RISK ANALYSIS OF A CRITICAL FACILITY THREATENED BY SEISMIC GROUND MOTIONS AND COLLATERAL HAZARDS

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RÉSUMÉ

Les tremblements de terre sont parmi les risques naturels les plus menaçants aux activités humaines. Ceci est dû à l'éventail d'effets qu'ils produisent : des dommages directs liés à la secousse sismique aux dommages indirects provoqués par des risques collatéraux tels que les feux, la liquéfaction, la densification du sol ou les glissements de terrain. Le degré de vulnérabilité et le niveau d'exposition des éléments menacés peuvent de plus en amplifier les effets. Dans ce sens, le risque sismique induit par une usine gazo-pétrolière de stockage située près d'un port commercial important en Italie méridionale a été analysé. L'usine est située dans un des secteurs avec les niveaux les plus élevés de risque séismique en Italie, frappé dans le passé par des tremblements de terre de magnitude 7. D'ailleurs, l'usine est située près du rivage et le fond marin y est caractérisé par la présence d'un canyon sous-marin remplie par des sols lâches et sous-consolidés provenant de l'excavation du chenal d'entrée du port. Étant donné ces conditions, les phénomènes suivants ont été étudiés : l'amplification locale, la liquéfaction, les glissements sous-marins ainsi et les vagues d'inondation associées. Les analyses de stabilité ont considéré la structure de l'usine elle-même ainsi que son emplacement. Une analyse de vulnérabilité a fournie la réponse aux mouvements du sol sous les réservoirs en acier formant la structure, alors que des analyses dynamiques donnaient la réponse des sols à l'éventail des divers types de ruptures possibles. En joignant tous les effets possibles qui pourraient déstabiliser l'usine, une probabilité globale pour la sécurité de l'usine a été calculée. Le risque a alors été évalué considérant les effets, en termes de pertes de vie humaines, produites par l'effondrement de l'usine. Ce risque a été alors comparé à ceux dérivant d'autres activités humaines afin de fournir une base raisonnable pour l'évaluation du risque acceptable.

ABSTRACT

Earthquakes are amongst natural hazards that are most threatening to human activities. This is due to the wide range of effects, from direct damage related to the seismic shaking to indirect damage caused by collateral hazards such as fires, liquefaction, soil densification and landslides. 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 harbor 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 harbor 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 acceptability evaluation.

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 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.

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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 seismic hazard [of the site] and structural vulnerability [of the system]:

$$\text{[seismic] Risk} = \text{[seismic] Hazard} \otimes \text{Vulnerability} \qquad [1]$$

These two terms are probabilities in turn, and the dot-product is the convolution of their functions. 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 occur, that is:

$$\text{Risk} = P[\text{failure}|h]\, P[\text{Hazard} = h|t] \qquad [2]$$

and reliability or survival, in turn, is the complementary of risk. Therefore, it is possible to explore the relations between hazard and vulnerability using a single non-structural parameter, hereinafter 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 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:

$$\text{Hazard} = P[\text{PGA} > a|t] \qquad [3]$$

where a is a PGA-value expected to be exceeded in time t, the structure's lifetime. 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).

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:

$$P[\text{Failure}|\text{PGA} = a|t] \qquad [4]$$

Of course, failure is a conventional definition of a certain limit state. A limit state is, in turn, a failure mode and a fragility curve, describing a certain failure mode, is therefore related to one limit state or structural performance.

In structural analysis, hazard and fragility are related to two random variables called load (S) and resistance (R); due to their randomness, L and R are completely described by their probability density functions ($f_{R,S}$). 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:

$$\text{Risk} = P[G<0] = P[S>R] = \int \left[\int f_R(r)\, dr\right] f_S(s)\, ds \qquad S[0\div\infty];\ R[0\div s] \qquad [5]$$

In the above equation, the integral in ds is the hazard function and the integral in dr is the vulnerability (≡fragility) function or, respectively, the demand and capacity (McGuire, 2004).

2.2 Consequence analysis

The main consequences that an accident due to earthquakes may produce have to be estimated (Figure 1). Different kinds of losses (human, social, economical or environmental) or long-term effects as well, must be related to failure modes of the system. The potential consequences strictly depend on the context within which the system is placed. This context defines the exposure of the socio-economical environment. As an example, referring to the potential for a life loss the exposure is given by:

$$E[L|\text{Risk}] = P[L|C] \otimes P[S|L] \otimes P[T|S] \qquad [6]$$

Life-vulnerability is given by probability of a person to lose his/her life due to a consequence (C) times his/her spatial (S) and temporal (T) presence at the moment of the event.

