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Seismic risk evaluation for refineries: The case of Augusta petrochemical area (Sicily, Italy)

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ABSTRACT: Industrial plants are complex systems consisting of numerous connections, equipment and components. These facilities can be severely damage by earthquakes and the definition of seismic hazard is one of the most important steps in their design against seismic actions. Seismic events showed a quite high vulnerability of these structures, where damage ranges from the simple failure of joints to the failure of supporting structures. With this aim, the paper reports some preliminary results of the seismic response analysis performed on the *Esso Italiana* refinery, located in Augusta (Italy), an area of Sicilian region characterized by high seismic hazard. A set of 7 spectrum-compatible accelerograms have been chosen and the comparison with the elastic spectrum of the Italian Technical Code for Construction (NTC 2008) has been considered. The analysis allows to assess in more accurate way the local amplification than the simplified approach proposed by NTC 2008.

1 INTRODUCTION

Industrial plants are complex systems and it is such a complexity, due to numerous connections, equipment and components, together with the complexity of their operations that makes them particularly vulnerable to earthquakes.

Activities carried out in process plants can also be arranged in series, which means that process activities are realized with specific sequence and boundary conditions. Consequently, the failure of a single element can get out of order the entire system. This is of fundamental importance for the seismic vulnerability of a plant (Paolacci et al. 2011).

Seismic action can cause serious accidents to industrial plants as shown in several occasions. The actual worldwide situation of major-hazard plants against earthquakes should be considered as critical. For instance, in Italy about 30% of industrial plants with major accident hazards are located in areas with a high seismic risk.

In a plant, an earthquake can cause many dead as consequence of components collapses, similarly to what happens to buildings; moreover, the consequences deriving from a seismic event, such as economic losses for interruption of the production, environmental damages due to releases of dangerous substances, damages to persons due to explosions, fires and release of toxic substances, have also to be taken into account (Bursi et al. 2015). Therefore, the usual safety requirements applied to civil buildings, together with the consequences of exceptional actions, are generally unsuitable for structures belonging to industrial plants.

In Italy these problems are particularly worrying for industrial plants, when they are often located in areas characterized by high seismicity and close to the coasts, where the effects of earthquakes can be added to the tsunamis. A correct prevention policy must take into account the seismic hazard of the sites and the vulnerability of the industrial structures.

The paper focuses on the *Esso Italiana* refinery, located in Augusta (Italy), an area of the Sicilian region characterized by high seismic hazard (Fig. 1). With this aim, seismic response analyses with different 1-D calculation codes, EERA (Bardet et al. 2000) and MARTA (Callisto 2015), have been performed by using a set of 7 spectrum-compatible accelerograms.

