

PRELIMINARY SEISMIC VULNERABILITY ASSESSMENT OF A STEEL OIL STORAGE TANK: GEOPHYSICAL ANALYSIS AND DESIGN SPECTRA DEFINITION

G. Massolino¹, C. Barnaba¹, S. Forchiassin², R. Romeo¹, D. Sandron¹, M. Santulin¹, A. Tamaro¹

¹OGS - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste-Udine, Italy

²SIOT - Società Italiana per l'Oleodotto Transalpino, Trieste, Italy

Introduction. It is well known earthquakes induce sloshing in tanks caused by long-period ground motion (Housner, 1963; Hanson, 1964; Manos and Clough, 1985). This aspect was dramatically emphasized in Japan, after the 2003 Tokachi-oki earthquake (M=8.0) occurred on 26 September, east of Hokkaido, north of Japan, when the oil storage tanks in Idmitsu Refinery suffered severe damage (Zama, 2004). Natural period of sloshing depends on the diameter of tank and the liquid height, and it is triggered by the power of seismic ground motion. Due to the slow attenuation of the long-period ground motion, a minimum freeboard is needed to accommodate the sloshing waves and to avoid oil leaks.

In this paper, it is presented a case study of a 10000 m³ hydrocarbon buffer storage tank, belonging to the pipeline system owned by the Società Italiana Oleodotto Transalpino (SIOT), part of the TAL group (Transalpine Pipeline), built in the 1960s in the NE Italy. This analysis is part of a study project funded by the European Social Fund, within the SHARM (Support Human Asset and Research Mobility) educational program. The study area, is close to the epicenter of the 1976 (M=6.4) Friuli earthquake and it was stuck in the past by several earthquakes of M>5.5 (Bressan *et al.*, 2003).

A seismic event can result in damages to the tank only if it is full of fluid. Since the structure is a buffer storage tank, it is almost empty most of the time, except in the case of extraordinary maintenance on the pipelines. The probability of an earthquake occurrence at the same time of rare and short maintenance operations is very low. Therefore, the scenario to be taken into consideration is the one in which the first shock causes the rupture of the pipeline, the tank is filled in order to restore the pipeline and then subject to a second quake. The first step of the study was the seismic site characterization, in order to define the soil condition for the design spectra determination. Passive seismic methods (Refraction Microtremors, Re.Mi.; Multichannel Analysis of Surface Waves, MASW) have been used to define the shear wave velocity profile.

To calculate the base shear stress, the overturning moment and the height of the sloshing wave, the simplified procedure proposed by Malhotra *et al.* (2000), integrated in Eurocode8, has been used. The method involves spectral acceleration with damping ratio of 2% and 0.5%, therefore the spectra have been calculated from a set of strong motion data, since the standard formulations were not valid for damping ratio lower than 5%. The amplification related to site effects was calculated through the 1D modeling by the software Pshake (Sanò and Pugliese, 1991), assuming as input those spectra, the stratigraphy and the Vs profile obtained from the geophysical analysis. Finally, the maximum vertical displacement of the fluid surface due to sloshing has been computed, and the safety condition verified. The moment and shear stress resistance calculation, instead, is still work in progress.

Geological characterization. The SIOT tank is located in the Friuli Venezia Giulia region, in the municipality of Paluzza (Udine, north-eastern Italy). The industrial plant is located in the flood plain of the Bût River at the average altitude of about 550 m. The River Basin Authority classifies the area as P1 class, with a moderate hydraulic hazard (Piano Stralcio per l'Assetto Idrogeologico, <http://www.adbve.it/>). The area is characterized by Holocene stabilized alluvial deposits, made of coarse gravels, sands and fluvio-glacial silt, surrounded by Permo-Trias carbonate rocks of the so-called Paleocarnic Chain (Venturini, 2009). The tectonic framework is complex and partially buried under Quaternary coverage. Normal faults and thrusts are evidenced in geological surface mapping, and the main one is the Comeglians-Paularo thrust (Servizio Geologico per l'Italia, Dipartimento per i Servizi Tecnici Regionali, 2002).