Common measures for industrial quantitative risk analysis (QRA) include the assessment of individual and societal risk. Individual risk, defined as the probability that an average unprotected person would get killed due to an accident induced by a system failure, is thus:

$$\text{Individual Risk} = \text{Risk} \otimes E[L|\text{Risk}] \qquad [7]$$

On the other hand, the 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; it is described by a frequency – number (FN) curve, i.e. the exceedance curve of the annual probability of an event and its consequences in terms of number of deaths.

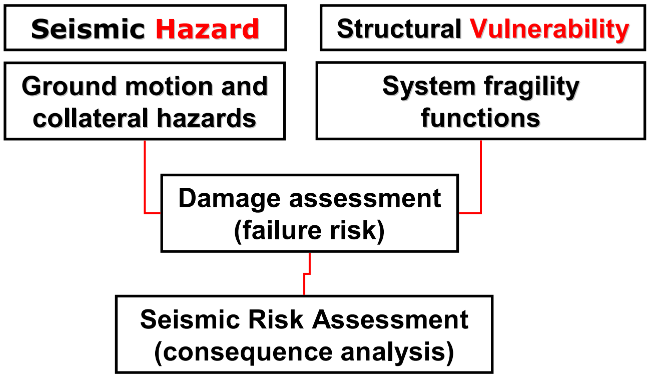

Figure 1. Flow-chart for seismic risk analysis.

3. CASE STUDY

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 2. Aerial view of the critical facility.

3.1 Demand and capacity characterization

Due to its particular location, the plant, besides strong ground motions amplified by the presence of loose soils, is threatened in case of an earthquake by ground liquefaction and the potential sliding of the adjacent submarine scarp. As a domino effect, the sliding of the submarine scarp may induce a sea wave run-up which may strike the plant area. Thus, it represents a good training case for a QRA of a system subjected to multiple hazards.

The facility is an Oil-Gas storage plant placed near a commercial harbor. A well documented regional seismicity record shows, in the last millennium, an intense activity with earthquakes as large as 7 in magnitude. A formal PSHA was carried out taking into account all the most recent seismotectonic knowledge of the region (Figure 2).

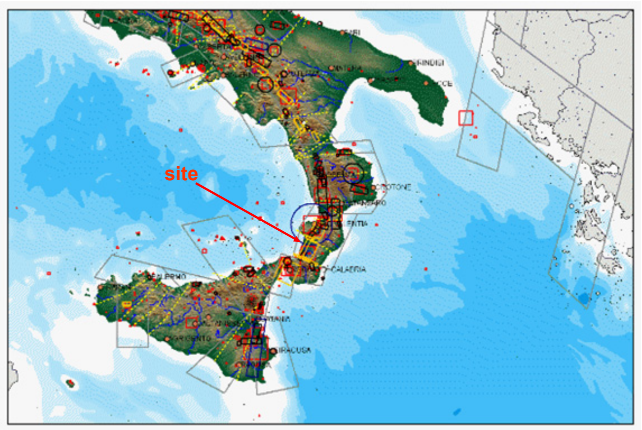

Figure 3. Seismotectonic model adopted for the PSHA.

Active faults were identified and diffuse seismicity was modeled as seismogenic source zones. Hazard curves were drawn for reference stiff-soil conditions, and several seismic IMs including PGA and spectral accelerations. (Figure 4).

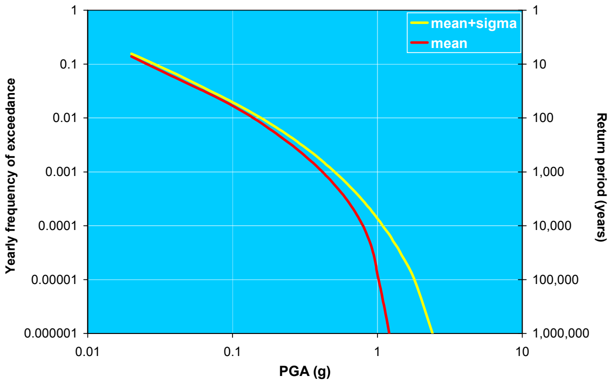

Figure 4. Seismic hazard curves for PGA.