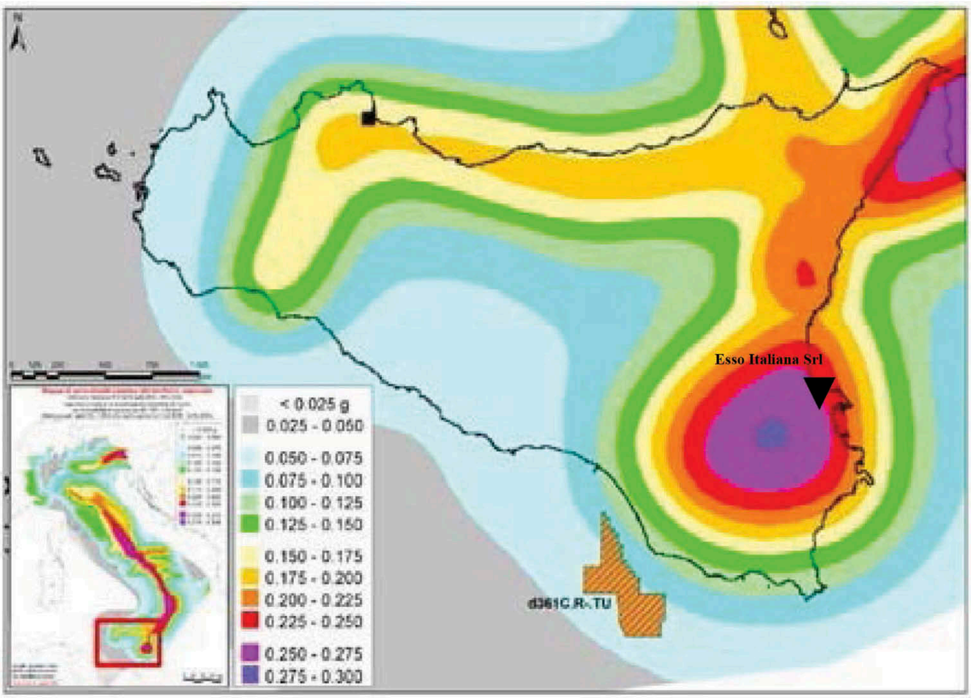

Figure 1. Hazard Seismic Map of Sicily.

2 CASE STUDY

The *Esso Italiana* refinery (Fig. 2) is located in Augusta near a flat segment of the coastal hinterland in front of the Augusta Gulf, on the orographic left of the Marcellino Torrent. The natural harbor of Augusta is a wide basin on the eastern coast of Sicily, whose surface covers about 23.5 km^2 with a maximum length of 8 km and a width of about 4 km.

Esso Italiana is the main company of the ExxonMobil group in Italy where it has been operating since 1891. A leader in the Italian oil industry, *Esso Italiana* runs - either directly or through controlled companies - activities in several business sectors: refining, petroleum products distribution and sales, and chemicals.

Thanks to its proximity to major sources of crude oil as well as to the main destinations of the world market for finished products, it is considered a strategic location for crude oil refining operations. Built in 1949, it became operational in 1950 under the name of RASIOM

Figure 2. *Esso Italiana* refinery.

(Raffinerie Siciliane Olii Minerali). Since 1961 the refinery has been owned by *Esso Italiana*, into which it incorporated in 1972, thereby changing its name into "Esso Italiana Raffineria di Augusta".

The site receives crude oil and other raw material/semi-finished products mainly by sea. The refinery includes plants for both primary refining and conversion into finished products. It also has plants for the production of lubricant bases, waxes and asphalts. Finished products are shipped from the refinery by sea, land or pipeline. By sea it ships diesel, gasoline, kerosene, aviation products, fuel oil, lubricants, waxes, asphalts and propylene. Some of them - such as asphalts, propane and aviation products - are also shipped by land. The refinery is also connected by pipeline with the neighboring Esso terminal for the transfer of products for transports.

Recently, the Augusta Refinery was sold to the Algerian Society (Sonatrach). In particular, Esso will work with Sonatrach to ensure careful management of the transition, with particular reference to employees, safety, relations with local communities and environmental protection.

Due to particular activities, natural events such as earthquakes can have uncontrollable catastrophic effects for this kind of area, making indispensable a detailed study of local seismic response, in order to evaluate the safety and planning the interventions on the existing facilities according to the Italian Technical Code for Construction.

3 SITE LOCAL RESPONSE

The definition of seismic hazards is one of the most important steps in the seismic design and safety evaluation of petrochemical facilities. Engineers that perform seismic design are usually not responsible for the assessment and quantification of seismic hazards. Yet they are often called upon by owners and regulators to interpret the results of seismic hazard analysis, and to justify their appropriateness. Therefore, it is important that design engineers have a clear understanding of how this information is developed by geologists, seismologists and geotechnical engineers.

The intent of this paper is not to instruct the engineers on how to perform seismic hazard assessment, rather it provides the necessary background information on techniques used to define and quantify seismic hazards. The development of a site-specific design response spectrum, in particular, has two main purposes: (1) the consideration of regional tectonics (faults and seismic sources, historic seismicity, earthquake recurrence rates, etc.), and (2) the influence of subsurface conditions at the site for which the response spectrum is being computed.