The knowledge of the soils and underground structure of the valley is very poor, and no stratigraphic investigations are available. An initial three-dimensional model of the valley was developed overlapping the orthophotos of the regional numerical technical map and the digital elevation model (RAFVG, 2014). The valley bedrock depth in correspondence to the industrial site is estimated at about 86 m, and this value was compared with those obtained with geophysical investigations.

Geophysical surveys. In order to better characterize the seismic properties of the shallow soils (i.e. unconsolidated sediments) at the test area, S-wave array measurements have been carried out by analyzing and inverting the dispersion curves of Rayleigh wave's fundamental mode. Seismic signals were induced by active and passive (ambient noise) sources.

A multichannel survey was performed using a 24 channel digital system SoilSpy Rosina (Micromed). Multiple weight drops were used to record redundant seismic data. The layout of the seismic profile was oriented along the longitudinal axis of the valley, in order to meet the physical conditions of 1-D medium and remove the apparent surface wave arrivals. With this test it was possible to define the "limits" of the velocity model (Fig. 1). It is achievable to read the chart from 50 Hz, with a correspondent speed of approximately 260 m/s, and therefore a 2.08 m depth. The dispersion curve starts to be not interpretable at about 10 Hz at a speed of 470 m/s. To define the profile, the dispersion curve in the fundamental mode was connected to the fitting of H/V at the site, obtaining a shear wave value for the upper 30 m of about 438 m/s, that set the site in B class, according Eurocode 8 classification.

Ambient seismic noise has been recorded all around the area where the tank is located to establish stationary site conditions. Data were acquired also on the top of the tank structure

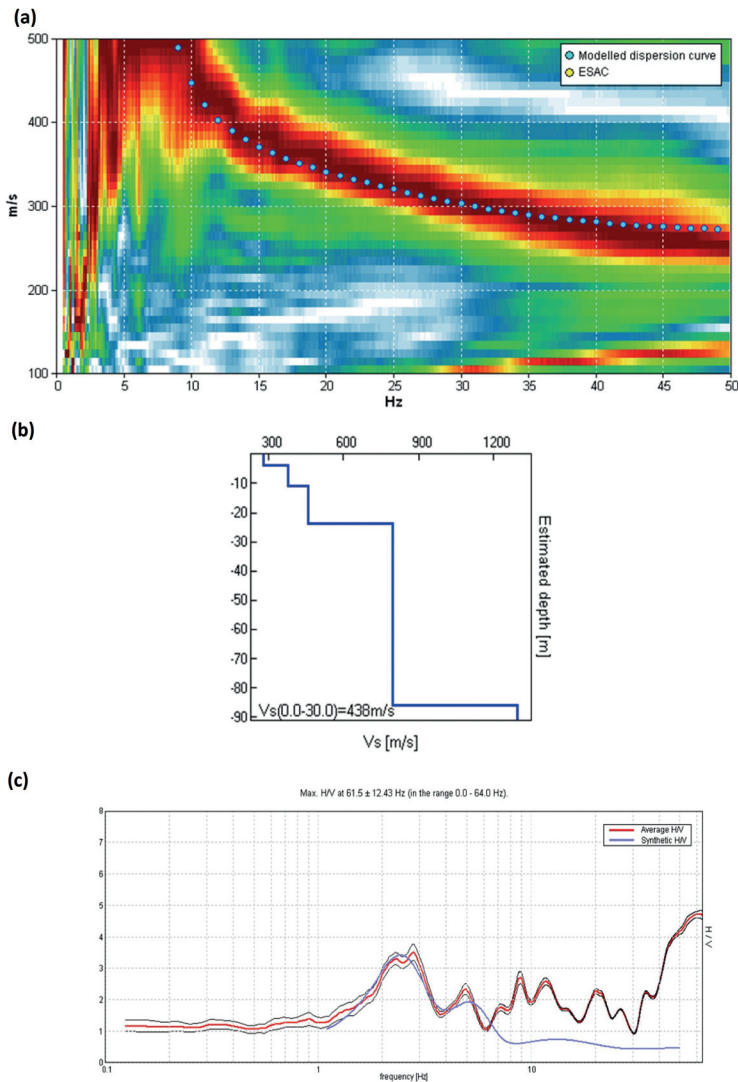


Fig. 1 – Theoretical and experimental dispersion curve (a); velocity ground model (b); HVSR fitting (c).

in order to quantify the periods of vibration. Single station tests were performed using the instrument Tromino (Micromed) and Lennartz Seismometer (with 1 Hz sensors). The results obtained with the two different instruments are basically in agreement (Fig. 2).

