SEISMIC ISOLATION OF LNG STORAGE TANKS IN ITALY WITH CURVED SURFACE SLIDERS

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Abstract

Liquified Natural Gas tanks (LNG) are lifeline facilities and strategically very important, since they have vital use in industries and nuclear power plants. These special structures are often located in seismic prone areas; in these cases, seismic isolation is worldwide extensively used to reduce the dynamic response of the tanks, thus avoiding typical forms of failure such as diamond-shaped buckling, elephant-foot buckling and roof damage due to sloshing. Moreover, base isolation, decoupling the motion of the tank from that of the ground, allows to optimize and therefore to reduce costs, not only of the superstructure but also of the substructure, such as foundation piles. This paper describes the seismic isolation of 2 x 10130 m^3 working capacity LNG full containment storage tanks located at Corsini port, Ravenna, Italy, area characterized by medium seismicity. Each LNG tank consists of an inner steel tank, which contains the LNG, and an outer prestressed concrete tank that encases and protects the inner tank. 182 high-friction curved surface sliders (91/tank) were designed, manufactured and tested by Freyssinet Italy, to ensure high lateral flexibility and energy dissipation capacity to the isolation system. This works represents the first important example of seismic isolation of LNG tanks in Italy through friction-based devices.

Keywords: LNG Tanks; Seismic Isolation; Energy Dissipation; Curved Surface Sliders

1. Introduction

Liquified Natural Gas (LNG) tanks are crucial facilities for a natural gas distribution system. Since they balance the difference between the gas demand, which usually varies constantly, and the supply from international ducts, they are used to store huge amounts of energy. Therefore, these are sensitive structures on which severe requirements are imposed to ensure high levels of safety in case of accidental actions such as explosions, fire, aircraft impacts, earthquakes, etc. [1]. When these structures are in seismic prone areas, base isolation represents represent an effective solution to reduce the seismic response, thus avoiding typical forms of collapse such as diamond-shaped buckling, elephant-foot buckling and roof damage due to sloshing (Fig. 1). Moreover, thanks to the seismic isolation interface, it is possible to reduce the costs of the whole structure due to decoupling of the ground motion from that of the superstructure.

Fig. 1 – Tank's typical forms of collapse: diamond-shaped buckling (top-left), elephant-foot buckling (right) and roof damage due to sloshing (bottom-left)

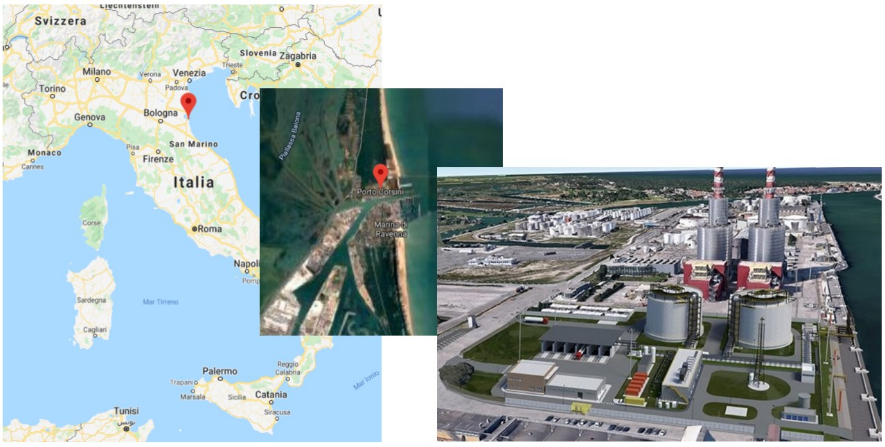


Fig. 2 – Location of future LNG tanks

This paper describes the base isolation system of two elevated LNG tanks that will be built during 2020 at the Corsini port of Ravenna, Italy (see Fig. 2). This project represents the first example of base isolation of LNG tanks in Italy through more than 180 friction-based anti-seismic devices. The paper also explains in detail the complex testing protocol of the isolators, in accordance with the European Standard EN 15129:2009 [2] and the Italian Building Code NTC 2018 [3] and illustrates main results of the dynamic response of the devices, with particular focus on the frictional properties, on which the dissipative capacity is directly connected.

