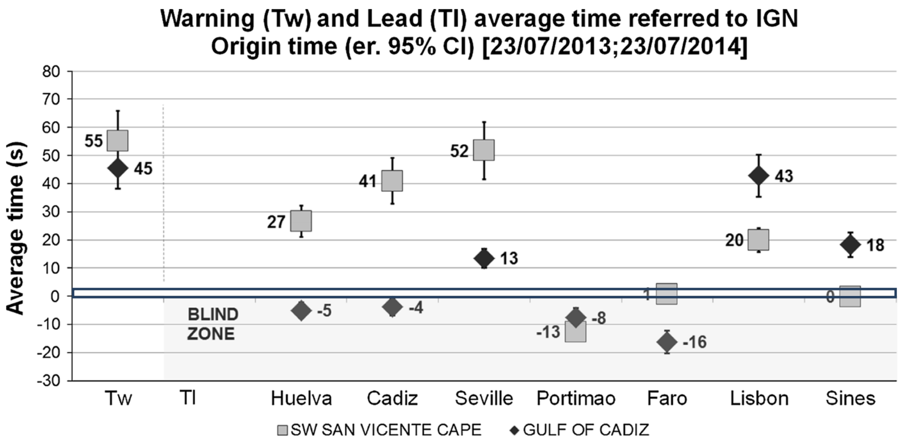

Figure 4
Average lead times and associated errors for the studied target locations with reference to the IGN origin times (289 km from Sines) (courtesy of Romeu *et al.* 2014) (warning times, from the origin time, are not important in this context)

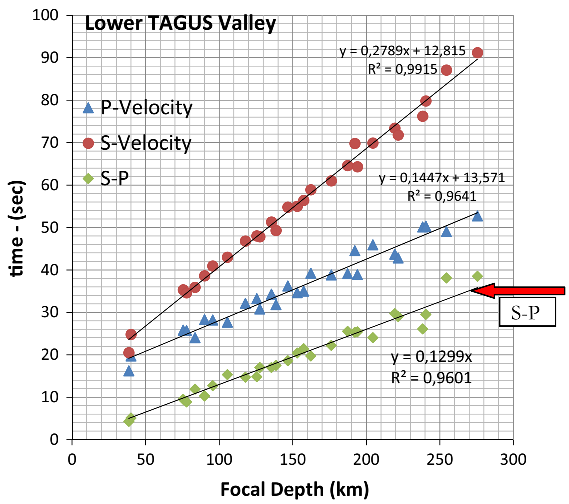

Figure 5
P, S and S-P times in seconds for epicentres located in the Lower Tagus Valley (LTV) to the north of Lisbon (Sines is around 110 km from the central LTV). From P and S arrival times at different stations, we obtain $V_P = 6.91$ km/s and $V_S = 3.58$ km/s, values much smaller than for the southern path

2.2. *Epicentre in the Lower Tagus Valley Region*

For the epicentres in the Lower Tagus River Valley (LTV), the situation is much different from the South West Iberia. We do not have enough information on past events to understand how much lead time we would have to send alerts to Sines. Only two small-magnitude recent events in the LTV zone (Table 1) allow an exercise similar to the one we carried out for events with an epicentre southwest of Continental Portugal where large magnitudes are expected (Fig. 5).

The distance from the LTV seismic sources to Sines varies quite significantly. If we concentrate only on the faults to the north of Lisbon with an epicentral distance of 110 km, and considering the values of Fig. 5 and not discounting the time for data treatment and transmission, the on-site S-P would be just 14 s, and if we use one station 40 km ahead of Sines detecting the onset of P waves, the lead time would be 24 s. For a feasible estimation, which would require more stations, the final lead time for EEW would probably be very little.

For other offshore epicentral locations, at smaller distances (<50 km) from Sines, the lead time for EEW would result solely from on-site S-P arrivals and would be as much as the epicentral distance would permit.

2.3. *Comparison of Lead Times for Different Early Warning Systems*

As the values obtained with the present configuration of the seismological network point to the conclusion that Sines is almost in the blind zone (option "on-site SP approach"), and before further research is done (new station configurations, algorithms), we decided to look at a hypothetical network composed of three stations placed close to San

Vicente Cape and another three near Lisbon to analyse the SS front detection system, which could be implanted almost immediately. Quoting Kanamori (2005), "For cases of the blind zone, the only possibility is using the on-site algorithm with a single-sensor approach… More rapid and robust onsite warnings are being developed to overcome uncertainties caused by the τ_c and P_d, especially if we talk about larger magnitude events (finite source $M > 7$)".

Assuming that S detection is more reliable than P detection and that the most critical seismic source zone causing larger ground motion is the one marked by the circles in Fig. 1b, and using the S-wave value as obtained previously, we made a Monte-Carlo simulation (@RISK 2014) in which epicentres were randomly located inside each seismogenic zone. The values obtained are presented in Table 4 (in the 5–95 % confidence interval). Of course, the best situation is not the "front-detection SS", but the "front-detection SP", as is clear in Fig. 3, where the upper values are presented for epicentres 100 km from the San Vicente Cape. This exercise points out that, even with all precautions due to the uncertainties present in all these phenomena, it is almost certain (Fig. 6) to obtain a lead time >13 s for the 1755 scenario (yellow circle, Fig. 1b).

In summary, in the future one should consider that hybrid solutions using SS, SP on-site and SP front-detection will be the best combination. As Kuyuk *et al*. (2013) put it, more research is needed on this topic to increase lead times for larger shakings keeping a high level of reliability.