Then, hazard deaggregation (Kramer, 1996) allowed determining the controlling earthquakes for different return periods and seismic IMs (Figure 5). Selected return periods were chosen according to the international practice in Performance-Based Earthquake Engineering (PBEE, Porter 2003) design, identifying in which different exceedance probabilities within the structure's lifetime are assigned in order to identify design earthquakes defined as frequent, occasional and rare (Table 1, for uniform hazard spectra).

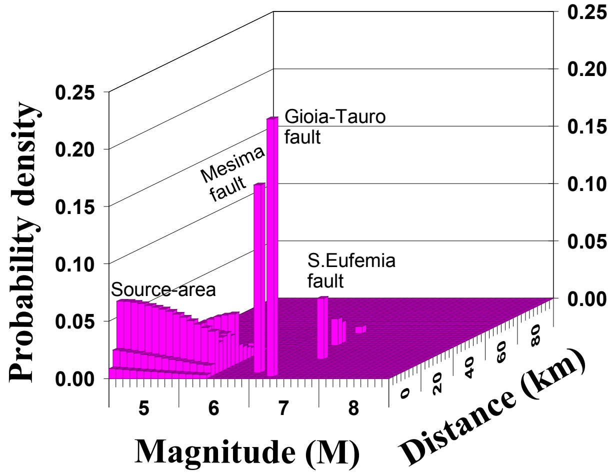

Figure 5. Seismic hazard deaggregation for PGA at long return period.

Table 1. Reference earthquakes extracted from the hazard deaggregation analysis for the studied site. Intensity is given in the MSK-intensity scale and distance in km.

Earthquake*	Magnitude	Distance	Intensity
Frequent	5.5	15	VI-VII
Occasional	6.1	15	VIII
Rare	7.0	10	X

*corresponding to return period of nearly 50, 100 and 500 years.

They were used to perform a LSRA and geotechnical stability analyses as well, on the basis field investigations carried out both onshore and offshore (Figure 6).

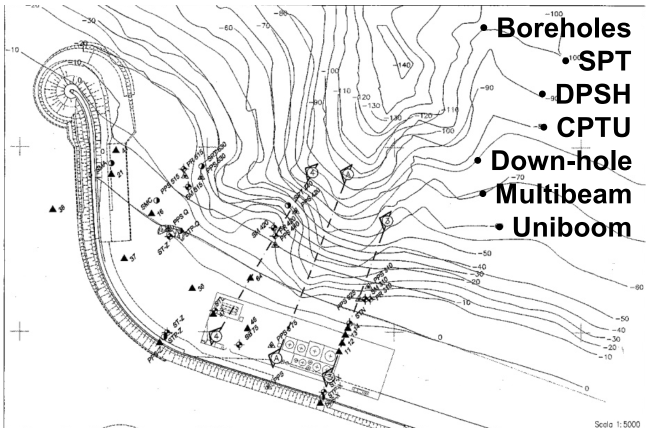

Figure 6. Plan of onshore and offshore investigations.

Dynamic analyses were carried out to highlight the zones of possible liquefaction; they were investigated in depth in order to compute failure probabilities due to liquefaction as well as flow failures (Hungr *et al.*, 2001; Figures 7 and 8).

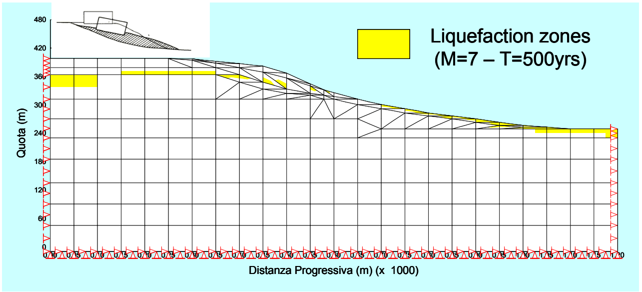

Figure 7. Dynamic analysis for liquefaction and flow-failure.

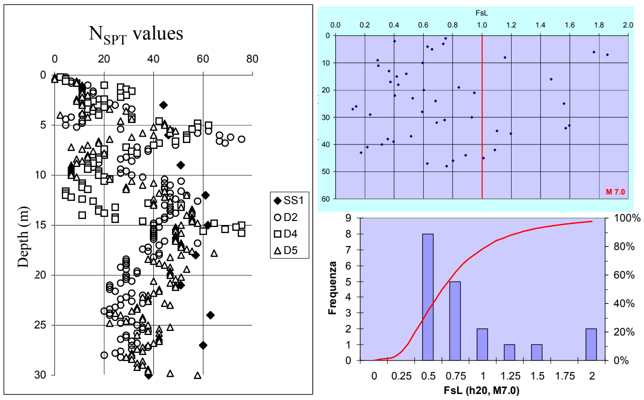

Figure 8. NSPT values carried out onshore and offshore (left). Right top: computed safety factors against liquefaction with depth, FsL=$f\{\tau_r(N_{SPT})/\tau_e(A_{max},\sigma_o)\}$. Right bottom: probability of liquefaction to a given depth.