2. Description of the tanks

In order to efficiently serve their main functions, i.e. preventing the atmospheric air from entering the tank, keeping the content from escaping to the environment, maintaining the appropriate conditions of pressure, temperature and defending the liquid content against external effects such as fire, explosion, earthquakes, etc., each LNG tank is configured as a double shell, as shown in Fig. 3.

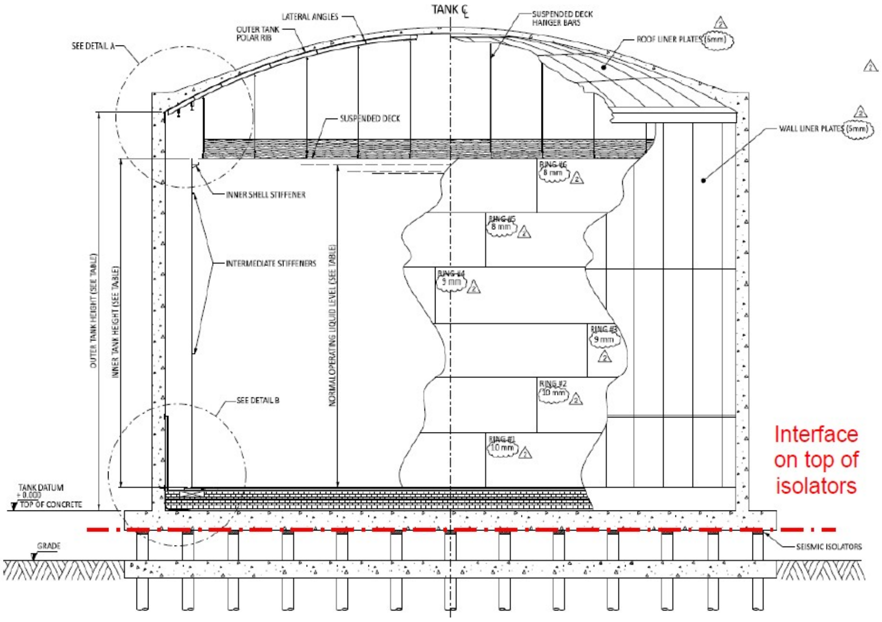
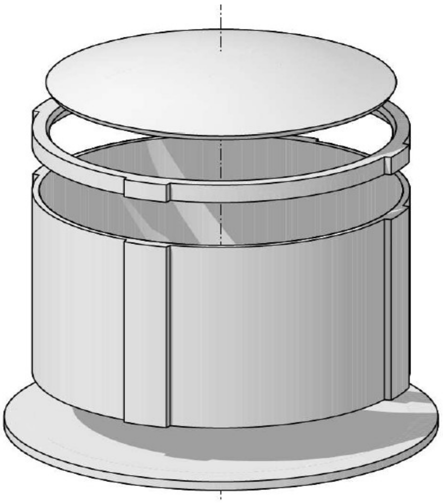


Fig. 3 – Overall layout of the LNG tanks and location of seismic interface

The outer prestressed concrete cylindrical shell (16.45 m-external radius, 22 m-height) is capped by a spherical reinforced concrete dome on which a suspended deck is attached as roof for the inner steel cylindrical shell (14.40 m-external radius, 18 m-height). The total concrete quantity for each outer tank is indicated in Fig. 4. The space between the two shells is filled with perlite to insure thermal insulation of the liquid content. The outer tank is than supported by 91 anti-seismic devices, in turn supported by 91 1.50 m-diameter x 1.60 m-height RC columns. Finally, the foundation system is made by a base slab plus 91 piles with 1.20 m-diameter and 42 m-length (see Fig. 5). LNG with a density of 487 kg/m^3 is stored in the inner tank up to 17.235 m, with a full working capacity of 10130 m^3 per tank.



