Vulnerability Study Of Steel Storage Tanks In A Large Industrial Area Of Sicily

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SUMMARY:
The vulnerability study of steel storage tanks of a large industrial estate in the gulf of Siracusa is presented. Due to the dangerous stored material, tanks become critical structures in an area characterized by high seismic risk and near to the sea. Starting from remote sensing analysis data, a two step assessment procedure is adopted. Firstly, mechanics-based fragility curves are computed through a simplified model described with random variables. Afterwards, the structures are analysed using a simplified methodology considering the reduced available data and the high number of tanks to be analysed. A simulated design procedure is implemented to derive the unavailable structural data. Then, the seismic structural performance of the storage tanks is computed with simplified analyses, validated with detailed FE analyses. Through a real-world example, this work describes the advantages of employing few data and simplified methodologies in large-scale vulnerability evaluation of a high seismic risk industrial area.

Keywords: Steel storage tanks, fragility curves

1. INTRODUCTION

The vulnerability study described in this paper belongs to the seismic risk evaluation of the large oil processing estate next to the gulf of Siracusa, Sicily, Italy. The involved municipalities are Priolo Gargallo, Melilli, Augusta and Siracusa. In this industrial area, four structural typologies are identified and studied: storage tanks, chimneys, pipelines and wharves. This paper focuses on the cylindrical steel storage tanks. Since the industrial risk analysis is related to the amount of dangerous material stored in an area, storage tanks become critical structural typologies to be carefully studied in this industrial estate characterized by high seismic risk and near to the sea.

Focusing on the aim of the study, the authors realized that some of the required data could be obtained from satellite images through suitable processing. Before starting the analysis, software tools were already available in-house, capable of extracting from satellite images pieces of information relevant to the intended study. The first step of the image processing was the identification of tanks, characterized by a round footprint. Then, the third geometric dimension was determined since the height is a fundamental information for a vulnerability study. Therefore, the results of the remote sensing analysis were used to define the volume of the storage tanks, as described in details in Borzi et al. (2011). As shown, for example, in Fig. 2.1, these data were integrated in the GIS (Geographic Information System) platform which represents a valuable support for handling large-scale vulnerability studies, as explained in the following sections.

2. VULNERABILITY STUDY

A two step assessment procedure with increasing level of details is implemented. Two damage mechanisms are taken into account for assessing the seismic fragility of the steel storage tanks:

- The damage of the tank wall as a consequence of elastic or elastic-plastic buckling mechanism, known in the technical literature as diamond or elephant-foot buckling, respectively;
- The overturning of the storage tank.
The aforementioned mechanisms are the ones that more frequently were observed in steel storage tanks after seismic events (Eidinger 2001).

Figure 2.1. Three-dimensional view of the storage tanks located in a part of the larger industrial area of Priolo Gargallo, object of the vulnerability study

2.1. First step – Probabilistic definition of seismic fragility

In the first step of the assessment, the fragility is described as the probability of reaching or exceeding a certain damage limit state condition for a given severity of the ground motion. In order to represent this probability, fragility curves are computed by means of (i) the probabilistic processing of the damage observed in the past seismic events, (ii) the in-depth study of the fragility curves already published in the technical literature, (iii) a simplified model of the structures described with random variables instead of deterministic quantities which univocally define the geometric dimensions and the mechanical properties of the materials. The fragility curves are derived selecting the Peak Ground Acceleration (PGA) as representative parameter of the ground motion severity. The curves produced for this study are mechanics-based.

The steel storage tanks are classified according to the ratio D/H, where D and H stand for the diameter and the height of the tank, respectively. According to the damage observed during past earthquakes hitting industrial plants (Eidinger 2001), this ratio has the highest influence on the seismic performance of the storage tanks. Four classes are taken into account:
- Class 1: $0.7 \leq D/H \leq 1.0$;
- Class 2: $1.0 < D/H \leq 1.5$;
- Class 3: $1.5 < D/H \leq 2.0$;
- Class 4: $D/H > 2.0$.