Offshore geophysical surveys allowed determining the submarine scarp's profile and bathymetry, for the subsequent slope stability analyses and sea wave run-up modeling. (Figures 9 and 10).

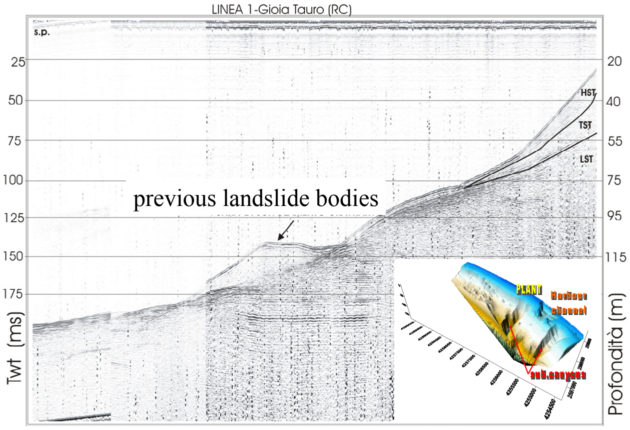

Figure 9. Uniboom investigations pointed out the presence of old submarine landslide bodies.

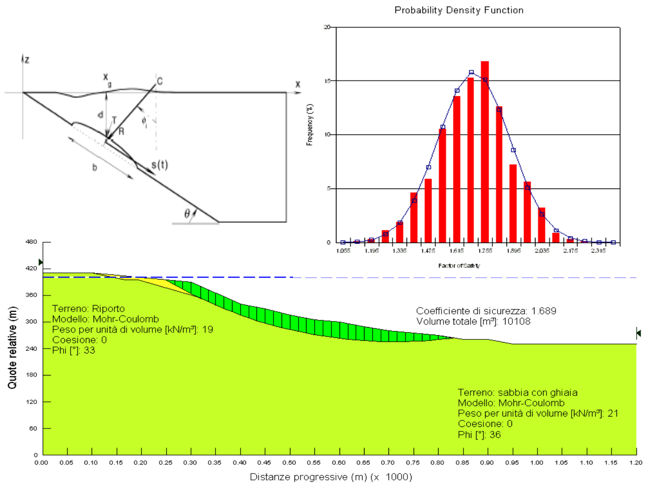

Figure 10. Stability analyses of the submarine scarp carried out for computing the probability distribution of the safety factors (Picarelli *et al.*, 2005) and for modeling the sea wave run-up due to a rapid flow slides.

Vulnerability of steel tanks was determined according to O'Rourke and So (2000). Two limit states were analyzed, corresponding to a moderate content loss (Serviceability Limit State, SLS) and an extensive content loss (Ultimate Limit State, ULS), the latter representing the condition for the consequence analysis described hereafter.

The fragility curves for SLS and ULS are shown in Figure 11 a function of PGA:

$$P(^{*}LS|PGA) = \Phi\ [1/\sigma \ \ln(PGA/\mu)] \qquad [8]$$

Where Φ is the cumulative normal standard distribution, μ and σ are mean and dispersion values of a limit state to be reached or exceeded. Figures 4 (as regard the GM-event) and 11 represent the system's capacity and demand, respectively.

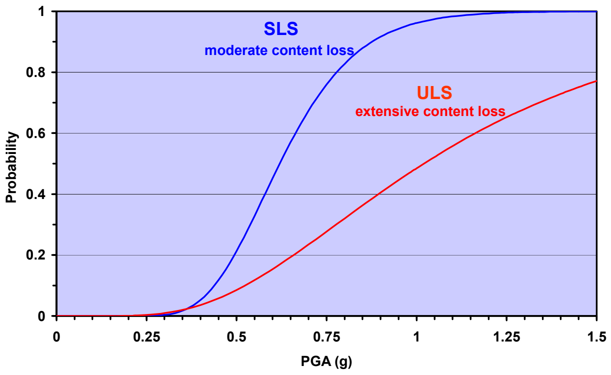

Figure 11. Fragility curves of the steel tanks for serviceability (SLS) and ultimate (ULS) limit states.

