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Vulnerability of Industrial Components to Soil Liquefaction

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Dynamic liquefaction of saturate loose sand deposit is a common geotechnical failure effect caused by an earthquake, which can lead to structural damage of buildings, lifelines and industrial components in general. Several damage cases have been observed in past events and have been documented in the technical literature and post-earthquake reconnaissance reports. Failure and malfunctioning of pipelines, tanks and wastewater treatment plants, induced by differential vertical settlements, horizontal lateral spread and uplift of underground structures, are described. All these permanent displacements could be directly related to co-seismic liquefaction of the foundation soil. Moreover, this failure mechanism is strongly site dependent and the abovementioned effects frequently occurred in coastal and fluvial plane areas, where industrial plants are often situated. The paper studies and compares the behaviour of some important industrial components during the liquefaction event. Empirical fragilities and threshold values were evaluated on the basis of the significant seismic parameter, accounting for the possible hazardous effects of the release of toxic and flammable fluids. These tools could be assessed by means of a comparison with similar ones proposed by current building codes and implemented in existing software for the risk assessment of industrial plants and lifeline networks.

1. Introduction

The seismic response of the industrial structures and components to natural catastrophic events is a crucial issue for the Quantitative Risk Assessment (QRA) of Industrial Plants. Among the NaTech (Natural Events Triggering Technological Accident) events, the effects of earthquakes on industrial equipment were largely studied in the last decade (Campedel et al., 2008; Krausmann et al., 2011). However, the complete description of the seismic phenomenon is not easy, especially when simplified tools, as fragility curves or threshold values, were used to describe the vulnerability of the structural components. In particular, no difference was generally made in terms of soil behaviour during the seismic action. Therefore, the geotechnical effects could be divided in: a) strong ground shaking (SGS) related to the transient deformations of soil under the seismic wave passage; b) ground failure (GF) which represents the co-seismic soil failure phenomena, as liquefaction, seismic landslides and fault movements. These latter have peculiar features (generally are site dependent) and should be treated separately in the risk evaluation. An effort was made by Lanzano et al. (2014a) for buried pipelines, for which the reference index for the seismic intensity is different between the transient and permanent deformations of the surrounding soil.

In this paper, the attention is focused on the liquefaction phenomenon. First, the main features of this failure phenomenon is summarized and some cases of structural damage, also to industrial components, induced by the liquefaction permanent deformation, are shown. Then, some significant tools for risk analyses are stated and adapted to describe the structural vulnerability to liquefaction. Finally, these tools are compared and discussed for future developments.

2. Seismic soil liquefaction

Seismic liquefaction is a particular soil failure phenomenon, associated to the rise of pore water pressure in loose saturated soils, mostly formed by medium-fine sand (Kramer, 1996). During liquefaction the cyclic

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loadings induced by the earthquakes cause shear strength reduction and the development of soil plastic deformations.
In view of the structural response assessment, the most relevant effect of the liquefaction occurrence is the development of permanent deformations in the soil. They can be divided in lateral spread, when the movement is mainly horizontal, and seismic settlement or uplift, when it is vertical. Some common empirical expressions, which correlate the permanent displacement and the seismic and geotechnical parameters, are given in Table 1. The selected intensity parameter, IM, for liquefaction is the Peak Ground Acceleration (PGA). This assumption may be valid because the moment magnitude, M_w, and the epicentral distance, R_{ep}, are commonly put in relation to PGA through the so-called Ground Motion Prediction Equations (GMPEs). Besides, when the strong ground shaking is accounted, PGA is commonly used to describe the structural fragility of the aboveground structures; while buried structures are instead better represented by the Peak Ground Velocity, PGV (Lanzano et al. 2013a).

Table 1: Empirical correlation for permanent displacement evaluation (δ =permanent ground displacement; M_w= moment magnitude; R_{ep}= epicentral distance; Y(or S)= slope inclination; PGA= peak ground acceleration; T_{15}= thickness of liquefiable soil layer; N= SPT blowcount).