Table 4

Lead time in seconds for Sines according to the different EEWS methodologies for the LTV and 1755 scenarios (S-arrival; P-arrival)

		Min	95 %−	95 %+	Med	Mode
Scenario LTV						
SS	Front detection	−9.8	−3.9	25.7	25.8	25.8
SP	On-site	4.0	6.0	18.9	20.2	12.1
	Front detection	−1.0	4.2	31.4	33.0	21.8
Scenario 1755						
SS	Front detection	13.0	14.5	22.5	19.4	19.7
SP	On-site	11.2	12.1	19.7	15.9	15.9
	Front detection	19.8	21.6	31.7	27.1	27.2

2.4. *Other Early Warning Developments*

Normally, we look at times until the arrival of S-waves as the onset of important shaking whose effects should be avoided or minimised. However, a structure takes some time to respond to the input ground motion, depending essentially on the ratio of the "predominant" frequency of ground motion and frequency of structure. In a simplified way and in case of a building (control installations), we want to launch actions before the building attains a certain level of danger to the people inside or to the functionality of control systems. Actions may be to escape from the building, to move to some shelter or safe place inside, to proceed to open doors to the outside, to keep the facility under control, etc. In other words, besides other considerations dealing for instance with mobility under strong shaking, or in the dark, or walking through toppled objects, we are also interested in how much time we may have after the onset of S-waves until the moment the building attains structural damage levels of the D2 (slight damage) to D4 (extensive damage) degree (Grünthal 1998) on a 5-level scale. It is important to notice that the effects of seismic actions on industrial equipment should be given not only in terms of structural damage, but also in terms of content release, which may be activated during or after the shaking (fire, leakage, toxic dispersion and so on) (Salzano *et al*. 2009). Damages and losses of certain types of containments may be more important than the direct inflicted damages. Also the effect of interdependences may be crucial to the functionality of other equipment and facilities. In these cases, short lead times might be sufficient to block the cascade effect caused by interdependences or reduce factors that contribute to leakage of toxic or dangerous products.

We present here the first steps to compute the time from the onset of the S-wave to attaining various levels of structural performance; this is the time it takes for a structure to reach several degrees of response related to the level of damage that the structure is suffering (Oliveira *et al*. 2014). First of all, a collection of strong ground motion records was selected to perform this analysis. Only earthquakes with $M > 6$ and especially $M > 8$ were used: Izmit 1999 and Duzce 1999 (nearby), Chile 2010 and four

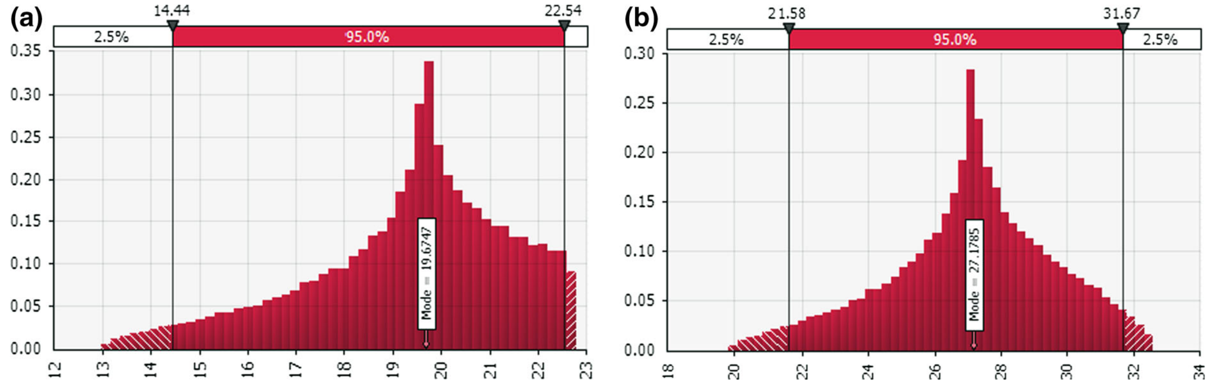

Figure 6
Probability distribution of lead time in seconds for Sines according to the 1755 scenario in case of front detection: **a** SS and **b** SP

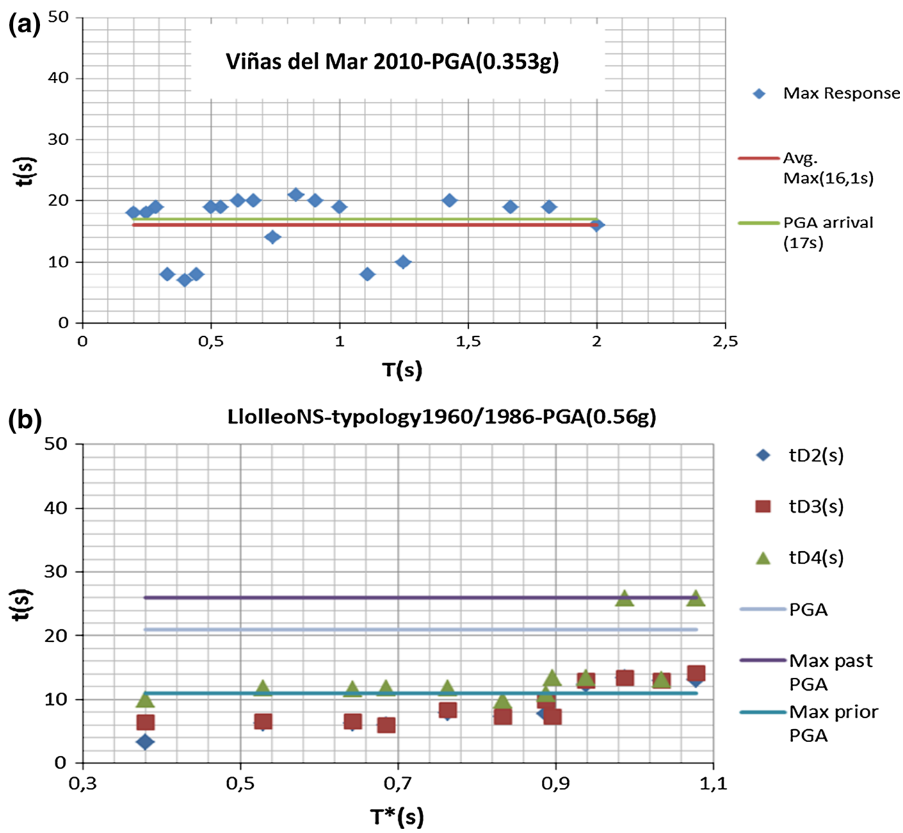

Figure 7
Time t(s) from the onset of the S-wave up to the attainment of various levels of structural performance for different structural periods T(s): **a** time to maximum response in a linear case (Viñas del Mar, Chile); **b** time to tD2, tD3 and tD4 for a non-linear case for building typologies constructed in the period 1960–1986 (Chile earthquake 2010). T(s), period; t(s), onset time; Max past and Max prior PGA represent the times to reach maximum values attained immediately after and prior to PGA

Japanese earthquakes that occurred from 2003 to 2012 (far away). Only two are shown in Fig. 7. We performed linear analysis for a group of single degree of freedom systems with periods varying from 0.2 to 2.0 s and non-linear analysis for a Takeda hysteretic response using the commercial programme