Within each class, the random variables chosen for the generation of random populations of tanks to be analyzed are:
-The tank diameter scattered according to a normal distribution whose mean and variance are computed on the basis of the available data of some tanks of the industrial area whose D/H ratio belongs to the same class;
-The D/H ratio with a constant distribution within the D/H range identifying the class;

-The steel mechanical properties, randomly selected within three possible categories following the Italian regulations (Decreto Ministeriale 1996) in relation to the assumed construction age of the tanks;
-The additional shell thickness for taking into account the corrosion, assuming a minimum value of 3 mm plus a percentage of the shell thickness without corrosion effects varying from 0% to 100% with constant distribution;
-The shear modulus G and the shear wave velocity V_s of the soil, both assumed normally distributed with mean and variance derived from the distributions of G and V_s parameters, respectively, evaluated from the mechanical properties of the soil of the industrial estate;
-The density of the stored liquid, with a constant distribution varying between 0.5 and 1.0 times the water density. This variability range is assumed considering the available information on the density of the liquids stored in the industrial area.

The shell thickness is not a real random variable since the code developed for evaluating seismic fragility curves is able to perform, for each generation of the random variables, the design of the tank wall as it will be explained in the Section 2.2.1.

The seismic demand of the steel storage tanks is computed according the Italian seismic code (NTC08 2008) and taking into account the uncertainty of the demand (e.g. choosing, as random variables, parameters that define the acceleration spectrum like the corner periods and the soil dynamic amplification factor). The PGA values used in the definition of the fragility curves have been employed to anchor the aforementioned spectral shape.

For each random variable, both describing the tank population and the uncertainty of the seismic input, a Monte Carlo simulation is carried out and, in the case of normal distributions, the Latin Hypercube sampling (Helton and Davis 2003) has been taken into account for a better evaluation of the distribution tails.

Finally, comparing the structural capacity with the demand for each tank of the sample, the developed code allows the calculation of the points of the fragility curve related to the tank wall buckling or the tank overturning. Anchored and unanchored steel storage tanks are considered. In addition, the fragility curves are computed considering or neglecting the soil-structure interaction since two different situations are studied: storage tanks on soil whose characteristics have been generated taking into account the site conditions of the area and storage tanks on rock. However, the difference between the obtained curves for the two considered site conditions is reduced due to the rigid soil conditions characterizing the area with an average V_s value of 600 m/s^2.

The derived fragility curves have been validated against the fragility curves published in the technical literature, as the ones suggested by HAZUS (FEMA 1999) and plotted in Fig. 2.2. The HAZUS curves refer to the moderate damage limit state condition and severe limit state condition, herein considered as corresponding to the activation of the tank wall buckling. According to HAZUS, the moderate damage and the severe damage limit states correspond to the following cases: the spillage of the tank content does not or does happen. The comparison in Fig. 2.2 shows that there is a good agreement between the fragility curves derived in this study and the HAZUS curves. However, it has to be pointed out that, in this study, there is no distinction between the condition of buckling without and with the spillage of tank content. This choice finds its justification since the limitation of the wall compression stresses keeps under control also the tension stress reduction in the base plate-wall joint, the collapse of which is always characterized by spillage of the tank content. Therefore, controlling the buckling implicitly preserves from dangerous spillage of the liquid stored in the tank.

According to the trend of the curves in Fig. 2.2, a further validation of the obtained results is that the fragility of the unanchored tanks increases when the ratio D/H decreases. This is in line with the higher level of damage observed on slender steel storage tanks during the past earthquakes.

The mechanics-based method implemented for the derivation of the fragility curves allows the computation of the curves for moderate-severe damage, since no data were available for identifying

other limit state conditions. Furthermore, for the target of this study, the damage limit condition beyond the possibility of spillage is not acceptable. Therefore, the only limit state condition taken into account for the computation of the conditional and unconditional probabilities of damage is the tank wall buckling. An additional check is implemented for slender tanks verifying that the overturning does not happen before the wall buckling.