Tank Concrete Volume	
Dome Roof	271 m³
Ringbeam	198 m³
Wall	1428 m³
Base	1122 m³
Total	**3019 m³**

Fig. 4 – Concrete quantity for outer tank (total weight: 75475 kN)

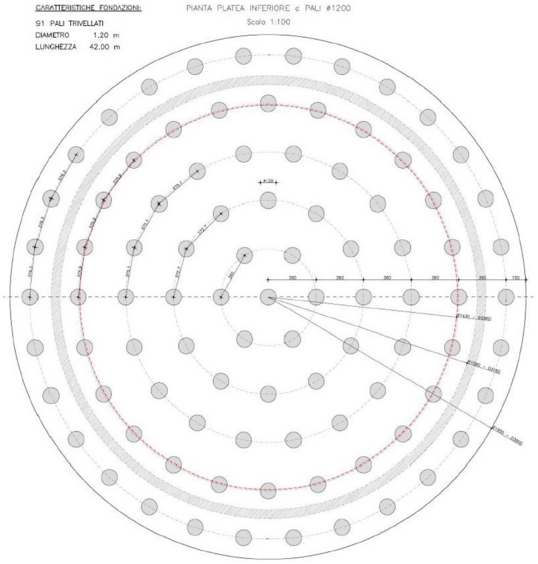


Fig. 5 – Radial distribution of foundation piles

3. Seismic input and definition of the isolation system

Since usually LNG tanks are used to store huge amounts of energy which could cause a major disaster if deliberated, very severe requirements are imposed concerning the ability of these special structures to withstand several prescribed accidental actions such as aircraft impacts, explosions, fire, major leaks, earthquakes, etc. Especially for earthquakes, it is usually required, as in this project, that LNG tanks should be able to sustain a major seismic event with a return period of about 5000 years without undergoing catastrophic damage, while should remain fully operational during a medium seismic event with a return period of 475 years [1]. Fig. 6 shows the elastic acceleration response spectra for the Operating Basis Earthquake level (OBE, 475 years return period) and for the Safe Shutdown Earthquake level (SSE, 4975 years return period). The site is characterized by a medium seismicity, with a design Peak Ground Acceleration (PGA) of 0.34g with a maximum spectral response up to 0.81g for periods between 0.25 sec and 0.75 sec. Furthermore, due to the presence of short reinforced concrete supports, the high shear stiffness may induce premature brittle failure of the columns [4, 5], as shown in recent seismic event. For example, during Izmit earthquake (1999) in Turkey, a group of elevated tanks for the storage of liquified oxygen were subjected to serious damage or collapsed [6]. This is a clear case in which base isolation technique represent an effective solution to reduce global seismic response [7, 8, 9]. Not last, seismic isolation allows to reduce the costs of the superstructure and foundation piles thanks to decoupling the motion of the tank from that of the ground.