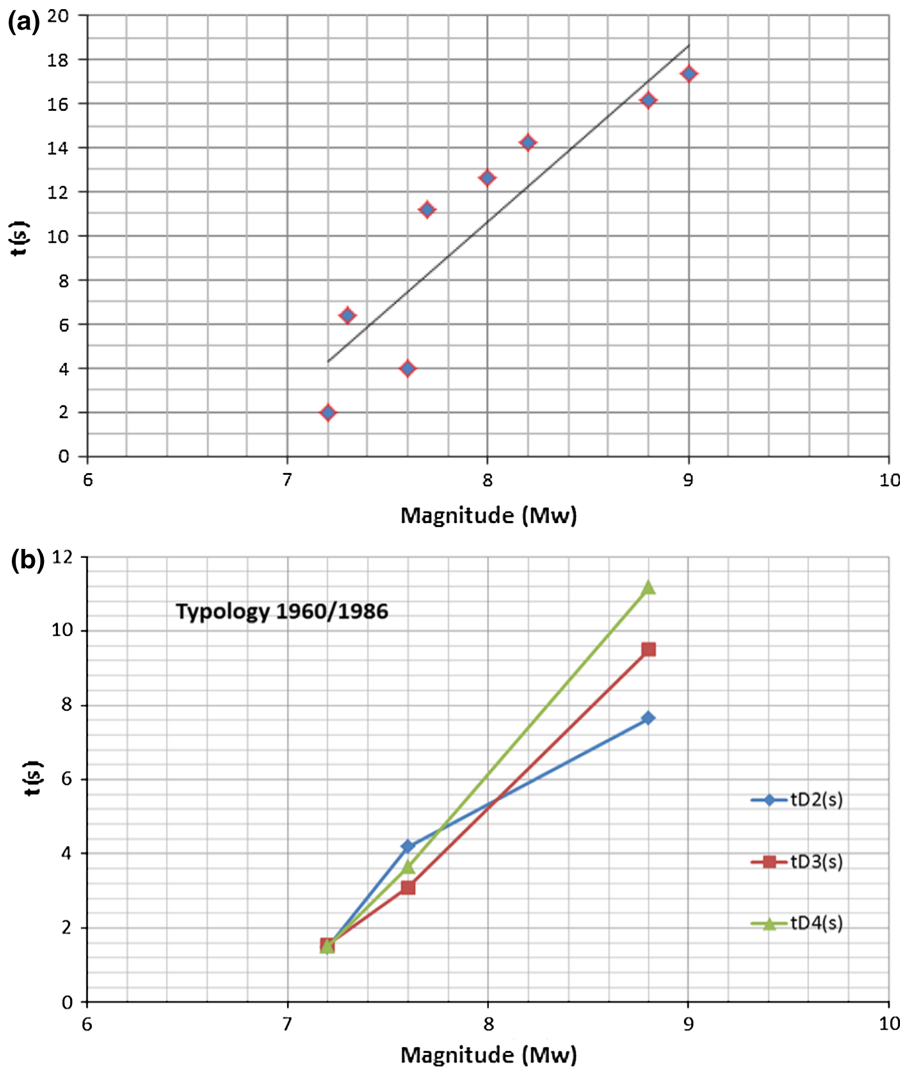

Figure 8
Time from the onset of the S-wave to attain various levels of structural performance as a function of the magnitude of event: **a** time to maximum response in a linear case for all records analysed; **b** time to tD2, tD3 and tD4 for the non-linear case for building typologies constructed in 1960–1986. (Note: the magnitude scale cannot reach values larger than 9.3)

CSI-SAP2000® (CSI 2008), representing the most common building structures existing in southern Portugal, including Sines. A Rayleigh damping ratio of 1 % was considered in the analysis, since the main source of energy dissipation is the hysteretic behaviour of structural plastic hinges. For these structures, we evaluated the time tDi for the structure to attain the level of response capable of inducing D2 to D4 damage levels. The preliminary results indicate that for near-field earthquakes the instant at which the PGA takes place is very close to the instant of the maximum of the building response, regardless of the period of the oscillator (Fig. 7a). Usually, depending on the magnitude, the time from the onset of the S-wave is only a few seconds. This time enlarges for larger magnitudes, as can be seen in Fig. 8.

Even though these preliminary results show that it might be possible to gain a few more seconds from the onset of the S-wave, especially for the very large magnitudes, many more examples should be carried out using both a larger selection of ground motion records and extending the type of structures under analysis before more sound conclusions can be made.

2.5. Conclusions on EEW for Sines

From the previous presentations, it is fair to say that Sines will benefit from an EEWS for the stronger shaking of earthquakes with an epicentre located in southwest Iberia and the Lower Tagus Valley if more stations are added to the current network at appropriate locations near the most relevant epicentres. Protection from near-field earthquakes with epicentres to the west of Sines will benefit only from an on-site EEW. Of course, further investigation is needed to reduce uncertainties about the lead times and increase the reliability of estimates. Both the configuration of the network and improvement of present algorithms will contribute to this desideratum. Based on these considerations, we proceed to the second part of this article, which deals with the question of how Sines end-users can take advantage of these new advancements, potentially able to provide 12 to 25 s lead times.

3. Sines Industrial Complex

3.1. Description

The Sines industrial complex, represented by its major stakeholders (herein "end-users"), was selected to develop a feasibility study for the implementation of an Earthquake Early Warning System (EEWS) (for seismic waves).

Major stakeholders were invited to participate and are associated with the REAKT project: the APS (harbour authority); REN Gasodutos, which manages the natural gas transportation network; PortSines, the harbour operator of the coal terminal, which supplies the Sines and other major power plant; the CLT (Companhia Logística de Terminais), which manages the harbour storage facilities for oil and petrochemical products; PSA, the container terminal; the Repsol petrochemical facility; REN major substation (REN manages the power transportation network); Águas de Santo André, the company responsible for the water supply and industrial sewage for the entire industrial complex; Artlant (the petrochemical facility that produces "PTA"); MetalSines, a factory for railway freight wagons; Euroresinas, which produces formaldehyde and the resins used by the textile and cork industries; and Carbogal, a factory that produces materials used in the fabrication of car tyres. The total number of companies visited and whose facilities were inspected at least once is 15. Several are considered as critical infrastructures (CIP 2011). Figure 9 presents a map of the area including the facilities of all the above-mentioned stakeholders, the urban area of Sines and most of the elements at risk. A preliminary soil microzoning of the area made in early 1970 (courtesy: Centro de Estudos de Geologia e Geotecnia de Santo André, CEGSA) describes the soil characterisation according to EC8 (2004) as follows: most of the industrial facilities are implanted in a sandy layer of variable thickness, conforming to soil type C; some are in soil type D, for which the PGA undergoes an increase of 50 to 80 % as compared to the bedrock.