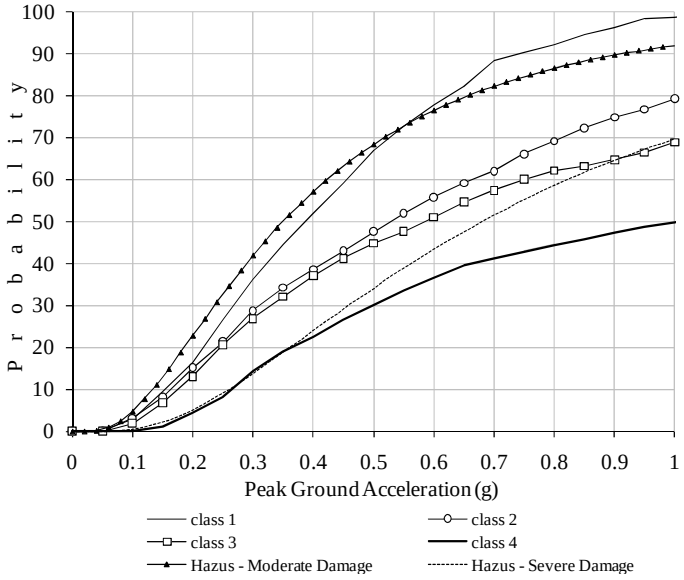

Figure 2.2. Comparison between the fragility curves computed in this study and the ones suggested by HAZUS (FEMA 1999) for the damage limit condition corresponding to tank wall buckling. Unanchored tanks are considered

2.2. Second step – Deterministic definition of seismic fragility

In the second step of the assessment, steel storage tanks are analyzed considering a simplified model due to the reduced amount of available data and the high number of structures to be studied. As already mentioned, the footprint size and the height of the tanks have been derived from remote sensing analysis. The simplified analysis methodology implemented in this study is characterized by the following phases: (i) definition of the wall thickness by means of simulated design procedure; (ii) definition of the tank seismic response according to a simplified methodology proposed by Malhotra (1997) and included in the Eurocode8 (2003); (iii) evaluation of the effects related to the vertical seismic component and to the soil-structure interaction that, in the Malhotra's methodology, were neglected; (iv) verification of the tank, as explained in the following paragraphs.

2.2.1. Simulated design procedure

Through remote sensing, the volume data are known. The other structural data required for the seismic performance evaluation of the structure are derived implementing a simulated design procedure. Starting from the available data on the volumes, thicknesses are assigned to the structures with reference to the design codes typically adopted for the storage tanks, as the API Standard 650 (1998). The weight of the tank is computed starting from the minimum thicknesses prescribed in the API 650 for the base plate, roof and wall. This weight is then increased of the certain percentage (30%) for taking into account the further thickness added for the corrosion, the presence of pipes and stairs connected to the tank and so on. However, the right evaluation of the tank self-weight is not a critical point of the analysis since it is much more important the right evaluation of the weight of the liquid stored in the tank.

The tank design starts from the minimum thicknesses prescribed in API 650, and then, if the steel properties are unknown, the simulated design is performed considering three possible steel mechanical properties according to the 1996 Italian design regulation (Decreto Ministeriale 1996) – Fe 360, Fe

430 and Fe 510.

The construction year of the tank is unknown. For this reason, it is not possible to define whether the structures were designed before or after the year of seismic classification of the area. Therefore, the simulated design is done considering or neglecting the seismic load. If the design year will be available in the future, only the design with the loads corresponding to the correct regulation will be taken into account. However, this and other limitations of the simulated design should have a minor influence of the results since steel storage tanks are standardized structures whose design rules have been slightly changed during the years.

In the case of non seismically designed tanks, the "1 foot method" and the "variable design method" have been followed since they are the two design procedures proposed in API 650 for tanks with a diameter less and greater than 60 m, respectively. When the seismic loads are considered, these are computed with reference to the 1996 Italian design regulation (Decreto Ministeriale 1996) and the system liquid-tank is approximated with a two degree-of-freedom system representing the impulsive and the convective modes of vibration. The API 650 suggests the formula for the period of vibration, mass and position of the centre of mass for the two above mentioned modes of vibration. Then, the overturning moment used for the verification of the thickness of the bottom course of the tank wall is computed through the combination of the two modal contributions by taking their root-mean-square value, as recommended in the API 650. Combining the stress due to the computed overturning moment with the stresses due to wall and roof self-weights and a percentage (10%) of the snow load, the compressive stress for which the tank has to be verified is derived and compared with the compressive stress allowable for the tank wall shell.

