Seismic Risk Analysis of an Oil-Gas Storage Plant

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ABSTRACT

The wide range of induced effects of earthquakes, from direct damage due to seismic shaking to indirect damage caused by secondary effects (e.g. liquefaction, soil densification and landslides) makes the seismic risk one of the most common cause of structural failures among natural hazards. The degree of vulnerability and the level of exposure of the threatened elements may further amplify such effects. In this sense, the seismic risk induced by an oil-gas storage plant located close to an important commercial harbour in Southern Italy is analyzed. The plant is situated in one of the areas with the highest levels of seismic hazard in Italy, hit in the past by earthquakes as large as 7 in magnitude. Moreover, the plant lies near to the shoreline and the facing seafloor is characterized by the presence of a deep submarine canyon filled by loose, unconsolidated soils coming from the excavation of the harbour channel. Given these conditions the following phenomena have been investigated: local site amplification, liquefaction, submarine landslides and sea-waves run-up. The stability analyses considered both the plant's structure itself and the site. A vulnerability analysis provided the response to the ground motions of the steel tanks forming the structure, while dynamic analyses gave the response of the soils to the wide range of possible ground failures. Joining all the possible effects that could destabilize the plant, an overall probability that the safety of the plant may be affected was computed. The total risk was then assessed considering the effects, in terms of human life losses, produced by the failure of the plant. This risk was then compared with those deriving from other human activities to provide a reasonable basis for risk the acceptability assessment.

Keywords: hazard, fragility, risk, seismic ground motion, secondary effects

1 Introduction

Industrial facilities provide for the needs of developed countries in several activities such as power production, transportation, and so on. Nevertheless, the risk related to their failure under the seismic activity has been under-rated for a

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long time, basically due to lack of sufficient knowledge about seismic hazard and/or seismic vulnerability.

In Italy, the recent (2003) seismic classification of the country, highlighted that about one-third of relevant risk plants (317 out of 1024) are located in medium to high seismic areas, where ground accelerations are expected to exceed 0.15g with a probability of 10% in 50 years.

Risk analysis of critical facilities consists in evaluation of potential losses related to relevant accidents. Amongst others, the consequences of a failure of a critical facility due to earthquakes, are given by the complete destruction of the near field, environmental pollution and long-term health effects. Moreover, the collapse of a system can extend the accident to nearby structures triggering an uncontrolled mechanism known as Domino Effect.

The target of a risk analysis is the probabilistic assessment that a given system may not survive all the possible occurrences of the considered source of damage; in other words, it is one minus the probability that the considered system completes its mission successfully (also termed as system reliability). Due to the stochastic nature of risk, it requires to be related to a given timeframe, usually consisting of the lifetime of the structure.

As a case study for the application of QRA, a petro-chemical facility located in a highly seismic area in southern Italy and potentially threatened by strong ground motions and earthquake-induced ground failures is shown (Figure 1).

Figure 1: Aerial view of the critical facility

2 Risk assessment

Since risk is based on the quantification of a failure probability, which is basically a non-dimensional quantity, it can include several failure sources (even airplane or meteorite accidents, or terrorism attacks). Events algebra allows keeping separate procedures for each considered mechanism and then combining the results.

This is why seismic risk, which includes several causes of damage (from ground motion to ground failures) is a failure probability, too. In the simplest way it can be considered as the convolution of the seismic hazard [at the site] with the structural vulnerability [of the system].

Traditional structural reliability methods define hazard and vulnerability in terms of demand and capacity, respectively. In the events algebra approach, risk is the failure probability – which includes vulnerability – given a certain event occurs:

$$\text{Risk} = \mathrm{P}[failure|Hazard] \cdot \mathrm{P}[Hazard|time] \tag{1}$$

and reliability or survival, in turn, is the complementary of risk. Therefore, it is possible to explore the relationships between hazard and vulnerability using a single non-structural parameter, commonly termed as [seismic] intensity measure (IM) or ground motion (GM).

2.1 Hazard and Vulnerability

The goal of probabilistic seismic hazard analysis (PSHA) is to assess the probability of exceeding various ground-motion (GM) levels at a site given all possible earthquakes. A GM parameter commonly adopted in PSHA is the peak ground acceleration (PGA), which is used to define lateral forces and shear stresses in the equivalent-static-force procedures of structural design, as well as in the liquefaction and landslide analyses:

$$Hazard = \mathrm{P}[PGA \geq a|t] = 1 - e^{-\lambda(a)\cdot t} \tag{2}$$

where a is the PGA-value expected to be exceeded in time t, that is the structure's lifetime, and $\lambda(a)$ is the annual frequency of exceedance of a, namely the hazard function. Seismic hazard assessment is commonly performed in a two-stage analysis: on a regional scale, it is carried out through seismological studies (PSHA sensu strictu); at local scale it is based on geophysical and geotechnical investigations (local seismic response analysis, LSRA).