Ground Failure	Empirical Correlation	Reference
Lateral spread	$\log(\delta_h + 0.01) = -7.28 + 1.017M_w$ $- 0.278\log R_{ep} - 0.026R + 0.497\log Y$ $+ 0.454\log S + 0.558\log T_{15}$	Bardet et al., 2000
Seismic settlement	$\delta = 0.3H_1 \frac{PGA}{N} + 2$	Takada & Tanabe, 1988

3. Performance of industrial equipment

Despite the liquefaction phenomenon was frequently observed in catastrophic earthquakes of the last centuries, Kramer (1996) has explained that "its devastating effects sprang the attention of geotechnical engineers in a three-month period in 1964 when the Good Friday earthquake was followed by the Niigata earthquake (Ms=7.5) in Japan. Both earthquakes produced spectacular examples of liquefaction-induced damage, including slope failure, bridge and building foundation failures, and floatation of buried structures". More recently, many interesting damage cases were described in the post-earthquake reports, concerning also the industrial equipment. Some relevant cases were shown in Figure 1. Many cases of liquefaction, including buildings and pipelines, have been collected for the Christchurch (New Zealand) earthquake in 2011 (Bray et al., 2013). Plastic pipelines (polyethylene and polyvinylchloride) for water and gas distribution network were severely damaged in the liquefaction area; for the transmission pipelines, damage occurred in several areas because of differential settlement, as, for example, shown in Figure 1a, between the backfill and the bridge. In Figure 1b, two buried LPG tanks were damaged because of liquefaction during the Chile (2010) earthquake: the tanks buoyed above the ground surface due to excess pore pressure generation (GEER, 2010). Finally, Figure 1c shows severe damage to an industrial building very close to a liquefaction area in the recent earthquake in Emilia (Italy), in 2012 (GdL, 2012; GdL AGI, 2013).

4. Vulnerability of industrial equipment to liquefaction

Two main problems should be solved in the vulnerability analysis of industrial structure to liquefaction: a) the site susceptibility to liquefaction; b) the damage probability for the main relevant components to permanent displacement induced by liquefaction.
The first topic was generally tackled by the European Building Codes in the geotechnical section (EN 1998-5, 2004; Santucci de Magistris, 2011). Some exclusion criteria were therefore given in terms of geotechnical properties and intensity parameters (PGA and Magnitude). Among the specified criteria, the liquefaction can be neglected when the PGA at soil surface is lower than 0.15 g. Emphasis could be given to this acceleration threshold in the preliminary design and verification of the industrial equipment. However, a recent data collection and statistical study suggested that this limit should be decreased to 0.09 g (Santucci de Magistris et al. 2013).

a)

b)

c)

Figure 1: Damage to industrial components induced by liquefaction during recent earthquakes: a) steel buried pipelines in the Christchurch (NZ) earthquake in 2011 (Yamada et al. 2011); b) uplift of a LPG buried tanks during the Chile earthquake of 2010 (GEER, 2010).; c) lateral spread in an industrial district during the Emilia, Italy, earthquake in 2012 (GdL, 2012; GdL AGI, 2013).

Other key aspects in the liquefaction susceptibility assessment, in the line with Eurocode 8 provisions, are based on the types and features of soil: in a very simplified way, this phenomenon mainly occurred in loose saturated sand, generally recognized in alluvial, fluvial and coastal plains or in human-made soil deposits (artificial islands), when not sufficiently compacted (Kramer, 1996). This aspect is very important, since industrial plants are frequently located in alluvial plains or port areas.
According to the procedure reported in Salzano et al. (2003) and Fabbrocino et al. (2005), the vulnerability of industrial equipment may be usefully expressed as the probability of damage of equipment with respect to the intensity parameters (seismic fragility):

$$P(IM) = f \quad \frac{1}{\beta}\ln\frac{IM}{\mu} \tag{1}$$

where μ and β are the median value and the standard deviation respectively; f is log-normal cumulated function. These tools are generally implemented in existing software for multi-hazard risk analyses. For example, HAZUS (FEMA 2004) was developed by U.S. Authorities for loss estimation. This code already accounted for soil permanent deformation in the fragility selection, but do not distinguish among the different occurring failure phenomena. However, the permanent ground displacement induced by soil failure are mainly related to structural breaks (severe damage), as stated for the pipelines.
In the next sections, the seismic fragility curves for some classes of critical industrial components are discussed, assessing the opportunity of using these expressions for liquefaction-induced structural damage.