2.2.2. Definition of the seismic response

The Malhotra's procedure (Malhotra 1997, Eurocode8 2003) is based on the following assumptions: (i) the tank hydrodynamic effects take into account only the first impulsive mode and the first convective mode; (ii) the given expression for computing the first natural period related to the impulsive mode is valid for rigid and flexible tanks; (iii) the impulsive and convective contributions are combined by taking the numerical-sum of the maximum values. Following this method, the seismic demand of each tank is computed deriving the total base shear and the overturning moment above and below the base plate, respectively.

2.2.3. Contributions of the vertical earthquake component and the soil-structure interaction

The actions corresponding to the vertical earthquake excitation are summed to the ones related to the horizontal seismic forces. In a response spectrum analysis, which is the simplified analysis performed in this verification methodology, the natural period related to the vertical motion of the tank has to be derived according to the API 650 recommendations.

The interaction problem between tank-fluid and soil system is taken into account following procedure originally proposed by Priestley et al. (1986) and suggested in Eurocode8 (2003). Modified natural periods are given for the impulsive effect (horizontal and vertical) for flexible tanks since only steel tanks area placed in the area. Finally, modified damping values of the tank-foundation system are suggested. In this simplified assessment procedure, the reference damping values are the ones suggested in Priestley et al. (1986) for rigid and flexible anchored tanks and flexible unanchored tanks and for soft and rigid soil conditions. Considering that the anchorage of the tanks is unknown, the mean values of damping ratios associated to anchored and unanchored conditions are assumed.

2.2.4. Storage tank verification

The damage mechanisms adopted to assess the behaviour in deterministic terms are the same adopted to generate the fragility curves. The activation of both the wall buckling and the tank overturning is checked. For the overturning, the tank is assumed to behave as a rigid body rotating around a corner. For the wall buckling, the computed maximum vertical compressive shell stress is compared with the critical stresses related to the elastic and elastic-plastic buckling. In the buckling assessment, the increase of compression due to unanchored tank uplift is taken into account according to New

Zealander regulations (Priestley et al. 1986) that follow the method originally proposed by Clough (1977).

Adopting the described simplified model of the storage tank, a response spectrum analysis is undertaken for all the considered ground shaking levels, which correspond to earthquakes with return periods of 30, 50, 475 and 1000 years, and for the deterministic seismic event hitting the area in 1963. Assuming the aforementioned ground shaking levels, a safety coefficient of the tanks has been computed. Taking into account all the assumptions of the simulated design phase (e.g. steel mechanical characteristics, density of the liquid stored in the tank), a minimum and maximum safety coefficient has been calculated. However, the developed simplified model is such that the input data can be updated. Therefore, once the data governing the tank structural performance will be available, the prediction of the vulnerability will automatically improve.

3. VALIDATION OF THE SIMPLIFIED MODEL FOR THE TANK ANALYSIS

The simplified methodology previously described is validated considering three storage tanks with three different D/H ratios. These tanks are unanchored. The geometric and structural characteristics of the tanks are summarized in Table 3.1. According to their D/H ratio, a prediction of the expected damage could be done considering the collapse mechanisms observed in the past seismic events. For the P8803 tank, the elastic-plastic buckling could occur before the elastic buckling; neither uplift nor overturning of the tank could happen. For the P5151 tank, the elastic-plastic buckling could occur before the elastic buckling; the uplift of the tank is expected. Finally, for the T729 tank, the elastic buckling could occur before than the elastic-plastic buckling; due to the slenderness of the tank, it could be subjected to overturning. Table 3.2 presents the comparison between the real thickness of the shell at the base-plate of the tank wall and the one derived from the simulated design phase, showing a good agreement of the results. For tanks P5151 and T729 the wall thickness seems to be underestimated of a couple of millimetres. This is due to the fact that in structural drawings the corrosion thickness is included, whereas it is not in the simulated design which only gives the "structural" thickness of the wall.