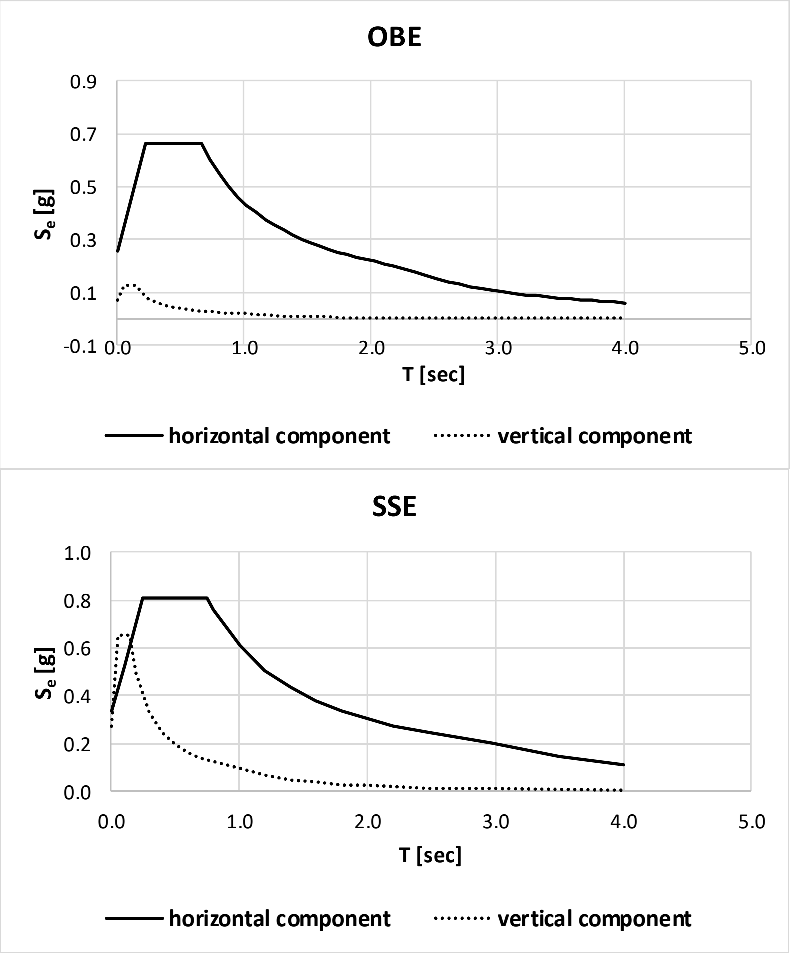


Fig. 6 – OBE (top) and SEE (bottom) design spectra

For the evaluation of the seismic response of the tanks, NonLinear Time-History Analysis (NLTHA) were conducted first using the simplified model described in Eurocode 8 – Part 4 [10, 11] in order to determine preliminary properties of the isolation system. Subsequently, NLTHA were carried out on a complete 3D model (see Fig. 7) to determine final characteristics of the anti-seismic devices as well as checks of all the structural elements above and below the isolation interface. Artificial spectrum-compatible accelerograms were used for all the analysis. The results of the preliminary analysis, confirmed later by the refined ones, let to the selection of friction-based anti-seismic devices, Curved Surface Sliders (CSS). Isolation devices based on sliding on single or multiple spherical polished steel surfaces of sliders coated with low or high friction materials have become more and more popular since they allow large relative displacements with a relatively low total height [12].

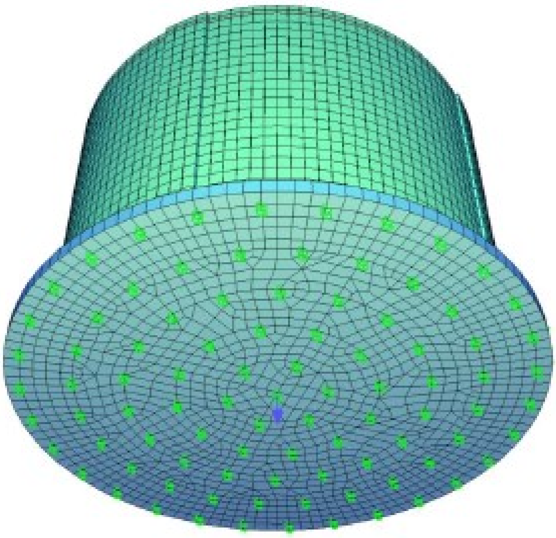


Fig. 7 – Bottom view of the outer tank FE model with springs

For this project, CSS with two sliding surfaces were selected to reduces the overall dimensions of the devices, as the displacement capacity results from the sum of the displacement capacity of each sliding surface (see Fig. 8).