4.1 Pipelines

HAZUS adopted the expression of Honegger & Eguchi (1992) for ground failure deformations. The pipeline performance is then expressed in terms of repair rate, RR, which is the ratio between the numbers of repairs and a reference pipeline length; the intensity parameters is given in terms of Permanent Ground Displacement induced by seismic soil failure. Recently, however, the fragility curves have been reformulated (Lanzano et al. 2014a) on the basis of large database of seismic damages for pipeline (Lanzano et al. 2014b). The main relevant differences compared to HAZUS correlations are:

1) fragility curves were developed similarly to aboveground and punctual structures;
2) intensity parameter IM was the peak ground acceleration (PGA);
3) formulation depending on different level of performance in terms of structural damage and intensity of release of hazardous materials;
4) fragility parameters and threshold values for the intensity of natural event were obtained both for liquid and gas buried pipelines.

The fragility parameters μ and β for large and uncontrolled release of the hazardous substances from pipelines are given in Table 1: the parameters are given as ratio of g, corresponding to the value of gravity acceleration 9.81 m/s^2, as is commonly done for PGA estimation. As observed by Lanzano et al. (2013b), most of the observed damage data were related to liquefaction.

Table2: Fragility parameters for buried pipelines under seismic ground failure (Lanzano et al. 2014a).

Type	Fluid	Material	Joints	μ [g]	β [g]
Ductile	Gas	Steel, ductile iron, HDPE	Welded, flanged	0.56	0.18
Brittle	Liquid	Concrete, cast iron, PVC	Bell and spigot	0.37	0.19

4.2 Tanks

Salzano et al. (2003) early reported some tools for risk assessment of industrial atmospheric tanks. Then, Salzano et al. (2009) considered different criteria to give the fragility parameters, distinguishing among aboveground tanks for oil storage, pressurized horizontal GPL tanks and other components. The seismic response was considered accounting for all the significant causes and mechanism of damage, including liquefaction. The parameters for fragility curves are given in Table 3 for large, rapid release of content.

Table 3: Fragility parameters for tank components (after Salzano et al. 2009).

Type	Fill level	μ [g]	β [g]
Anchored	Near full	1.25	0.65
Unanchored	Near full	0.68	0.75
Pressurized horizontal		4.91	0.84

In HAZUS, the fragility curves for ground failure were defined only for buried tanks: in particular, the functions for atmospheric concrete or steel storage tanks are fully implemented into the software. These fragilities were expressed in function of the permanent ground deformation, δ, which can be evaluated, in the case of liquefaction, according to the empirical formulas of Table 1. The parameters of the fragility functions, in the case of complete damage/collapse, are given in Table 4. Quite clearly, the intensity of release of hazardous materials from the damages structure should be then considered for environmental concerns. This issue is certainly of relevant and needs further development.

Table 4: Fragility parameters for buried tanks under soil permanent deformations. The median is given in inch as in HAZUS (FEMA 2004).

Type	μ [cm]	β [cm]
Concrete	30.5	1.27
Steel	61	1.27

4.3 Wastewater treatment plants

An effort towards the definition of seismic fragility curves for wastewater treatment plants (WWTP) has been carried out by Panico et al. (2013). Because of the scarcity of data, the fragility was given only for municipal WWTPs: the curve parameters for severe damage are μ= 0.311 g and β = 0.338. It is pointed out that the damage occurred for different causes, including the failure of foundation soil; therefore, in the empirical collection of damage also liquefaction cases has been accounted. Similar approach has been carried out in HAZUS, where no difference seemed to be shown for the effect of permanent and transient deformation.