Table 3.1. Main Characteristics Of The Analysed Steel Storage Tanks

Tank name	P8803	P5151	T729
Diameter (m)	66.44	24.4	8.24
Filling level (m)	19.50	18.3	14.46
Steel type	Fe 510	Fe 360	Fe 360
Wall thickness (mm)*	9.53 ÷ 31.45	7 ÷ 18	6 ÷ 8
Specified density**	0.98	1.0	0.86
D/H	3.41	1.33	0.57

* Range of values; ** given with respect to the water density

Table 3.2. Thickness Of The Wall Bottom Course: Comparison

Tank name	P8803	P5151	T729
Real thickness (mm)	31.45	18	8
Designed* thickness (mm)	31.50	16	5

* the additional thickness for corrosion is not accounted for

Then, the three tanks are analyzed with LS-DYNA code (V. 971), through detailed finite element (FE) models, and selecting the explicit solver. A dynamic analysis is performed for each storage tank. The spectrum-compatible acceleration time-history plotted in Fig. 3.1 is taken into account, starting from the spectrum computed according to the NTC08 (2008) for the tank site.

The verification of the buckling mechanism is performed for the three tanks and summarized in Table 3.3. Comparing the critical stresses ($\sigma_{cr\_elastic}$ and $\sigma_{cr\_elastic\text{-}pl}$), it can stated that, for the P8803 and P5151 tanks, the elastic-plastic buckling is firstly activated, and this is in good agreement with the damages observed in the past seismic events for tanks characterized by D/H ratios close to the ones of P8803

and P5151. The T729 tank is affected by diamond buckling. According to the past damage observations, its D/H value represents a limit value for the activation of the elastic buckling before then the elastic-plastic one.

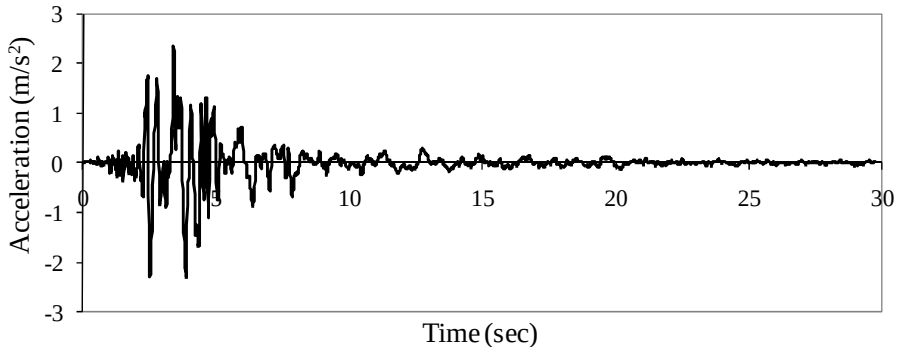

Figure 3.1. Spectrum-compatible acceleration time-history applied in the dynamic analyses of the tanks

Table 3.3. Buckling Stresses And Comparison Of The Results Obtained From Simplified Analysis And Advanced FE Analyses

Tank name	P8803	P5151	T729
Buckling $\sigma_{cr\_elastic}$ (MPa)	111	127	123
Buckling $\sigma_{cr\_elastic\text{-}pl}$ (MPa)	72	42	131
Simplified analysis σ_{shell_wall} (MPa)	20	100	-
Detailed FE analysis σ_{shell_wall} (MPa)	25	64	-

If the simplified analysis is compared with the detailed FE analysis, the P8803 tank is not affected by uplift in both cases. There is the uplift of the P5151 tank even if the vertical displacement of the FE analysis is less than the one derived from the Clough's model implemented in the simplified analysis. This is a limit of the equivalent static procedure like the one suggested by Clough which tends to be very conservative. An improvement of results in the case of tank uplift could be achieved introducing a correction coefficient which could be set by performing many comparisons between simplified and proper FE numerical analyses. The definition of such correction factor could be the object of further studies.