In Figure 2 the site-specific seismic hazard curve for PGA is shown.

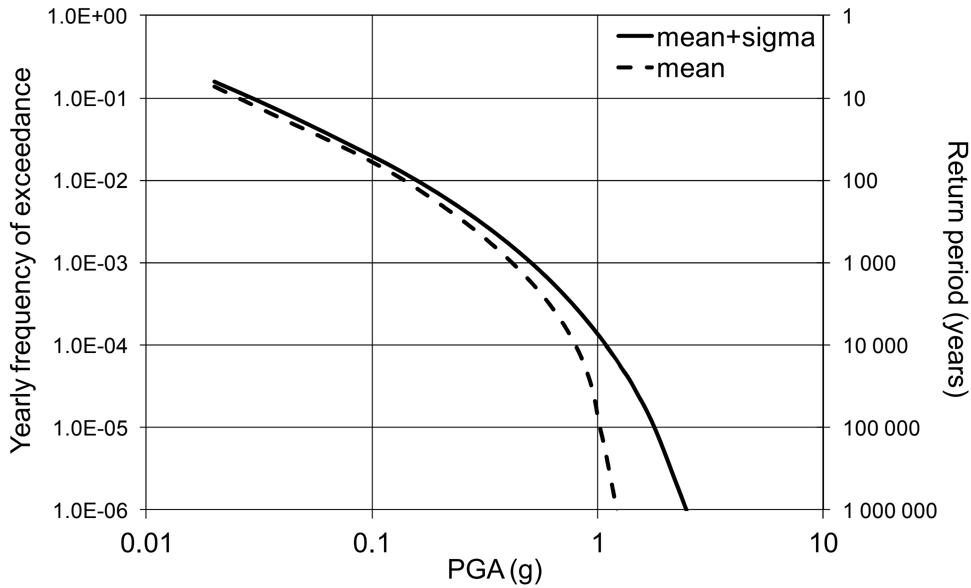

Figure 2: Seismic hazard curves for PGA

Vulnerability can be expressed by failure probability as a function of the same IM as hazard. In other words, probability of an event (=failure) given that an earthquake-related ground motion parameter has just occurred: in such a form vulnerability is called fragility function:

$$Fragility = \mathrm{P}[Failure|PGA] = \Phi\left[\frac{1}{\sigma}\, ln\left(\frac{PGA}{\mu}\right)\right] \quad (3)$$

where Φ is the cumulative normal standard distribution, μ and σ are, respectively, mean and dispersion values of a limit state to be reached or exceeded. Two limit states were analyzed, corresponding to a moderate content loss (Serviceability Limit State, SLS) and an extensive content loss (Ultimate Limit State, ULS), whose fragility functions were derived according to O'Rourke and So [1] and shown in Figure 3.

In structural analysis, hazard and fragility are related to two random variables called load (or demand, S, figure 2) and resistance (or capacity, R, figure 3). Due to their randomness, S and R are completely described by their probability density functions, $f_{S,R}(s,r)$. The probability that the system remains in the safe domain during its lifetime, is the probability that S never exceed R, or, invoking the performance function G=R–S, that G>0, therefore:

$$Risk = \mathrm{P}[G < 0] = P[S > R] = \int\left[\int \mathrm{f_R(r)\,dr}\right]\mathrm{f_S(s)ds} \quad (4)$$

where the limits of integration are: S[0÷∞] and R[0÷s].