The H/V analysis performed show no clear peaks, that suggests the absence of impedance contrasts and therefore the gradual velocity increase with depth (Fig. 2). The amplification of about 2.5 Hz, recognizable at all sites can be interpreted as a layer of over consolidated gravel deposit (bedrock-like), which is supposed to have an S-wave velocity of about 800 m/s.

Design spectra. The simplified procedure of Malhotra *et al.* (2000) proposed in Eurocode 8 uses spectra calculated over a 2% and 0.5% damping in order to evaluate the base shear stress, the overturning moment and the sloshing wave height. However, it is not possible to define the spectra according to the legislation formula with a damping ratio lower than 5%, since the factor involved in the relations (depending on the damping ratio) is defined only above this value. Therefore, it was necessary to use accelerograms to define the elastic design spectra needed to the simplified computations.

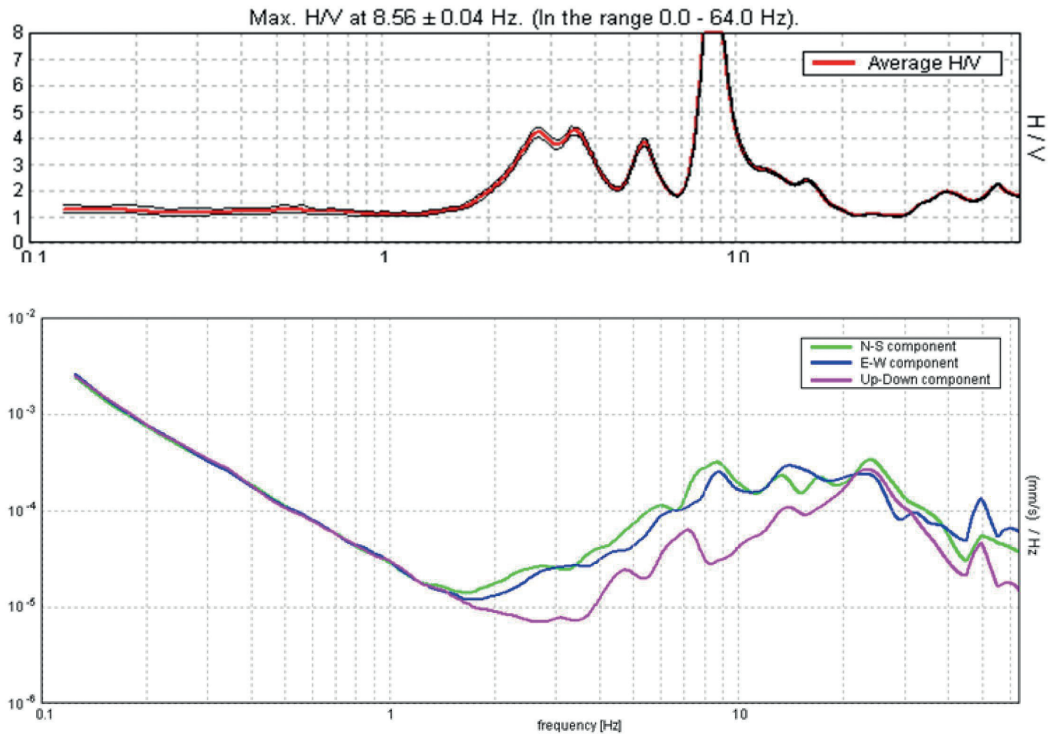


Fig. 2 – Horizontal to Vertical Spectral Ratio and 3 components velocity diagram (smoothing 10%) obtained by Tromino® instruments.