Site-specific design response spectra can be computed through either a probabilistic seismic hazard analysis (PSHA) or a deterministic seismic hazard assessment (DSHA), with the local site effects considered explicitly through a seismic local response analysis.

For seismic local response we mean quantitative evaluation of the changes in amplitude, duration and frequency content suffered by a seismic motion, relative to a bedrock, crossing the layers of ground above the surface. This means that the same seismic event produces devastating effects at a great distance from the epicenter than minor distance, or that in the same site affected by an earthquake an area is more damaged than another area with the same kind of building.

The local effects have a fundamental role in seismic design and must be evaluated from time to time. The property of a soil deposit can influence, in addition to the intensity, also the frequency field in which a deposit produces amplifications of the seismic waves, and in particular, the low frequencies will amplify by softer deposits, while the higher frequencies will amplify by rocky layers. For the local seismic amplification study of the *Esso Italiana* refinery two computer programs (EERA and MARTA) for 1D equivalent-linear analyses have been used.

3.1 *Seismic input*

Nowadays, the scientific community has widely accepted the use of natural records to reproduce a real input, for several reasons. For many engineering application, the purpose of selection and scaling of real earthquake (Bommer & Acevedo 2004) is to fit the code design spectrum considering the seismological and geological parameters of the specific site. To comply with the seismic codes set of accelerograms, regardless its type, should basically match the following criteria:

- minimum of 3 accelerograms should be used;
- the mean of the zero period spectral response acceleration values (calculated from the individual time histories) should not be smaller than the value of $a_g \times S$ for the site in question (S is the soil factor, a_g is the Peak Ground Acceleration);
- in the range of periods between $0.2T_1$ and $2T_1$, where T_1 is the fundamental period of the structure in the direction where the accelerogram will be applied, no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be $<90\%$ of the corresponding value of the 5% damping elastic response spectrum.

To help engineers in selecting a proper set of records, some tools have been proposed in the literature. The most recent is REXEL proposed by Iervolino et al. (2006). According to the above considerations, for the analyzed case study, it has been decided to use natural records and select 7 accelerograms compatible with the spectra (NTC 2008) of Figure 3 (see Tab. 1 and 2). For the case study the records were taken from national and international database (Rota et al. 2012; Corigliano et al. 2012), using the following hazard and compatibility conditions (Tab. 2).

Figure 3 shows the normalized elastic spectrum of the selected natural records for the site in which Esso refinery is located, in comparison with the target spectrum. In Figure 3 the red line is the average spectrum according to the Italian Building Code.

3.2 *Geotechnical model*

The geotechnical model to use in the seismic response analysis play an important role and its reliability is necessary for the accuracy of the results. Starting from the available data on the studied area and planning a detailed in situ and laboratory tests, the soil geotechnical model have been constructed.

Three boreholes (S1, S2, S3) within the Esso refinery (Fig. 4a) have been considered to performed several analysis by using the stratigraphic columns. As an example, Figure 4 represents