Finally, the T729 tank is affected by rocking as a result of the simplified analysis (rocking safety coefficient equal to 99%). The results of the FE analysis, plotted in Fig. 3.2 - 3.3 - 3.4, show a motion very close to the rocking since only a small portion of the base-plated results to be in contact with the foundation.

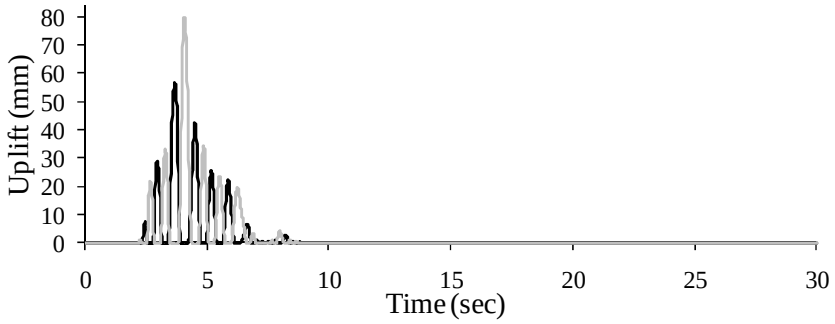

Figure 3.2. Uplift of the T29 tank considering two points diametrically opposed of the structure perimeter

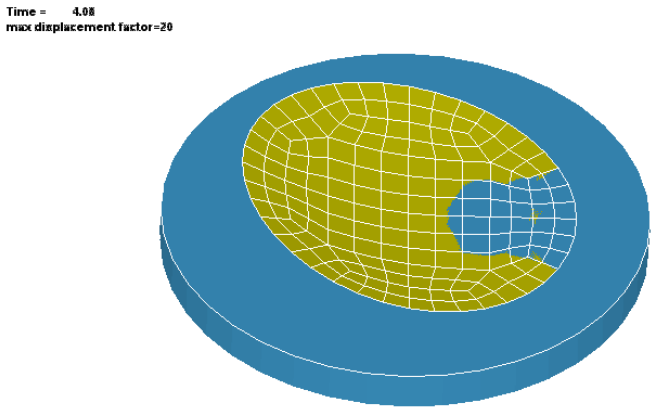

Figure 3.3. Deformation of the T29 tank base-plate for t = 4 sec corresponding to the maximum uplift

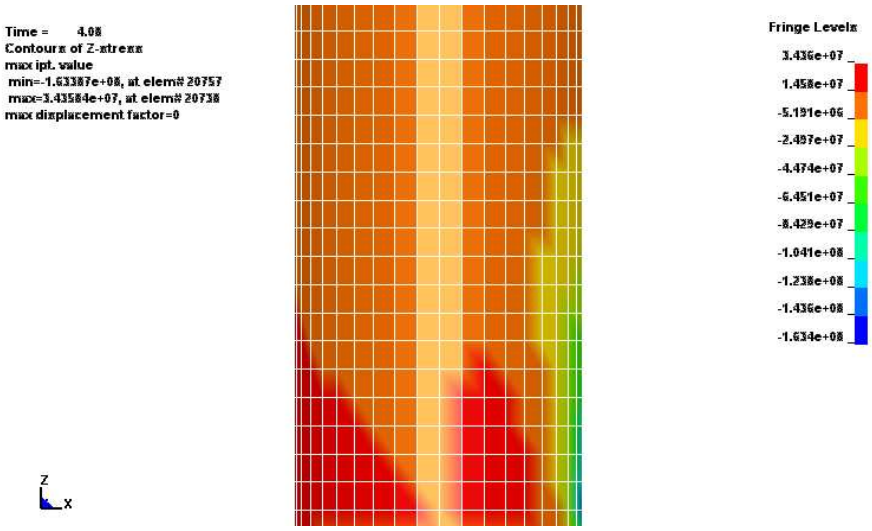

Figure 3.4. Contour plot of the vertical stresses (MPa) for t = 4 sec corresponding to the maximum uplift