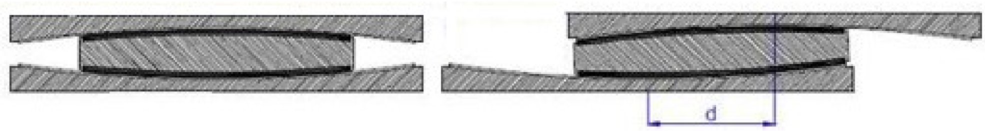


Fig. 8 – CSS in static (left) and dynamic (right) configuration

For each tank, Freyssinet Group supplied 91 CSS named ISOSISM® PS 3300/700 were placed at the base of each tank to support the weight. High-friction devices were selected to dissipate more seismic energy and hence to decrease most of the response parameters; a sliding period close to 4 sec was defined to effectively decouple the motion of the ground from that of the tank during a seismic event. Table 1 summarizes the main technical characteristics of the devices. The devices are equipped with a special frictional material, named ISOGLIDE®, characterized by excellent wear resistance (up to 50 km) and temperature resistance (up to 90° C) and high characteristic compressive strength (i.e. 180 MPa). Fig. 9 illustrates details of the device.

Table 1 – ISOSISM® PS 3300/700 technical data

Item	**Symbol**	**Value**
dynamic friction coefficient	μ_{dyn}	6.0%
equivalent radius of curvature	R_{eq}	3700 mm
sliding period	T_r	3.86 sec
displacement capacity	d	+/- 350 mm
maximum vertical load in static condition	$N_{ULS,max}$	3300 kN
maximum vertical load in seismic condition	$N_{Ed,max}$	2860 kN
average quasi-permanent vertical load	N_{Sd}	1520 kN