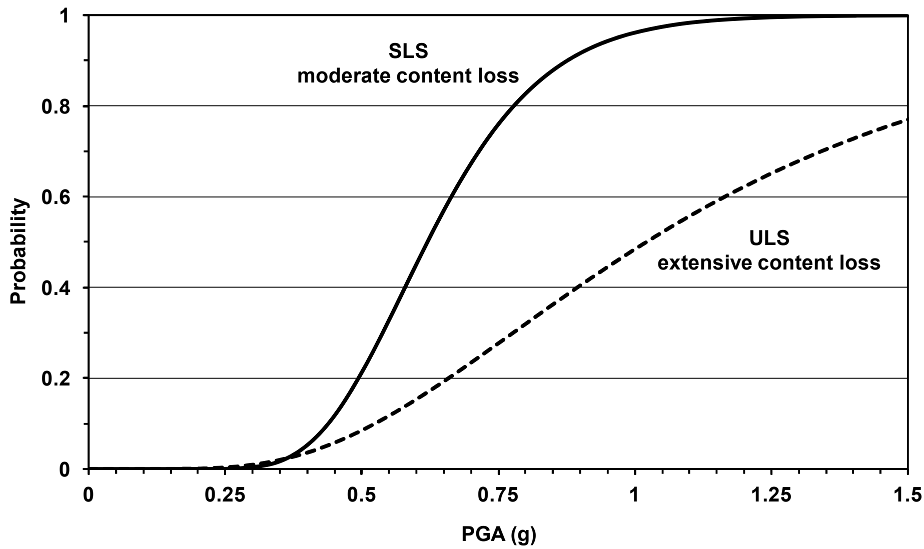

Figure 3: Fragility curves of the steel tanks for serviceability (SLS) and ultimate (ULS) limit states design

In the equation above the integral in *ds* is the hazard function and the integral in *dr* is the fragility function or, respectively, the demand and capacity (McGuire [2]).

2.2 Consequence analysis

The potential consequences strictly depend on the context within which the system is placed. This context defines the exposure of the socio-economical environment. For instance, referring to the potential for a life loss (L) the exposure is given by:

$$\text{Life-Loss Exposure, } \mathrm{E}[L] = \mathrm{P}[C(L)|Risk]\cdot \mathrm{P}[space, time|C] \quad (5)$$

Life-exposure is given by the probability of a person to lose his/her life due to a consequence (C) of the failure risk times his/her spatial and temporal presence at the moment of the event. The overall assessment of risk is schematically shown in Figure 4.

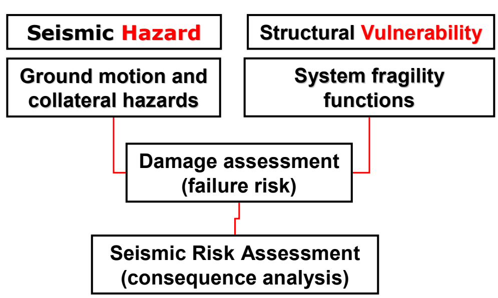

Figure 4: Flow-chart for seismic risk analysis.

3 Collateral hazards (secondary effects)

When dealing with seismic risk analysis, a relevant cause of damage is given by secondary effects induced by the seismic shaking. Many geotechnical hazards can be triggered by earthquakes, such as liquefaction, landslides and ground settlements, among others. Nonetheless, some of them may trigger others, such as flow-failures due to liquefaction, dam-breaks due to lateral spread of embankments, or sea-wave run-up due to submarine landslides. Thus, in addition to the risk of failure given by seismic ground motion, there is also a risk of failure given by seismic geotechnical hazards. Apart from ground settlements that can influence the assessment of manifold limit states, most of the geotechnical hazards can only affect the stability of the structure as a whole, that means they are relevant only for the assessment of the ultimate limit state (e.g., liquefaction and run-up). The approach is not different from that shown for the assessment of the risk of failure due to the ground shaking, provided that in this case the binomial distribution is more consistent than the Poisson distribution to characterize the hazard. For the case-study the stability of the plant can be threatened by liquefaction and induced flow-failures and by the sliding of the adjacent submarine scarp that may trigger, in turn, a sea-wave run-up striking the plant area. These effects are well documented to have occurred in the studied area: during the earthquakes that hit Southern Italy in 1783 several liquefaction were observed throughout the coastline; on July 12, 1977 more than 5 million cubic metres of material slid down the submarine canyon facing the harbour, causing a sea-wave up to 5 metres high that damaged many cranes and other harbour facilities. To investigate these phenomena an extensive survey was carried out, consisting in several onshore and offshore investigations. Equivalent statistic and dynamic analyses (Hungr et al. [3]) were performed to determine the failure probability due to liquefaction (Figure 5) and the initiation of a sea-wave run-up due to a submarine landslide (Figure 6).