It has been decided to search for real ground motion records through Italian and European Strong-Motion Data Base [ITACA: Luzi *et al.* (2008), <http://itaca.mi.ingv.it>; ESMD: Ambraseys *et al.* (2002), <http://www.isesd.hi.is>]. The choice of the accelerograms has been taken according with the disaggregation of the PSHA results in terms of distance and magnitude (Meletti and Montaldo, 2007). Earthquakes with magnitude between 5.5 and 6 within a distance of 20 km have been seek (INGV - Istituto Nazionale di Geofisica e Vulcanologia, 2007). Ground type A accelerograms were extracted, since the intention was to model the site effects through the software Pshake (Sanò and Pugliese, 1991). Response spectra for each selected accelerogram (Tab. 1) were compiled using the SeismoSignal software (Seismosoft, 2013c).

The average spectrum obtained must match the one calculated in accordance to the 2008 Italian technical regulations (Consiglio Superiore dei Lavori Pubblici, 2008). A 50 years nominal life expectancy is assumed for the structure. The importance class is IV: “buildings

Tab. 1 - Ground motion records used in the spectra definition, according with the disaggregation of the PSHA results in terms of distance and magnitude.

Earthquake	Date	Hour	Mw	Station	Soil type	Distance (km)
L'Aquila	7 th April 2009	17:47:37	5.5	AQP	A	13.2
				MI05	A*	5.3
				RM13	A*	15.59
Umbria Marche III shock	14 th October 1997	15:23:09	5.6	CAG	A*	16.2
Marmanno	25 th October 2012	23:05:24	5.3	VGG	A*	10.267

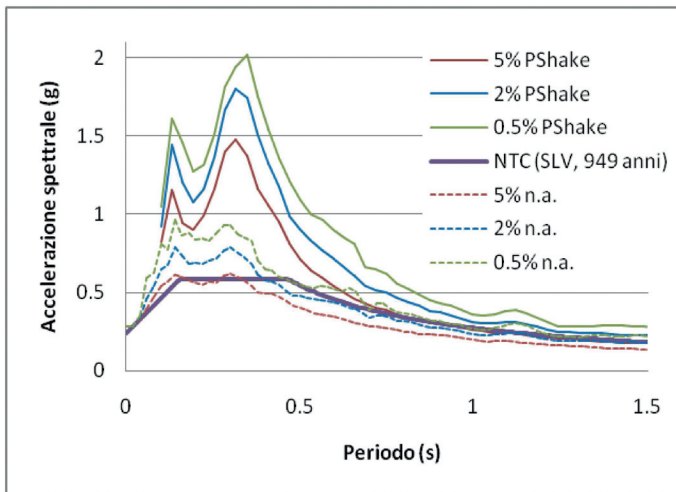


Fig. 3 – comparison between spectra obtained with accelerograms and amplified with PShake software and the non amplified ones (n.a.), with and the spectrum obtained in accordance to the legislation (diagram cut at 1.5 s for a clear display of results and comparisons).

with important public or strategic functions, also in regard to the management of civil protection in case of calamity. Industries with activities particularly dangerous for the environment [...]”. Therefore, the conventional design life of the tank, obtained by the product of the nominal life expectancy and the importance factor (2, in this case), turns out to be 100 years. This value for the design life leads to the following reference return periods for each limit state: no – collapse requirement 1950 years, life safety requirement 949 years, damage limitation requirement 101 years and operational requirement 60 years. From the velocity model based on the geophysical analysis, the V_{s30} parameter is equal to 430 m/s, which suits ground type B, but the spectra have been calculated on a ground type A, as the site effects have been taken into account through the software Pshake (Sanò and Pugliese, 1991). The T1 topography category has been adopted, since the tank is located on a flat ground.