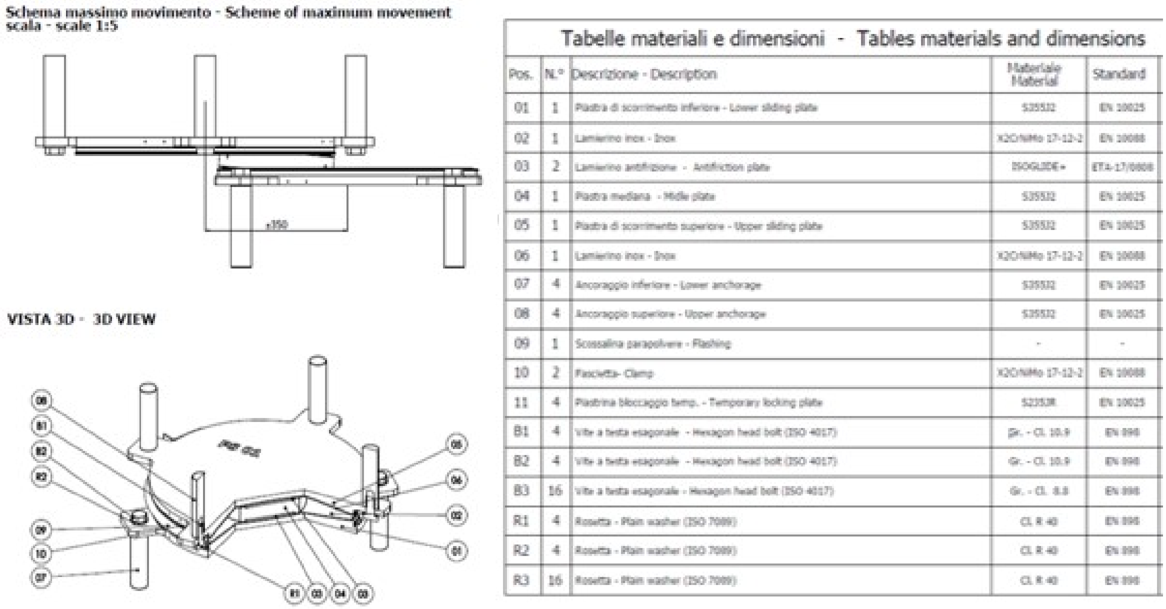


Tabelle materiali e dimensioni - Tables materials and dimensions

Pos.	N.°	Descrizione - Description	Materiale Material	Standard
01	1	Piastra di scorrimento inferiore - Lower sliding plate	S355J2	EN 10025
02	1	Lamierino inox - Inox	X2CrNiMo 17-12-2	EN 10088
03	2	Lamierino antifrizione - Antifriction plate	ISOGLIDE+	ETA-17/0808
04	1	Piastra mediana - Midle plate	S355J2	EN 10025
05	1	Piastra di scorrimento superiore - Upper sliding plate	S355J2	EN 10025
06	1	Lamierino inox - Inox	X2CrNiMo 17-12-2	EN 10088
07	4	Ancoraggio inferiore - Lower anchorage	S355J2	EN 10025
08	4	Ancoraggio superiore - Upper anchorage	S355J2	EN 10025
09	1	Scossalina parapolvere - Flashing	-	-
10	2	Fascetta- Clamp	X2CrNiMo 17-12-2	EN 10088
11	4	Piastrina bloccaggio temp. - Temporary locking plate	S235JR	EN 10025
B1	4	Vite a testa esagonale - Hexagon head bolt (ISO 4017)	Gr. - Cl. 10.9	EN 898
B2	4	Vite a testa esagonale - Hexagon head bolt (ISO 4017)	Gr. - Cl. 10.9	EN 898
B3	16	Vite a testa esagonale - Hexagon head bolt (ISO 4017)	Gr. - Cl. 8.8	EN 898
R1	4	Rosetta - Plain washer (ISO 7089)	Cl. R 40	EN 898
R2	4	Rosetta - Plain washer (ISO 7089)	Cl. R 40	EN 898
R3	16	Rosetta - Plain washer (ISO 7089)	Cl. R 40	EN 898

Fig. 9 – Technical drawing of PS 3300/700

4. Testing of the anti-seismic devices

This section explains the testing details performed on the CSS, according to EN15129:2009 requirements. For this project, compliance with NTC 2018 prescriptions were requested too, where appropriate. The devices were tested at ISOLAB, the innovative testing facility of Freyssinet Group, based in Montebello della Battaglia, Pavia, Italy. ISOLAB Testing Lab was developed thanks to 20 years of experience in earthquake engineering, manufacturing and testing of anti-seismic devices and structural bearings. The Lab is equipped with different press capacity machines and allows testing in static and dynamic conditions and to perform Type Tests and Factory Production Control Tests in accordance to European and worldwide Standards. Fig. 8 shows the 70 MN ISOLAB Dynamic Press, the most powerful of the laboratory, which allows to perform static tests with vertical loads up to 70 MN and dynamic tests with horizontal force up to 3000 kN, 1000 mm stroke and peak velocity up to 850 mm/s. Two prototypes of the CSS have been tested by a Notified Body as per procedure to obtain CE certification for construction products and to qualify the isolators for the project design specifications; the tests have been performed with the client and the construction manager. Fig. 10 shows the device under the press.

Fig. 10 – 70 MN ISOLAB Testing Machine (left) and ISOSISM® PS 3300/700 under the press (right)

Table 2 shows the complete Type Test matrix to verify both the sliding isolation behaviour and the load bearing capacity.

Table 2 – Type Test matrix according to EN 15129:2009

Type of Test	**Test run**	**Main dof**	**Displacement**	**Peak velocity**	**Load shape**	**Compression load**	**Number of complete cycles**
-	**-**	**-**	**[mm]**	**[mm/s]**	**-**	**[kN]**	**-**
Pre-test	PT	vert	-	-	-	1520	-
Friction resistance	FR	long	-	0.1	ramp	1520	1
Service	S	long	± 10	5	sine	1520	20
Benchmark	P1	long	± 223	50	sine	1520	3
Dynamic 1	D1	long	± 56	513	sine	1520	3
Dynamic 2	D2	long	± 112	513	sine	1520	3
Dynamic 3	D3	long	± 223	513	sine	1520	3
Seismic 1	E1	long	± 223	513	sine	2856	3
Seismic 2	E2	long	± 223	513	sine	627	3
Bi-directional	B	long	± 223	513	sine	1520	3
Property verification	P2	long	± 223	513	sine	1520	3
Load bearing capacity	BC	vert	-	-	-	3040	-

Table 3 shows the Factory Production Control Test protocol performed on 20% of the mass production (i.e. 37 devices in this case) as prescribed by the Italian Building Code NTC 2018.