Figure 10 illustrates the types of critical infrastructures (CIs) existing in the Sines Complex. Within REAKT, we have analysed the seismic performance of the equipment in several of these structures, namely the refinery chimney, some spherical tanks, the control room of one end-user and a flare. Below we present an example of a fragility curve for a spherical tank made by non-linear computer analysis of the respective support structure, columns and diagonals.

The operation of the port of Sines started in 1973. Sines is located at an important geographical position in the world, being a privileged axis at the crossroads of maritime routes. It is a deep-sea port and has good conditions for port expansion and secured direct access to railway and road networks.

In 2013, Sines handled 35 million tonnes of cargo. The container terminal handled almost 1 million 20-foot equivalent units (TEU), which is expected to reach 1.7 million TEU in 2015. Liquid bulk cargo traffic amounted to 16.2 million tonnes. The expansion of the Panama Canal in 2014, with a direct link from the Pacific to Atlantic Ocean for larger ships, may lead to an increased flow of trade among the Pacific basin, both coasts of North America, the Mercosur and Europe. Ports like Sines will be strategic for Europe (Moreira 2013). Furthermore, at present, 35,000 tonnes of gasoline are exported to the US per week, emphasising the Portuguese and international dependence on Sines' functionality.

Interdependencies between industrial infrastructures were studied in a preliminary analysis to

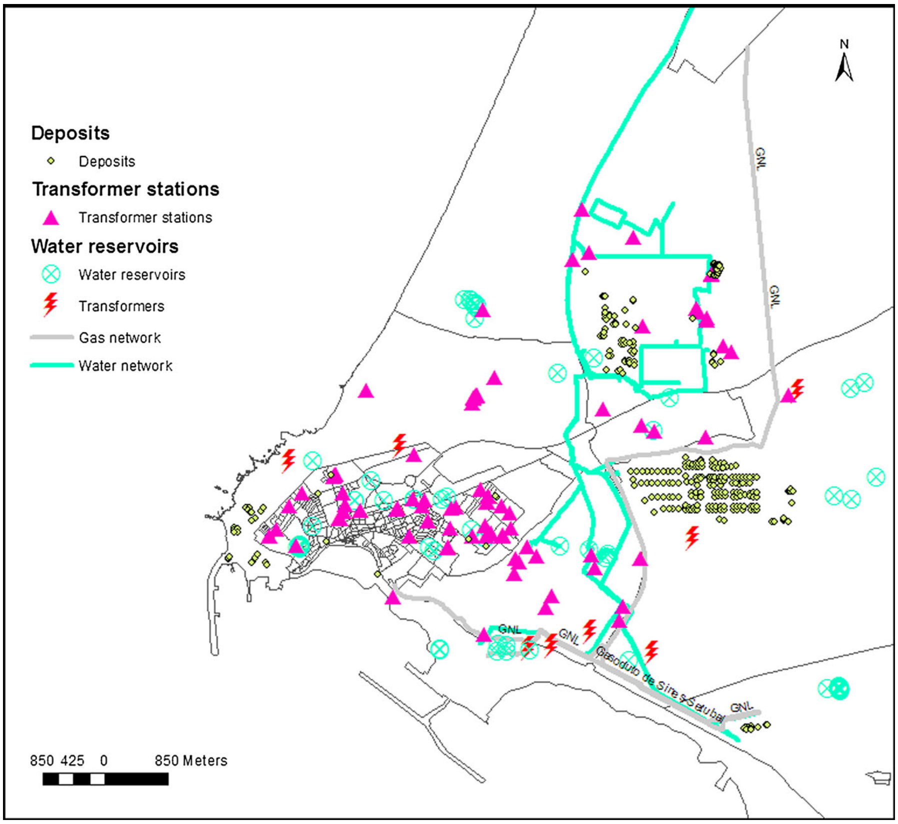

Figure 9
GIS platform showing an overview of the various Sines stakeholders

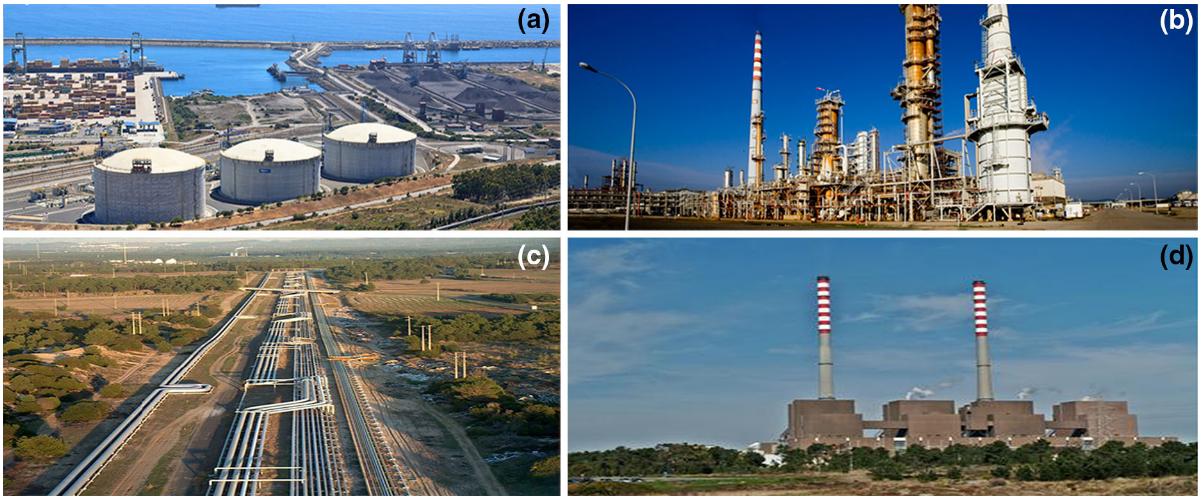

Figure 10
a Sines liquefied natural gas terminal (LNG). **b** The refinery; **c** piping tracks; **d** electric power plant