Despite several attempts it was not possible to find ground motion records compatible, nor within the Italian or European database. However, the national seismic code allows to scale the selected accelerograms in order to satisfy the target spectrum. We proceeded this way through the software SeismoMatch (Seismosoft, 2013a) developed by Abrahamson (1992) and then updated by Hancock et al. (2006). The software modifies an acceleration time history in the time domain in order to make it match with a specified spectrum using the technique proposed by Lihanand and Tseng (1987, 1988). This technique employs waves forms called wavelets, that uses the answer of elastic SDOF systems (Single Degree of Freedom) in the time domain. In the software procedure three phases can be distinguished: 1) the calculation of an elastic SDOF answer under the action of the acceleration time series, for each reference period and for each defined damping ratio; 2) the comparison between the peak of each SDOF answer with the target amplification and the calculation of the difference between the two; 3) the addition of wavelets with appropriated amplitudes to the ground motion data, suiting the phase in order that the peak of each answer corresponds to the target amplitude. A single wavelet is used to match each single SDOF answer.

The matched accelerograms were then processed again with SeismoSignal (Seismosoft, 2013c) in order to get three spectra with a damping ratio of 5%, 2% and 0.5% for each accelerogram. The average between the 5 spectra for each damping value has then been calculated and used as input for the 1D model through Pshake.

The amplification is considerable for periods between 0.15 and 0.5 s (Fig. 3).

Structural period. The calculation of the seismic response in the case of a tank is fairly complex. In fact, the structural period needs to be combined with the one of the liquid contents. It was shown that a part of the liquid moves in long-period sloshing motion, while the rest moves rigidly with the tank wall. This part of liquid, also known as the impulsive liquid, experiences the same acceleration as the ground and contributes predominantly to the base shear and overturning moment. The sloshing liquid (or convective) determines the height of the free surface waves, and hence the freeboard requirement to a safety condition. In this paragraph the convective and impulsive periods and the safety height for the Paluzza SIOT buffer tank is calculated, starting from the elastic design response spectra determined in the previous paragraph.

Periods of convective and impulsive responses (Eurocode 8: design of structures for earthquake resistance; UNI EN 1998-4: 2006 Part 4: Silos, tanks and pipelines) are calculated through Eq. (1)

$$T_{\text{imp}} = C_i \frac{\sqrt{\rho} H}{\sqrt{s/R} \sqrt{E}} \quad (1)$$

$$T_{\text{con}} = C_c \sqrt{R}$$

where H is the design height of the fluid, R is the radius of the tank, s is the equivalent uniform thickness of the wall of the tank, ρ the density of the liquid mass and E the modulus of elasticity of the material. The coefficients C_i and C_c are obtained from an exact model of the tank-liquid system and included into Appendix 1 in Eurocode 8.4. C_i is a non dimensional coefficient, while C_c is expressed in $\text{s/m}^{1/2}$. Replacing the value of R (in meters) in the equation, therefore, the correct value of the convective period is obtained. For tanks with non-uniform wall thickness, s can be calculated by taking a weighted average on the wet height of the tank wall, assigning the highest thickness weight near the base of the tank where the maximum deformation occurs. The impulsive and convective mass m_i and m_c , which are necessary to calculate the shear stress and the overturning moment, are given again in appendix A of Eurocode 8 part 4, expressed as fractions of the total liquid mass m .

Seismic response on theoretical formulations. The oil tank in Paluzza is a vertical cylindrical steel structure, with a capacity of approximately 10000 m^3 . The radius of the tank is 13.72 m (diameter 90 feet), the height 17.07 m (corresponding to 56 feet). The structure has both a fixed coverage and a floating steel roof.

The theoretical calculation of impulsive and convective periods and maximum vertical displacement of the fluid in the tank is performed according to the formulations provided by Eurocode 8 part 4.

The computation of the period has been carried out considering the worst scenario: upstream pipeline collapse condition and spill of all the fluid in the storage tank until its maximum fill. The height of the tank is 17.07 m, however the maximum filling level is about 16 meters, considering the presence of the floating roof. It is assumed, as fluid density, the minimum and maximum density of the fluids normally transiting in the system, 780 and 900 kg/m^3 respectively. The check is then completed adopting the period value to which corresponds the higher spectral acceleration, for security reasons. Convective periods, on the other hand, being only dependant on the radius, does not change.