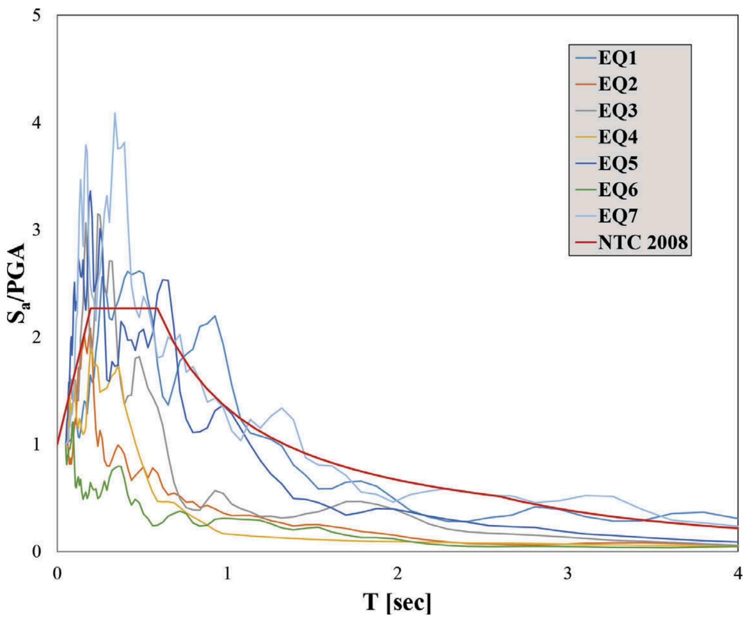

Figure 3. Comparison between normalized elastic acceleration response spectra for seven selected accelerograms and that proposed by NTC 2008 for safe life limit state.

Table 1. Seismic design parameters of the support structure of case study.

	Limit State		T_R	a_g	F_0	T_c^*
Serviceability	Operational limit state	OLS	30	0.045	2.499	0.258
	Damage limit state	DLS	50	0.063	2.505	0.271
Ultimate	Safe life limit state	SLLS	475	0.250	2.267	0.421
	Collapse limit state	CLS	975	0.358	2.349	0.469

Table 2. Hazard conditions for natural record selection.

Latitude (ED50)	Longitude (ED50)	Epicentral distance R_{min} - R_{max} km	Magnitude M_{min} - M_{max}
37.214488	15.169559	0 - 30	4 - 8

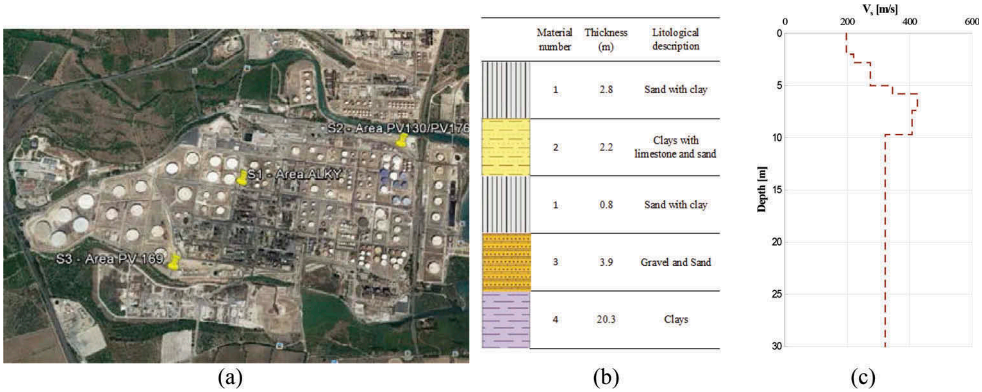

Figure 4. Location (a) of the boreholes in the ESSO area; Geotechnical model (b).

the geotechnical model (Fig. 4b) in which are detailed thickness and description of the soil associated to the different material (from 1 to 4) derived from the borehole S1.

The soil profiles gained from the borings show that the soil is composed of four lithotype such as: filling material including silty sands and limestone material up to 5 m, gravely sand up to 10 m, blue-grey clay below 10 m, which represent the basic plio-pleistocenic formation.

The shear waves velocity V_S profile (Fig. 4c) have been obtained as result of Down Hole Tests (DH) performed down to a depth of 30 m. From Figure 4c it can be seen that the velocity of waves is increasing till about 10 m depth where a decreasing appears. In the blue-grey clay stratum, from 10 m to 30 m depth, the shear waves velocity is equal to 330 m/s. Previous literature studies (Carbone 1985; Frenna & Maugeri 1995) performed on the same area confirm that from 10 m until 80 m depth the shear wave velocity assume a constant value of about 350 m/s. The bedrock depth has been fixed from 30 m from ground surface, as suggested by NTC for deposits with substrate depth exceeding 30 m, considering the properties of the soil layers up to that depth.