As a matter of fact, risk resulting in a limit state to be reached or exceeded, that is, failure probabilities of the steel tanks due to the occurrence of one accident event, is shown in Table 2.

Table 2. Results of risk (failure) analysis. Values refer to the application of equation [5] for each kind of event.

Ground motion		**Liquefaction**	**Landslide***
SLS	ULS	ULS**	ULS**
$9.52 \cdot 10^{-3}$	$4.14 \cdot 10^{-3}$	$3.46 \cdot 10^{-3}$	$0.04 \cdot 10^{-3}$

*including sea wave run-up
**corresponding to a safety factor below unity

Risk due to GM-induced steel tanks structural failure showed to be the worst case scenario, followed by a failure due to liquefaction and, lastly, due to a submarine landslide including sea wave run-up.

3.2 Consequences due to an event accident

Catastrophic failures of the steel tanks may give rise to potential accidents listed in table 3.

Table 3. Characteristics of tested soils.

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

*vapor cloud explosions

Thus, the consequence of an accident is conditional to the spatial presence of a person within the radii shown in table3. Intrinsic life vulnerability, P[L|C], is assumed to be equal to one for the high mortality and greater than 50% for serious life-threatening injury. Spatial and temporal probabilities of a person to be involved in an accident can be inferred from figures 12 and 13.

The consequence analysis leads to the computation of the probability of an individual to loss his/her life due an accident may be triggered by the occurrence of a failure event (Table 4).

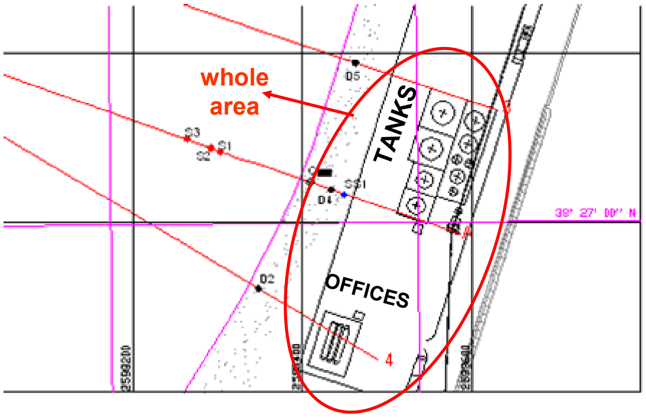

Figure 12. Map of the plant area used to compute spatial probabilities of a person to be hit by an accident. The three zones (offices, tanks and whole plant area) are referred to the people working in the facility (see figure 13).

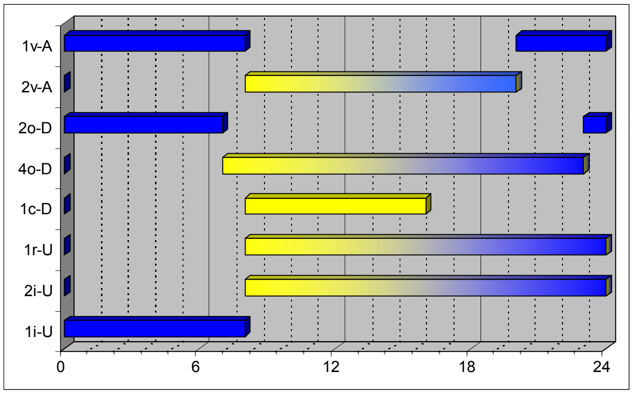

Figure 13. Time-plan of the people working in the plant. LEGEND: v, private security guard; o, worker; r, chief; I; employee. A, whole area; D, tanks' area; U, offices (see figure 12). Numbers refer to the amount of people.

Table 4. Consequence analysis results: annual probabilities of a life loss (from the application of equation [7]).

	Offices	Tanks	Whole area
Workers	3	5	2
Exposure* (%)	15.4	20.8	21.8
Ground motion	$6.4\cdot10^{-3}$	$8.6\cdot10^{-3}$	$9.0\cdot10^{-3}$
Liquefaction	$5.4\cdot10^{-3}$	$7.3\cdot10^{-3}$	$7.6\cdot10^{-3}$
Landslide	$5.4\cdot10^{-3}$	$6.4\cdot10^{-3}$	$6.4\cdot10^{-3}$
Total Risk	$0.06\cdot10^{-3}$	$0.08\cdot10^{-3}$	$0.09\cdot10^{-3}$

*exposure refers to equation [6].