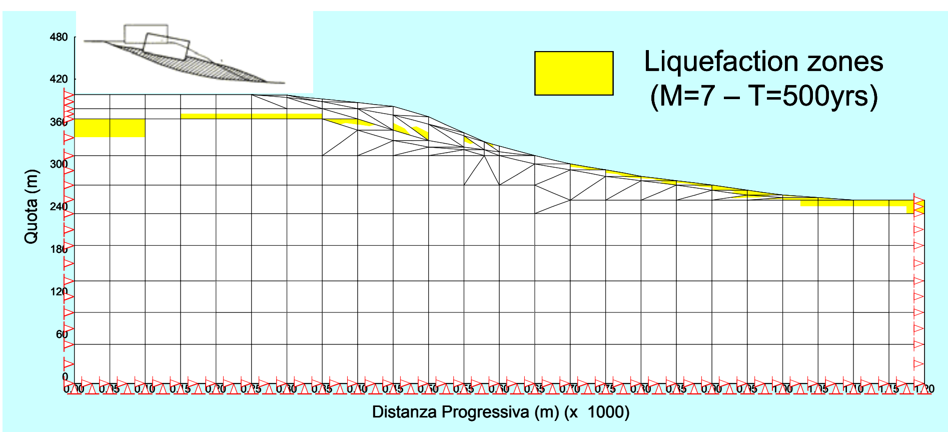

Figure 5: Dynamic analysis for liquefaction and flow-failure

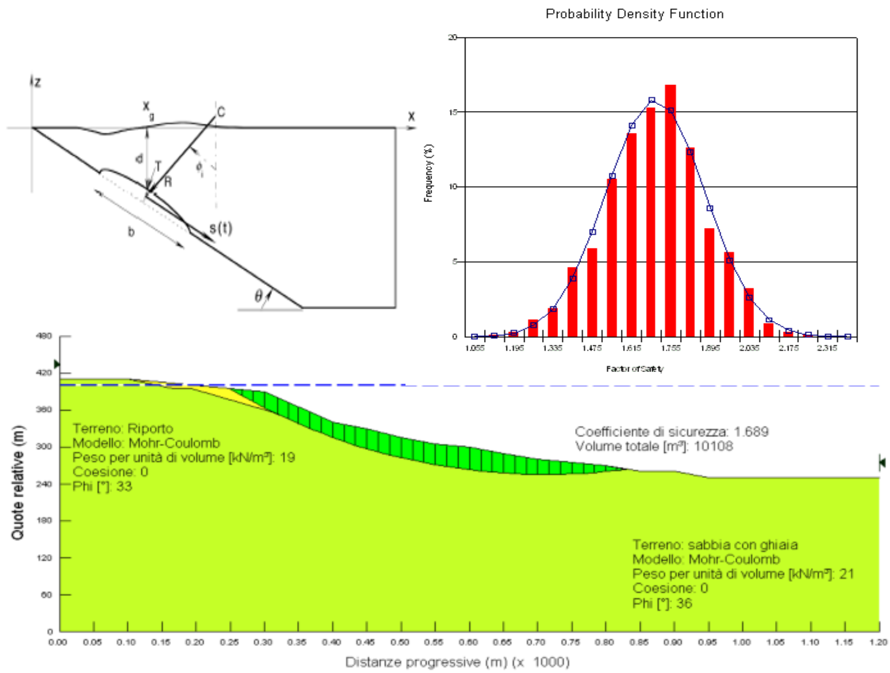

Figure 6: Stability analyses of the submarine scarp carried out for computing the probability distribution of the safety factors (Picarelli et al., 2005) and for modelling the sea wave run-up due to a rapid flow slides

4 Results

Catastrophic failure of the steel tanks may give rise to potential accidents listed in Table 1. Thus, the consequence of an accident is conditional to the spatial presence of a person within the distances shown in Table 1.

Table 1: Spatial extent of potential accidents due to a failure

Accident	Begins of death (m)	High mortality (m)
Pool fire	80	60
Flash fire	220	160
UVCE/BLEVE*	250	190

*vapour cloud explosion

The life-loss vulnerability (P[C(L)] in equation 5) is assumed to be equal to 1 for high mortality and greater than 50% for serious life-threatening injury. Spatial probabilities refer to three work locations, tanks, offices and the whole plant area, depending on the working tasks of employed people. Temporal probabilities are inferred from the employees' working time plan.

Consequence analysis leads to the computation of the probability of an individual to loss his/her life due to an accident is triggered by the occurrence of a failure event (Table 2).

Table 2: Annual probabilities of a life loss

	Offices	Tanks	Whole plant-area
Workers	3	5	2
Exposure (%)	15.4	20.8	21.8
Ground motion	6.30E-04	8.54E-04	8.93E-04
Liquefaction	5.31E-04	7.20E-04	7.53E-04
Landslide & run-up	0.54E-04	0.74E-04	0.77E-04
Total Risk	1.22E-03	1.65E-03	1.72E-03

The table shows, for each place within the plant area, the probability that a worker may loss his/her life due to an accident triggered by a failure of the plant triggered by either ground motion, or liquefaction, or a landslide and induced sea-wave run-up. Despite ground motion is the triggering of liquefaction and landslides, too, each event can take place independently from the others, thus the overall risk of an individual to loss his/her life is given by the total probability theorem:

$$\text{Total Risk} = 1 - \prod_i (1 - P_i) \qquad (6)$$

where P_i is the annual probability of a life loss due to the accident triggered by the i-th event.