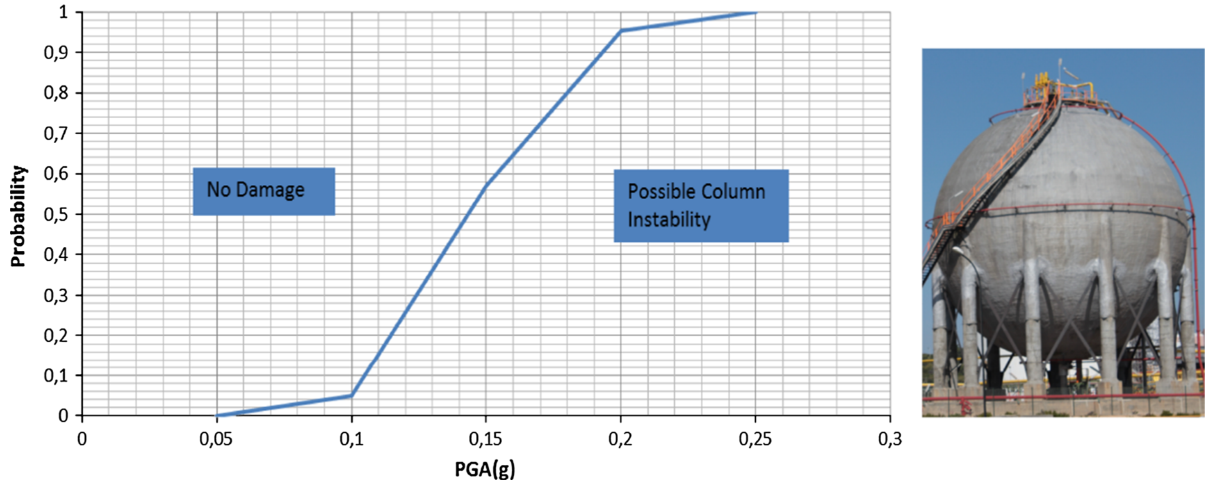

Figure 11
Fragility curves for typical spherical steel tanks ($\Phi = 16$ m supported by nine columns) that are fully loaded

estimate the consequences in a territory with a threat to one or several infrastructures. In this approach we choose the main infrastructures (macro-scale) necessary to describe the quality of service to different entities:

– Elements may suffer faults or failures, which may be propagated to other elements.
– The capability of each element to provide the required resources may depend on its operative condition, which is based on the availability of the resources it requires and on the severity of the damages that affect it.

To estimate the critical infrastructure damage degrees and cascade effects, we used the QuakeIST® earthquake scenario simulator (Mota de Sá *et al.* 2014), which can use any number of layers (provided that vulnerability and geographic information exists), such as those presented in Fig. 9. For the present case, vulnerabilities developed in several studies (HAZUS99 1999; SYNER-G 2013, among others), including WP5 (Work Package 5) of the REAKT project, were used. However, some infrastructures have their own peculiarities and are not reported in the usual bibliographies. In those cases, and if their criticality or importance is of concern, it is necessary to have fragility curves well adapted to them. As such, we started using the published results for a group of standard structures, but great effort was made to use non-linear dynamic structural analysis to produce more appropriate curves. One example is given in Fig. 11 where the fragility of spherical gas tanks is computed (Lopes *et al.* 2014).

3.2. *The End-User Point of View*

As far as seismic waves are concerned, the importance of launching an alert is quite different depending on the type of system we are analysing. For instance, if the shutdown of a facility/equipment may stop its operation for a long period because several hours or days are necessary to put it back into normal working condition, as is the case for an electric power plant, a false alarm can have a great negative economic impact with few advantages. However, for other installations such as gas terminals, a shutdown has almost no negative impact and allows turning down the valves, which may greatly reduce the internal pressure, which is one the main factors triggering damage (leakage). However, in either of the cases referred to, the EEWS informing about the early arrival of the waves is important, as it allows the personnel to be prepared.

Depending on the type of facility and equipment, the ideal threshold of a parameter representative of the seismic movement above for which the alarm must be triggered may vary substantially. For instance, there is no interest in triggering an alarm for seismic accelerations that cause no relevant damage.

Examples differentiating the importance of EEWS:

- *Electric power plant* It takes a few minutes to reduce the angular velocity of turbines and hours to put them back in service. A false alarm is very costly. A true alarm is favourable but only allows slight reductions in damages.
- *Refinery* Three days is the minimum time to put the entire facility back in operation. A false alarm is extremely costly. A true alarm is very beneficial. Indeed, if an emergency response is not activated before an expectable "blackout", the whole system and surrounding areas can be at severe risk.
- *Gas Distribution System* It takes a few seconds to significantly reduce the pressure and flow in the piping system by starting to close the valves, leading to less damage. In case of a false alarm, there is no problem, and the valves are opened again. Reduction of flow is very important for the safety of the entire gas transportation system.
- *Electricity Distribution System* It is very important to act a few seconds in advance in order to initiate the shutdown of substations, and re-direct the transportation network. This will contribute to avoiding fires and explosions in many facilities that receive power from the electric network. A false alarm is costly, but a good alarm is very beneficial.
- *Harbour facilities* Cranes, pumping systems, shutdown valves, etc., are not much affected by false alarms, but they benefit quite significantly from a few seconds of alarm. As an illustration, for the pipes used for transferring liquids from or to vessels, the larger the diameter of the piping, the longer it takes to close the valves. But even for these large pipes, the initiation of closure will be of critical importance for the overall performance of the transportation system under strong shaking as it will reduce the inside pressure and flow and therefore will reduce damage. Synchronisation of equipment on board and on the quay has to be achieved to avoid water hammer problems.
- *Water network* This involves the same considerations as above.
- *Communication Systems* False alarms are not very important, but a few seconds of alarm are extremely important as communications are critical to all control systems. If used before they are reached by the "blackout", different orders can be transmitted without problem.

These examples differentiate the importance of EEWS at the level of:

- *The labour force* There is no direct problem with false alarms, but there may be future problems due to the loss of credibility of the EEWS. Great benefits are derived from a few seconds of warning. Security measures, including safer worker positions and preparation of fire brigades for potential critical zones, are activated.
- *Managerial force* There are some problems with false alarms and great benefits with true alarms.