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 event (GM, liquefaction or landslide induced). Assuming independence between events, the probability of an individual to loss his/her life is given by the total risk equation:

$$\text{Total Risk} = 1 - \prod_i (1 - P_e)_i \qquad [9]$$

Where Pe,i is the annual probability of a life loss due to the accident triggered by the i-th event.

May a risk (consequence) be acceptable or not is usually a social and political choice. Nevertheless, a comparison with other industrial risk activities may facilitate this choice. In figure 14 the societal risk of several industrial activities are shown (modified from Whitman, 1984), along with the risk computed for the studied facility.

Though the computed risk results may be considered acceptable, if compared with other categories of risks, countermeasures to mitigate the risk are nevertheless appropriate. In the case-study shown, the countermeasures proposed to withstand failure events were:

- Liquefaction: vertical drains to reduce pore-water overpressures;
- Landslide and sea wave run-up: protection wall and piled diaphragm wall against shear stresses;
- GM-effects (tanks' stability): fill-up limitation against sloshing and spillage.

The sizing of the remedial works must then follow a cost/benefit analysis, in order to design them to effectively reduce the risk without increasing too much the mitigation costs (Figure 15).

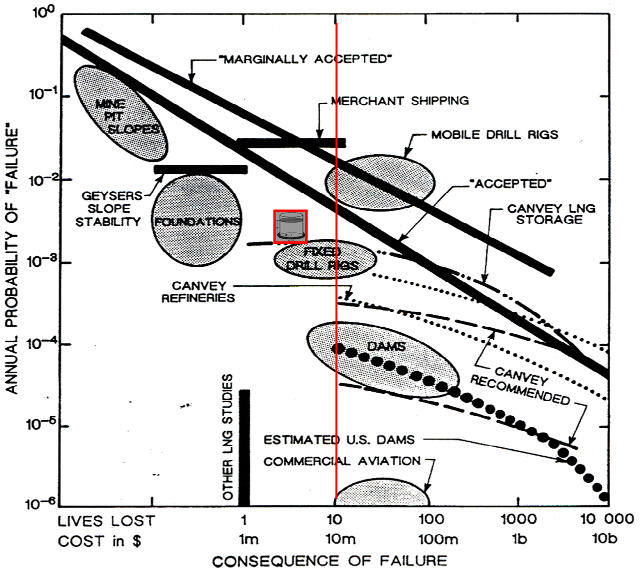

Figure 14. F-N curve for various industrial risk activities. The societal risk of the studied plant is shown in the middle of the figure with the symbol of a cylindrical tank. The vertical red solid line marks the limit of people that could in theory be involved simultaneously in the plant's activities.

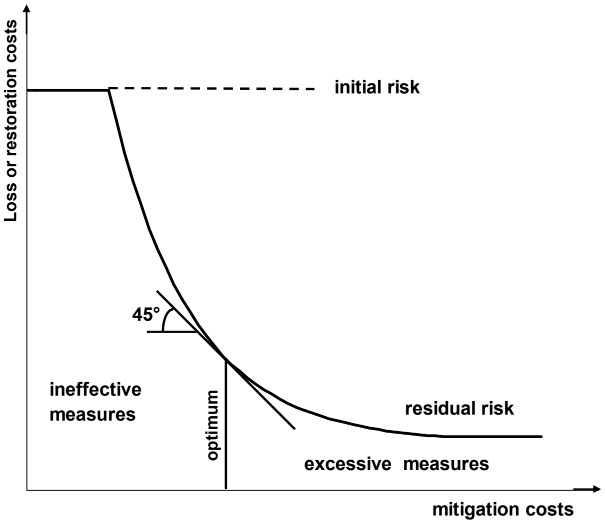

Figure 15. Cost/benefit scheme for the design of optimal mitigation measures.

4. CONCLUSIONS

Modern approach to safety and risk management of critical industrial facilities requires taking into account accidents due to structural failures induced by earthquakes. This isn't an easy task and needs the integration and interaction of different skills. Furthermore, the innovative concepts of Consequence Based Engineering (Abrams *et al.*, 2002) and Performance Based Earthquake Engineering 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 existing facilities; it relates to steel tanks for oil-gas storage plants threatened by seismic ground motions and collateral hazards (earthquake-induced ground failures).

5. ACKNOWLEDGEMENTS

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