May a risk (the negative consequence of an event or activity) be acceptable or not is a social and political choice. Nevertheless, a comparison with other industrial risks may facilitate this choice. In Figure 7 the societal risk of several industrial activities are shown (modified from Whitman [4]), along with the risk computed for the studied facility. Societal risk is defined as the probability that a group of N or more people would get killed due to an accident triggered by a system failure. This is commonly expressed by a frequency – number (FN) curve, representing the annual frequency of exceeding N or more casualties given a failure.

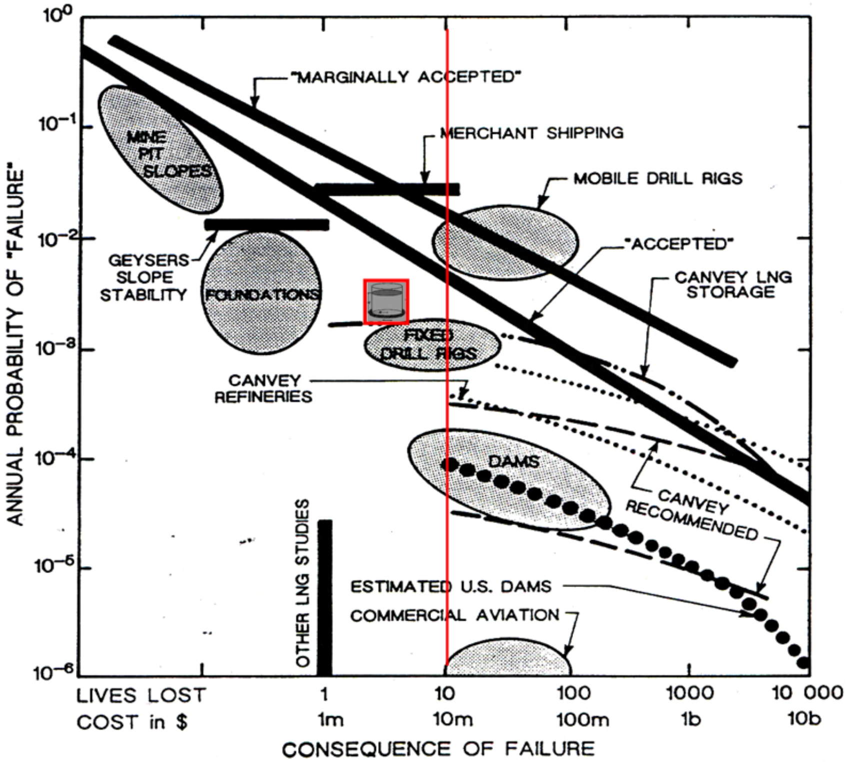

Figure 7: F-N curve for various industrial risk activities. The societal risk of the studied plant is shown in the middle of the figure with the symbol of a cylindrical tank. The vertical red solid line marks the limit of people that could in theory be involved simultaneously in the plant's activities

5 Conclusion

The innovative concepts of Consequence Based Engineering (Abrams et al. [5]) and Performance Based Earthquake Engineering (Porter [6]) are founded on the availability of reliable tools to forecast losses (human, social, economical, etc.) due to the collapse under seismic actions of civil engineering structures.

In the above contexts, deterministic analyses don't represent the best answer, since they aren't able to take into account all the uncertainties regarding the resistance demand and system's capacity. Conversely, a probabilistic approach allows for a rational choice and a consistent risk mitigation management.

In this paper, the main aspects related to the development of a risk assessment procedure taking into account site features (hazard) and structural performance (vulnerability) have been reported. The procedure shown is well suitable for both the retrofitting of existing facilities and the design of new ones. The case-study shown in this paper is a worthwhile example of a multi-hazard based seismic risk analysis of an oil-gas storage plant threatened by seismic ground motion and collateral hazards (earthquake-induced ground failures). The main implications of the study regard the possibility to establish acceptability or not of an industrial activity in relation to the possible negative consequences of a failure, the decision about the feasible countermeasures to be adopted to mitigate the risk, and the establishment of consistent insurance fees to cover the losses eventually resulting from a system's failure.

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