It can be concluded from the above that the level of reliability ideal for different operators may be quite different. Therefore, the optimum balance between reliability and lead time may vary significantly between end-users, and some may even be interested in more than one option.

3.3. Cost-Benefit Analysis

Is it worth implementing an EEWS in Sines? This is the question placed to all end-users, and at this moment it is very difficult to answer.

First of all, Sines is not a place where we can say that it will be a long time before a larger seismic event takes place again. In fact, rare events such as the 1755 scenario, according to some authors (Lomnitz 1994), should be associated with ground motion larger than what its return period should suggest if we consider that large events are non-memoryless (Hurst model). As time goes by without occurrences, the probability of a large event increases significantly.

Second, in the case of Sines and for "a hypothetical" oil storage park where fragility curves are very similar to the ones presented in Fig. 11, vulnerabilities are higher for older installations (Fabbrocino *et al.* 2005) as they were designed before modern earthquake codes (RSA 1983).

We performed a few trial tests with decision analysis and Monte-Carlo simulation to reach some numbers that could help us develop recommendations (Mota de Sá *et al.* 2015). Decision trees were used for the analysis of an adverse event (Fig. 12). To carry out this exercise, we need information on the cost of losses (if no EEWS is present) and the gains due to EEWS implementation in a certain time period (namely 20 and 50 years) and then measure the expected loss reduction in relation to investment (Fig. 13). Losses should reflect the cascade impact, which can be computed by an Industrial Disruption Index similar to the Urban Disruption Index (Ferreira *et al.* 2014). Other ratios such as the "EWS" (Early Warning System Number) have been proposed by Salzano *et al.* (2009) as the measure of EEWS efficacy. However, measuring the costs and benefits of such an event requires a much deeper study, not only because losses cannot only be measured in monetary units, but also because, prior to everything else, it is necessary to have a clear idea of what can be done in a few seconds. In other hand, cascading effects require a clear understanding of physical and functional fragilities and interdependencies, which in many cases constitute business "secrets" that stake-holders are unwilling to reveal. Our conclusion, based on very preliminary analysis that ought to be pursued, indicates that EEWS, if reliable, is always a winning bet especially for the more frequent events liquely to cause some damage because then the emergency response can be triggered. For very strong events, the benefits vary with the level of seismic resistance of the equipment: (1) if equipment is old and has insufficient seismic resistance, a complete collapse of equipment is more likely to occur and huge direct destruction may take place regardless of the existence of an EEWS; the gains are smaller, but lives could be saved; (2) if equipment was designed for earthquake resistance, complete collapse is less likely to occur, and the EEWS may contribute to reducing the damage and risk of fires, explosions or release of toxic and dangerous products, as well as save lives.

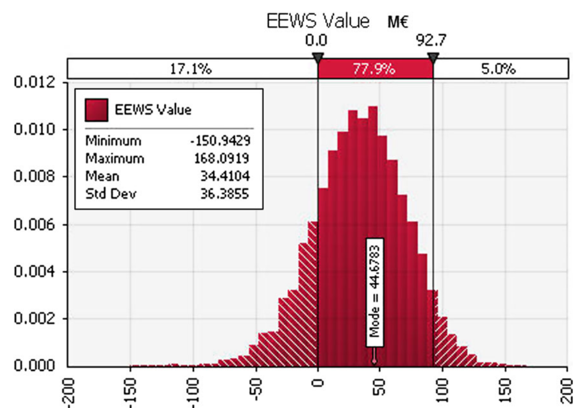

Figure 13
Chances of losses/gains generated by Monte-Carlo simulation over the decision tree of Fig. 12

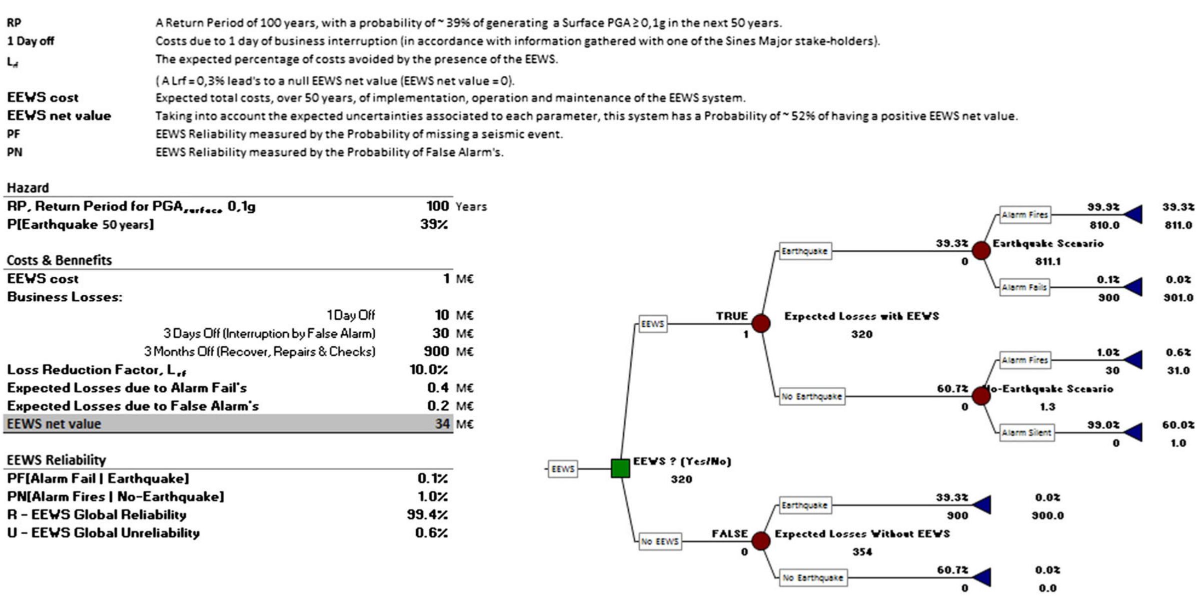

Figure 12
Cost-benefit tree used to illustrate the trial tests of EEWS efficiency for a given Sines stakeholder

4. Earthquake and Tsunami Early Warning Systems. A Survey

A survey was developed and sent to the Sines stakeholders of the REAKT project to test these assumptions and explore the views of potential users concerning the following issues, demonstrating how various stakeholders position themselves in relation to early warning:

- how these stakeholders might use warnings of 12- and 25-s lead time (these numbers consider average values resulting from different locations and an improved network of stations); the perceived benefits, costs and challenges of using of an earthquake early warning system;
- determine what benefits the early warning system can realistically provide and what is outside its capacities;
- analyse the ratio between lead time (early warning) and the time necessary to perform some actions;
- understand peoples' behaviour after they receive a warning—particularly how they prioritise different risks;
- identify actions that might be taken within 12 and 25 s;
- analyse the importance of false alarms, errors and missed events;
- what do end-users think is the best balance between lead time and reliability for their equipment.