5. PGA threshold values

Based on the given fragility parameters, threshold values could be obtained from fragility curves by a probit analysis. This is a binary regression models, which gives the probability of failure (response) given a certain dose (Finney, 1971). With reference to seismic failures, the general expression of the probit function is than:

$$Y_{equip} = k_1 + k_2 \ln(IM) \tag{2}$$

where k_1 and k_2 are the probit coefficients. The benefit of probit formulation consists in the opportunity of retrieving a threshold value. For any equipment, for any damage level (as in HAZUS) or intensity of release of content (as in Salzano et al., 2009 and Lanzano et al., 2014a), the value of IM for which Y ≈ 2.71 corresponds to the null probability. Results for the abovementioned fragility are shown in Table 5. Furthermore, a focus on the considered geotechnical mechanisms for fragility construction is also given: “all” is used when both soil shaking and failure triggered by earthquake have been considered.

Table 5: Threshold values of industrial components for large release of content or structural collapse of equipment.

Type	Treated fluid	Geotechnical mechanisms	PGA [g]	δ_0 [cm]	Starting Reference
Ductile pipelines	Gas, oil	Soil Failure	0.20	-	Lanzano et al., 2014a
Brittle pipelines	Water	Soil Failure	0.14	-	Lanzano et al., 2014a
Unanchored vertical tanks (full)	Gas, oil	All	0.27	-	Salzano et al., 2003
Anchored vertical tanks (full)	Gas, oil	All	0.12	-	Salzano et al., 2003
Pressurized horizontal tanks	GPL	All	0.53	-	Salzano et al., 2009
Municipal TP	Wastewater	All	0.12	-	Panico et al., 2013
Concrete buried tanks	Water	Soil Failure	-	1.3	FEMA, 2004
Steel buried tanks	Fuel	Soil Failure	-	16.0	FEMA, 2004

It is worth noting that the thresholds value by HAZUS, expressed in terms of permanent displacements δ is difficult because additional parameters for the geotechnical description of the site, as the thickness of liquefiable soil which can only obtained by in-situ tests for liquefaction verification, are needed.
All the PGA thresholds reported in Table 5 are higher than the threshold value for the liquefaction occurrence, which is 0.09 g, as reported in Santucci de Magistris et al. (2013).

6. Conclusions

Liquefaction is a soil failure phenomenon, which occurs under site specific condition (loose saturated sand), but compatible to the most common site of the industrial plants (coastal and fluvial plane). On the basis of the field post-earthquake observation, this phenomenon represents as a crucial issue for the risk assessment of industrial components under seismic actions, particularly for buried structures. However, specific tools as fragility functions and threshold values for the evaluation of structural vulnerability to liquefaction for most common components, as tanks, pipelines and wastewater treatment systems, are still missing. Further work will be then devoted to the definition of these function.
Recent advancement on the liquefaction phenomenon have set a threshold value in terms of seismic intensity at PGA = 0.09 g for the occurrence of the phenomenon. It is important noting that this value is lower than all other lower limits for the collapse of industrial equipment (Table 5).

References

Bardet J-P., Mace N., Tobita T., 1999, Liquefaction-induced Ground Deformation and Failure. Report to PEER/PG&E, Task 4A - Phase 1.

Bray J.D., O' Rourke T. et al., 2013, Liquefaction Impact on Critical Infrastructure in Christchurch. Final Technical Report, U.S.G.S. Award Number: G12AP20034, 51pp.

Campedel M., Cozzani V., Garcia-Agreda A., Salzano E., 2008, Extending the quantitative assessment of industrial risks to earthquake effects. Risk Analysis, 28(5), 1231-1246.

EN 1998-5, Eurocode 8, 2004, Design of structures for earthquake resistance – Part 5: Foundations, retaining structures and geotechnical aspects, CEN, Bruxelles, Belgium.

Fabbrocino G., Iervolino I., Orlando F., Salzano E., 2005, Quantitative risk analysis of oil storage facilities in seismic areas. Journal of Hazardous Materials, 23, 61-69.

FEMA 2004, Using HAZUS-MH for Risk Assessment (http://www.fema.gov) accessed 06.02.2014.

Finney D. J., 1971, Probit analysis. Cambridge University Press, Cambridge, UK.