4. DEVELOPED GIS PLATFORM

Remotely sensed data, procedures for vulnerability evaluation and their results have been integrated in a GIS platform, which is a powerful tool for large scale vulnerability assessment in which the data have a meaning only if geographically located. In the seismic risk assessment, the structural fragility is integrated with the expected severity of the ground shaking. The latter is a function of the hazard at the site and of local amplification effect related to soil stratigraphy and morphology. The possibility of georeferencing the fragility and the ground shaking data considerably simplifies the integration operation and allows to visualize the results of the seismic risk assessment through a valuable graphical support. Figure 4.1 is an example of the results that can be easily obtained from the developed GIS platform related to the Priolo Gargallo industrial estate. With the GIS platform, it is possible to read or update the geometric and structural data of the tanks leading to a powerful and flexible tool.

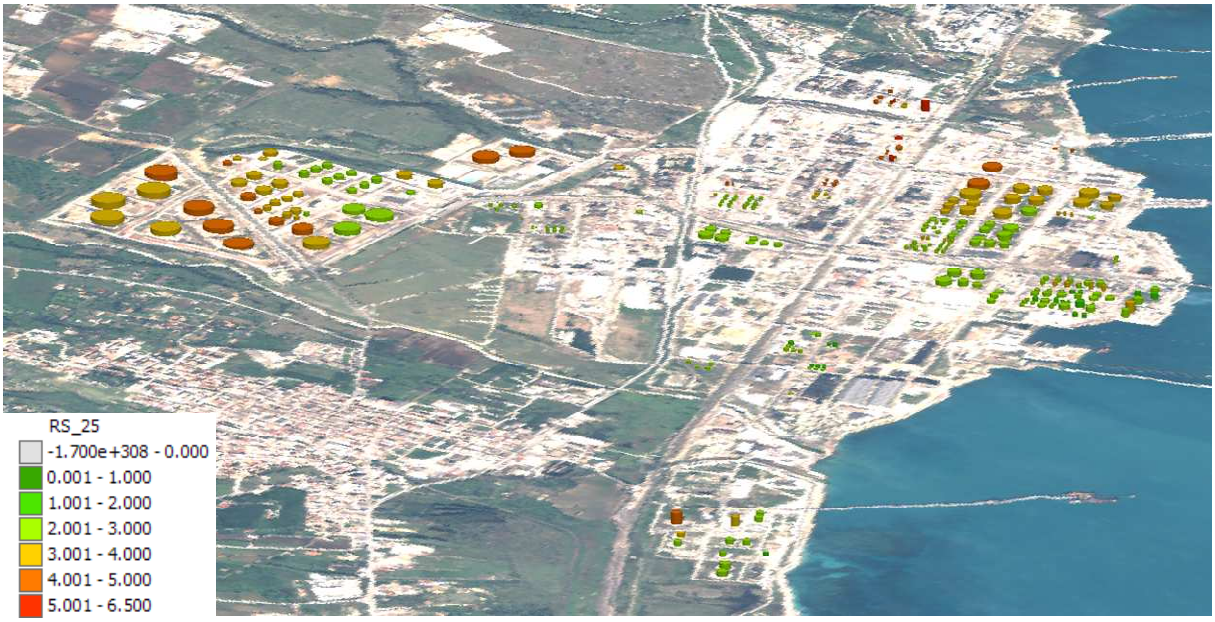

Figure 4.1. Example of seismic risk map obtained for some of the tanks of the Priolo Gargallo area considering a time window of 25 years

5. CONCLUSION

Through a real-world case study, this work has presented the advantages of employing simplified methodologies and reduced amount of data in large-scale evaluation of vulnerability of an industrial estate in a high seismic risk area. The validation of the implemented simplified methodology leads to satisfactory results that could be strongly improved when additional input data will be available. Delivery of results in GIS-compatible format is a key factor in speeding up and making more efficient the entire analysis process.

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