In many cases of other types of risk, a lack of understanding of the uncertainty of estimations led some final users and the public in general to interpret some predictions that did not take place as wrong predictions and to believe that estimations could no longer be trusted. Statements such as "there is a 20 per cent chance that rainfall will be above the inter-annual mean" present information in an unfamiliar language. In fact, communicating risk is not an easy task. People do not understand probabilities and do not like uncertainties, nor are they able to perceive and measure intangibles and extremes. As such, it is important to report, communicate and have appropriate and effective interaction among the main actors in the early warning process, such as the scientific community, stakeholders and decision makers. In addition, the scientific community's message should communicate and be clear about the level of uncertainty and the possibility of a false or missed alarm. This requires the message from the scientists to the final users to be stated in simple language so that it is understood by those who receive it.

The survey on user acceptability performed within the framework of REAKT was conducted between March and June 2014 to identify how the organisations might may take advantage of warnings of 12 and 25 s, and the perceived benefits, and to assess the factors that may influence the acceptance and use of such a system.

A summary of the survey results is presented below:

(1) Were your facilities hit by some disaster (e.g., fire, floods, tornadoes, etc.) and you did NOT receive any warning of their occurrence?

Yes: 0; no: 100 %.

(2) How satisfied are you with the available warning systems for your installations?

	Do not know (%)	Very satisfied (%)	Satisfied (%)	Poor satisfied	Not satisfied
Central phone		60	40		
Sirens (light)	40		60		
Sirens (sound)		40	60		
Loudspeakers	40	40	20		
Radio/TV	100				
SMS	100				
Email	40	40	20		
Others	40				

(3) Do you consider early warning systems for fires, release of toxic substances, etc., as a strategy to effectively reduce the risk and vulnerability of your facilities/installations and community?

Yes: 100 %; no: 0.

(4) Knowing that your installation can be hit by strong earthquakes (and possibly tsunamis), do you consider installing a warning system for earthquakes and tsunamis in your industrial facility of utmost importance?

Yes: 83 %; no: 17 %.

(5) Consider the occurrence of an earthquake and its vibrations (shaking). Do you think that 12 s (with a 95 % probability of success) is sufficient to take

effective actions to reduce the risk of fire/explosion/spills/other (e.g. equipment shutdown) and allow preparing an appropriate response?

Yes: 17 %; no: 83 %.

(6) Consider the occurrence of an earthquake and its vibrations. Do you think that 25 s (with a 70 % probability of success) is sufficient to take effective actions to reduce the risk of fire/explosion/spills/other (e.g. equipment shutdown) and allow preparing an appropriate response?

Yes: 17 %; no: 83 %.

(7) What is the importance of a false alarm (vibration) to your facility?

	Don't know	Very important (%)	Indifferent (%)	Low important (%)	Not important (%)
In terms of safety		33	33	17	17
In terms of costs (to restart the system)		67		23	

(8) List the equipment that could benefit most from an early warning system (vibration).

Valves connecting pipes and storage tanks as well as pressurised vessels containing liquefied gases, methanol, formaldehyde, paraxylene and acetic acid storage tanks (all of them are located at the Sines harbour), the respective pumps, the pipeline connecting the Sines LNG terminal to the natural gas transport network and all rotating equipment.

(9) List some advantages and disadvantages of implementing an early warning system for vibrations (shaking) as well as for tsunamis for your industrial installations.

Advantages Avoid casualties and damage and evacuate people from buildings or allow self-protection from falling objects. The tsunami warning can save lives. For fixed equipment, little or nothing can be done; however mobile machinery and vehicles can be taken to a safe area, assuming a notice of at least 20 min.

The initial shutdown of pumping devices, piping transport and similar actions can be activated within the EEWS alert time. However, a full shutdown will take more time.

Disadvantages The warning time is not sufficient to take effective action in many cases. In some cases a false alarm can incur in high costs.

5. *Final Considerations*

In the present article we discussed the problems with feasibility of the EEWS and provided information on the minimum amount of lead time required for several infrastructures existing in the Sines Industrial Complex, south of Lisbon, comparing it to the possible “lead time” that scientific methods can make available for the region.

- For the most important seismic sources SW of Continental Portugal, it is possible to provide a lead time in the range of 12 to 25 s, even though the level of reliability (the inverse of the probability of false alarms or not detected events) is not the highest. The level of reliability can be increased at the expense of using more stations to assess an event, therefore increasing the time for processing data, reducing the lead time.
- It was found that the stakeholder requirements may vary significantly, depending on the economic consequences of false alarms. The threshold values of earthquake characteristics, for instance, the soil horizontal acceleration to trigger the alarm may also vary between the stakeholders and even within a single facility for different equipment.
- It should be emphasised that the potential impact of tsunamis in the lower areas of Sines harbour might be of great importance, and a Tsunami Early Warning together with an Earthquake Early Warning may mitigate those impacts.
- According to the survey, it is necessary to provide information to stakeholders on the pros and cons of the EEWS.

For the public in general and the people in their homes or working places, whatever the lead time, conveyed information is always of great value as long as false alarms are not too frequent. Of course, in all cases the larger the “lead times” are, the larger the benefits.

As a final word, one should emphasise the Portuguese and international economic dependence on Sines' functionality, which shows the relevance of the seismic protection of the Sines Industrial Complex.

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References

Allen, R.M.; Gasparini, P.; Kamigaichi, O.; Bose, M. (2009). "*The status of earthquake early warning around the world: An introductory overview*". Seismological Research Letters, *80*, 5. doi:10.1785/gssrl.80.5.682.

Atkinson, G.M.; Boore, D.M. (2006). "*Earthquake Ground-Motion Prediction Equations for Eastern North America*". Bulletin of the Seismological Society of America, *96*, 6, 2181–2205, doi:10.1785/0120050245.