GEER 2010, Geo-Engineering Reconnaissance of the February 27, 2010 Maule, Chile Earthquake. Report of the National Science Foundation-Sponsored Geo-engineering Extreme Events Reconnaissance (GEER) Team, 0.6 Liquefaction and lateral spreading.

GEER 2011, Geotechnical Quick Report on the Kanto Plain Region during the March 11, 2011, Off Pacific Coast of Tohoku Earthquake, Japan. Quick Report 3:Preliminary Observations of the Effects of Ground Failure and Tsunami on the Major Ports of Ibaraki Prefecture, 24pp.

GdL 2012, Guidelines for the local and global operations on industrial single-storey buildings designed without anti-seismic criteria. Italian Working Group for the seismic safeness of industrial buildings (in Italian).

GdL AGI 2013, Guidelines for the local and global operations on industrial single-storey buildings designed without anti-seismic criteria: geotechnical aspects. Italian Geotechnical (AGI) Working Group for the seismic safeness of industrial buildings (in Italian).

Honegger D. G., Eguchi R. T., 1992, Determination of the relative vulnerabilities to seismic damage for San Diego County Water Authority (SDWCA). Water transmission pipelines.

Kramer S.L., 1996, Geotechnical Earthquake Engineering. Prentice Hall, Upper Saddle River, New Jersey, 653 pp.

Krausmann E., Cozzani V., Salzano E., Renni E., 2011, Industrial accidents triggered by natural hazards: An emerging risk issue, Natural Hazards and Earth System Science 11, 921-929.

Lanzano G., Salzano E., Santucci de Magistris F., Fabbrocino G., 2014a, Seismic vulnerability of gas and liquid buried pipelines. Journal of Loss Prevention in the Process Industries, 28, 72-78.

Lanzano G., Santucci de Magistris F., Fabbrocino G., Salzano E., 2014b, Integrated approach to the seismic vulnerability assessment of industrial underground equipment and pipelines. Bollettino di Geofisica Teorica e Applicata, DOI: 10.4430/bgta0095.

Lanzano G., Salzano E., Santucci de Magistris F., Fabbrocino G., 2013a, Seismic vulnerability of natural gas pipelines. Reliability Engineering & System Safety, 117, 73-80.

Lanzano G., Salzano E., Santucci de Magistris F., Fabbrocino G., 2013b, Vulnerability of Pipelines Subjected to Permanent Deformation Due to Geotechnical Co-seismic Effects. Chemical Engineering Transactions, 32, 415-420.

O'Rourke M. J., Liu X., 1999, Response of buried pipelines subjected to earthquake effects. MCEER Monograph No.3. Buffalo, USA: University of New York, USA

Panico A., Lanzano G., Salzano E., Santucci de Magistris F., Fabbrocino G., 2013, Seismic Vulnerability of Wastewater Treatment Plants. Chemical Engineering Transactions, 32, 13-18.

Santucci de Magistris F., Lanzano G., Forte G., Fabbrocino G., 2013, A database for PGA threshold in liquefaction occurrence. Soil Dynamics and Earthquake Engineering, 54, 17-19.

Santucci de Magistris F., 2011, Beyond EC8: the New Italian Seismic Code, Geofizika, 28,65–82.

Salzano E., Garcia Agreda, A., Di Carluccio A., Fabbrocino G., 2009, Risk assessment and early warning systems for industrial facilities in seismic zones, Reliability Engineering & Systems Safety, 94, 1577-1584.

Salzano E., Iervolino I.,Fabbrocino G., 2003, Seismic risk of atmospheric storage tanks in the frame work of quantitative risk analysis. Journal of Loss Prevention in the Process Industry, 16, 403-409.

Takada S., Tanabe K., 1988, Estimation of earthquake induced settlement for lifeline engineering. Proc. of the 9th World Conference on Earthquake Engineering, August, Vol. VII, pp. 109-114.

Yamada S., Orense R., Cubrinovski M., 2011, Geotechnical Damage due to the 2011 Christchurch, New Zealand. International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Bulletin, 5-2, 27-45.