To evaluate the dynamic properties of the soil (Castelli & Lentini 2010; Castelli et al. 2016a; 2016b; 2016c; 2017) and in particular to determine the degradation law of shear modulus G and the increase law of damping ratio D several tests were performed with the Resonant Column/Cyclic Torsional Shear apparatus.

Soil non-linear behaviour was analysed by means of fixed-free Resonant Column/Torsional Shear (RC-CTS) devices available at Soil Mechanics Laboratory of the University of Enna

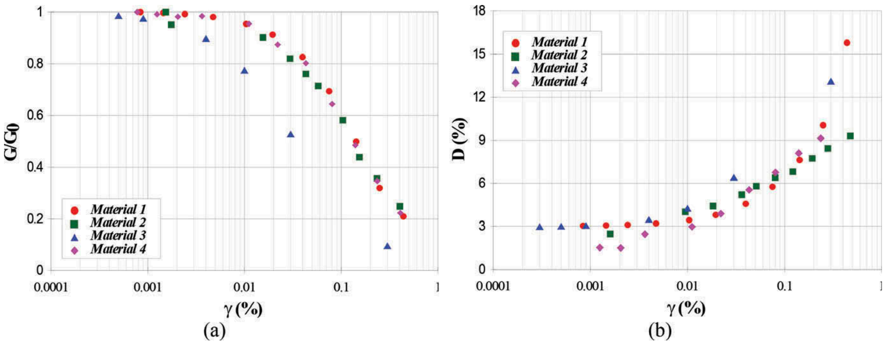

Figure 5. Normalized shear modulus (a) and damping ratio (b) versus shear strain from RC and CTS tests.

"Kore". The specimens were consolidated isotropically to the estimated in situ stress. At the end of the consolidation stage, the cyclic and/or dynamic tests were performed with increasing shear load levels, to investigate the behaviour of the soils for shear strains ranging between 0.0001 and 1%. As usual, the tests were interpreted in terms of linear equivalent parameters, i.e. shear modulus G and damping ratio D.

Figure 5 shows the experimental results obtained from the RC-CTS device in terms of normalized shear modulus G/G_0 (Fig. 5a) and damping ratio D (Fig. 5b) versus shear strain γ.

3.3 *Numerical analysis and results*

Local seismic response study of the Esso refinery area has been performed by EERA and MARTA codes at the aim to evaluate the amplification effects due to the stratigraphy. One dimensional analysis according to the equivalent linear approach have provided the seismic response of the soil.

Analyses of 1-dimensional soil columns have been performed with different geotechnical models derived from the results of in situ and laboratory test. According to NTC 2008, the soil column is excited by seven input ground motion (EQ1, EQ2, EQ3, EQ4, EQ5, EQ6, EQ7) applied at the bedrock that has been located at 30 m deep.

As an example, Figure 6 shows the results obtained in terms of the maximum horizontal acceleration a_{max} [g] profiles versus depth depicted in different colors for the seven accelerograms selected. In particular, Figures 6a and 6b provide the values of a_{max} derived by EERA and