Atkinson, G.M; Boore, D.M. (2011). "*Modifications to existing ground-motion prediction equations in light of new data*". Bulletin of the Seismological Society of America, *101*, 1121–1135.

Carranza, M.; Buforn, E.; Colombelli, S.; Zollo, A. (2013). "*Earthquake early warning for southern Iberia: A P-wave threshold-based approach*". Geophysical Research Letters, *40*, 1–6, doi:10.1002/grl.50903.

CIP (2011). Critical Infrastructure Protection. Good Practices Manual for CIP Policies. RECIPE EU Project.

CSI (2008). CSI-SAP2000®, Computers and Structures, Inc., Berkeley, Calif, USA.

EC8 (2004). "Eurocode 8. Design of Structures for Earthquake Resistance. General rules, seismic actions and rules for buildings," BS EN 1998-1:2004.

EMSC-CSEM (2014). European-Mediterranean Seismological Centre: http://www.emsc-csem.org/about: (consulted on November 2014).

EN1998-1 (2011). Anexo Nacional (NP) EC8, NDA "National Document of Application", IPQ, Lisbon. (in portuguese).

Fabbrocino G.; Iervolino, I.; Orlando, F.; Salzano E. (2005). "*Quantitative Risk Analysis of oil storage facilities in seismic areas*", Journal of Hazardous Materials, *123*, 61–69.

Ferreira, M.A.; Mota de Sá, F.; Oliveira, C.S. (2014). "*Disruption Index, DI: an approach for assessing seismic risk in urban systems (theoretical aspects)*". Bulletin of Earthquake Engineering, *12*, 1431–1458, doi:10.1007/s10518-013-9578-5.

Gasperini, P.; Manfredi, G.; Zschau, J. (editors, 2007). "Earthquake Early Warning Systems" Springer-Verlague.

Grünthal, G. (Ed.) (1998). "European Macroseismic Scale 1998 (EMS-98)". Cahiers du Centre Européen de Géodynamique et de Séismologie 15, Centre Européen de Géodynamique et de Séismologie, Luxembourg, 99 pp.

HAZUS99 (1999). "Earthquake loss estimation methodology". Federal Emergency Management Agency, Washington D.C.

IPMA (2014). (Instituto Português do Mar e Atmosfera): (consulted on November 2014).

Kanamori, H. (2005). "*Real-time seismology and earthquake damage mitigation*", Annual Review Earth Planet Science, *33*, 195–214.

Krausmann E.; Cozzani V.; Salzano E.; Renni E. (2011). "*Industrial accidents triggered by natural hazards: an emerging risk issue*". Natural Hazards and Earth System Sciences, *11*, 921–929.

Kuyuk, H.S.; Allen, R.M. (2013). "*Optimal seismic network density for earthquake early warning: a case study from California*". Seismological Research Letters, *84*, 6, 946–954. doi:10.1785/0220130043/s10518-013-9578-5.

Lomnitz, C. (1994). Fundamentals of Earthquake Prediction, John Wiley, New York.

Lopes, MS; Camacho, V.; Oliveira, CS (2014). "Fragility curves of industrial spherical tanks supported in columns". (paper in preparation).

Moreira, P.J.P. (2013). "The port of Sines: contribution for the emergence of a regional cluster". Resume from MSc Thesis in Portuguese Economy and International Integration, ISCTE-Business School, Lisbon, http://catalogo.biblioteca.iscte-iul.pt/2.

Mota de Sá, F.; Ferreira, M.A.; Oliveira, C.S. (2014). "QuakeIST earthquake scenario simulator". Proceedings, 2ECEES, Istanbul, Turkey, 24–29 August.

Mota de Sá, F. et al.(2015). "Cost-benefit analysis in a EEWS context". (paper in preparation).

Oliveira, C.S.; Lopes, M.; Camacho, V.; Mota de Sá, F. (2014). "Time from the onset of S-wave to attain various levels of structural performance". (paper in preparation).

Pazos, A.; Romeu, N.; lozano L.; Colom, Y.; López-Mesa, M.; Goula, X.; Jara, J.A.; Cantavella J.V.(2014). "A regional approach for earthquake early warning in south west Iberia: a feasibility study", (Submitted to *Bulletin of the Seismological Society of America*).

Pereira, N.; Carneiro, J.F.; Araújo, A.; Bezzeghoud, M.; Borges, J.F. (2014). "*Seismic and structural geology constraints to the selection of CO2 storage sites—the case of the onshore Lusitanian basin, Portugal*", Journal of Applied Geophysics, *102*, 21–38.

REAKT (2011) Strategies and tools for Real Time EArthquake RisK ReducTion. FP7-ENV-2011. http://www.reaktproject.eu/.

@RISK and DecisionTools Suite software (2014) Palisade. (http://www.palisade.com, consulted on June 2014).

Romeu, N.; Goula, X.; Jara, J.A.; Colom, Y.; Susagna, T. (2014). "Development of an earthquake early warning system based on earthworm: application to SW Iberia". Submitted to *PAGEOPH Special issue on EEWS* (E. Buform Editor).

RSA, (1983) Regulamento de Segurança e Acções para Estruturas de Edifícios e Pontes (Decreto - lei n°. 235/83 de 31 de Maio). Casa da Moeda. Lisbon. (in portuguese).

Salzano, E; Agreda, A.G.; Di Carluccio, A.; Fabbrocino, G. (2009). "*Risk assessment and early warning systems for industrial facilities in seismic zones*". Reliability Engineering and System Safety, *94*, 10, 1577–1584.

Salzano, E,; Basco, A,; Busini, V.; Cozzani, V.; Renni, E.; Rota, R. (2013). "*Public awareness promoting new emerging risks: Industrial accidents triggered by natural hazards*", Journal of Risk Research, *16*, 469-485.

Stucchi *et al*., (2012) "*The SHARE European Earthquake Catalogue (SHEEC) 1000–1899*". Journal of Seismology, doi: 10.1007/s10950-012-9335-2.

SYNER-G (2013). Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures. European Research Project funded by FP7. Project reference: 244061. http://www.vce.at/SYNER-G/.(consulted on June 2014).

Wenzel, F.; Zschau, J. (editors, 2014). "Early Warning for Geological Disasters", Springer-Verlague.

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