Tabs. 2 and 3 summarize the computation for the tank in Paluzza with the expected height of sloshing at about 0.07 m. Actually, considering the spectrum calculated with the EC8 formulation, but with the damping at 5%, since it's not possible to calculate it for a value lower than that, the maximum wave height would be 20 cm. In both cases, if the maximum fluid height is set to 16 m, the security conditions are respected.

Single Station top – bottom surveys. One of the most delicate issues about the Malhotra simplified approach is the estimation of the convective and impulsive periods. Thus, the results

Tab. 2 - Convective and impulsive periods calculated with EC8 part 4 formulations and comparison with the experimental data.

	T_{imp} [s]	T_{conv} [s]	f_{imp} [Hz]	f_{conv} [Hz]	Exp. f_{imp} [Hz]	Exp. f_{conv} [Hz]
Water tank (full)	0.20	4.9	4.97	0.20	4	<0.3
Oil tank (full)	0.24-0.26	5.59	3.85-4.14	0.18	/	/
[Oil tank (empty)]	≈0.05	≈8.47	≈19	≈0.12	≈10	<0.3

Tab. 3 - Theoretical parameters used in the computation of shear stress, overturning moment and maximum sloshing height at the Paluzza storage tank.

	R(m)	H(m)	C_i	C_c (s/m ^{1/2})	T_{imp} (s)	T_{conv} (s)	F_{imp} (Hz)	F_{conv} (Hz)	D(m)
Oil tank (full)	13.72	16.00	6.35	1.51	0.26	5.59	3.8	0.18	0.07
Water tank (full)	10.668	14.325	6.3	1.5	0.20	4.9	4.97	0.20	0.06
[Oil tank (empty)]	13.72	2.58	≈10.14	≈2.28	0.05	8.47	19.63	0.12	/

obtained by using theoretical relations provided by the regulations have been compared with the results of the single station top – bottom tests carried out on the structure.

It was not possible to perform the test while the tank was full, since it is a buffer tank, while the coefficients used in the Malhotra approach are valid for H/R value higher than 0.3. In the Paluzza tank, instead, the actual H/R value is 0.18. As a side note, speculating over the possibility of extending the relations until 0.19, the results of the comparison between theoretical and experimental periods would be quite promising.

However, to be more accurate, it has been decided to perform the same test on a fire protection water tank located in Trieste, since that one was full at the moment. In the test performed, the diagram representing the ratio between horizontal components acquired at the top and at the bottom of the structure shows a peak at about 4 Hz. This is very close to the impulsive frequency calculated with the EC formulations (4.97 Hz). Additionally, the experimental data show the beginning of a peak below 0.3 Hz: it wasn't possible to investigate below this frequency, due to instrumental limitations, however that peak likely represent the convective one calculated with the formulations, which is equal to 0.2 Hz.

The consistency of the data in this test suggests that the period estimated according to Eurocode reports provides acceptable results in this situation.

Conclusions. Both single station and multichannel surveys have been carried out to define a stratigraphic model. This representation has then been used to estimate the spectra amplification due to site effects. The spectra with different values of damping ratio (2% and 0.5%) have been calculated through the use of strong motion data. In order to obtain the base stress and the overturning moment values through the Malhotra simplified approach suggested by EC8 part 4, the convective and impulsive periods have been considered. Single station top – bottom tests have been performed on the structure in order to validate the theoretical formulations.

In conclusion, the shear stress, the overturning moment (above and below the base plate) and the sloshing wave height calculated are, respectively:

$$Q = 6.15 \cdot 10^7 \text{ N}$$

$$M_{above} = 4.21 \cdot 10^7 \text{ Nm}$$

$$M_{below} = 6.1 \cdot 10^7 \text{ Nm}$$

$$d = 7 - 20 \text{ cm}$$

In order to better validate through experimental evidences the relations used in the codes, further tests, both in Paluzza and Trieste sites, will be performed.

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