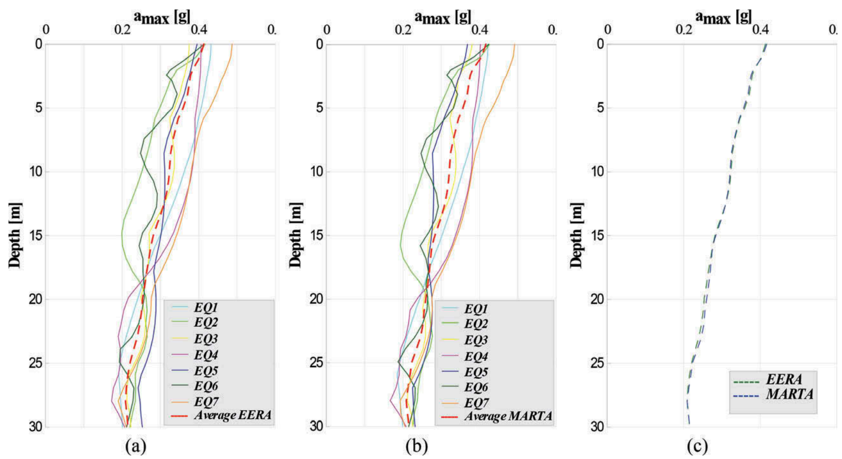

Figure 6. Seismic analyses response obtained by EERA (a) and MARTA (b) calculation codes; comparison between average response obtained by EERA and MARTA.

Table 3. Comparison among results obtained by EERA and MARTA codes and NTC 2008.

	S_S	a_{max}
		g
EERA	1.653	0.413
MARTA	1.666	0.416
NTC2008	1.360	0.340

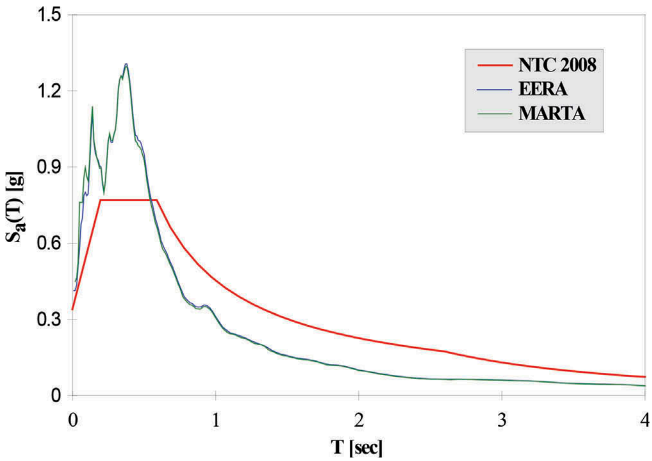

Figure 7. Comparison among the mean acceleration response spectra computed by EERA and MARTA codes and that suggested by NTC08.

MARTA respectively. The average profile of maximum acceleration is represented as a red dashed line in both Figures 6a and 6b. The comparison of average values provided by EERA ($a_{max} = 0.413\,g$) and MARTA ($a_{max} = 0.417\,g$) are depicted in Figure 6c in which the maximum acceleration profiles versus depth are green and blue lines for EERA and MARTA respectively.

According to the values obtained by seismic response analysis, the stratigraphic amplification coefficients S_S has been computed as the ratio between surface maximum acceleration value and the value of a_g provides by NTC for safe life limit state ($T_R = 475$, soil C). Table 3 summarized the results obtained by seismic response analysis in terms of maximum horizontal acceleration values a_{max} [g] and stratigraphic amplification coefficient S_S and the comparison with the same values provided by Italian Technical Code.

Finally in Figure 7 the comparison among the mean acceleration response spectra computed at surface by EERA and MARTA codes and that suggested by NTC08 is represented.

4 CONCLUSION

Recently, the attention paid on the protection of industrial facilities against natural phenomena is increasing, especially for the catastrophic consequences of strong events that induced severe damages to people and environment. Among the natural phenomena capable to determine serious hazards to industrial plants, earthquakes should be taken into account especially because they are capable to generate multiple sources of releasing of dangerous substances and domino effects within the same plant, determining the complete destruction of the site. The analysis of past accidents induced by earthquakes has shown the high vulnerability of some typical industrial components and the severity of the consequences.

The seismic design of a refinery requires careful consideration of a number of issues: definition of an appropriate seismic action; application of a proper analysis method; and use of suitable design methods.

The paper presents the preliminary results related to the local seismic response analysis of the Esso refinery performed trough EERA and MARTA codes. The results obtained by two calculation codes, in terms of surface maximum accelerations values a_{max} [g] and the stratigraphic amplification coefficients S_S, are major than those provides by NTC.

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