Table 3 – Factory Production Control Test matrix according to EN 15129:2009

Type of Test	**Test run**	**Main dof**	**Displacement**	**Peak velocity**	**Load shape**	**Compression load**	**Number of complete cycles**
-	**-**	**-**	**[mm]**	**[mm/s]**	**-**	**[kN]**	**-**
Friction resistance	FR	long	-	0.1	ramp	1520	1
Benchmark	P1	long	± 223	50	sine	1520	3
Load bearing capacity	BC	vert	-	-	-	3040	1

Given the particular importance of the LNG tanks, as well as the key role of the anti-seismic devices in protecting the structure and therefore the surrounding environment form the effects of a seismic event, it was decided to go beyond what is prescribed by the European and Italian Standard; that is, additional 37 PS were tested according to a “reinforced” protocol, deforming the devices up to the design displacement corresponding to 4975 years (i.e. the SEE earthquake level) to further check the stability of the isolators, globally testing 40% of the supplied. Details of the extra protocol are shown in Table 4.

Table 4 – "Reinforced" Test

Test name	**Test run**	**Main dof**	**Displacement**	**Peak velocity**	**Load shape**	**Compression load**	**Number of complete cycles**
-	**-**	**-**	**[mm]**	**[mm/s]**	**-**	**[kN]**	**-**
Safe Shutdown Earthquake	SSE	long	± 338	513	sine	1520	3

Tests S, P1, D1, D2, D3, E1, E2, B and P2 aim to evaluate the dynamic behavior of the device in terms of friction coefficient, damping capacity, restoring stiffness, stability under repeated cycles. Therefore, the sliding behavior was fully characterized, identifying and quantifying main causes of friction variability [13, 14] as velocity effect, compression load effect, displacement effect and cyclic effect. Fig. 11, Fig. 12, Fig. 13 and Fig. 14 illustrate the different effects abovementioned. Finally, test BC is performed to verify the overload capacity of the device and the absence of any kind of damage and progressive flow or deterioration of the sliding material due to inadequate mechanical resistance, bonding or confinement.

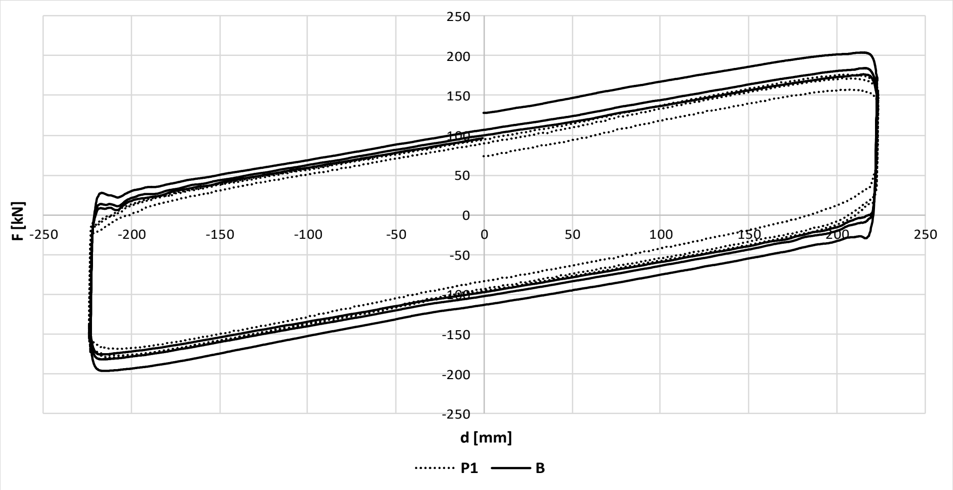


Fig. 11 – Velocity effect

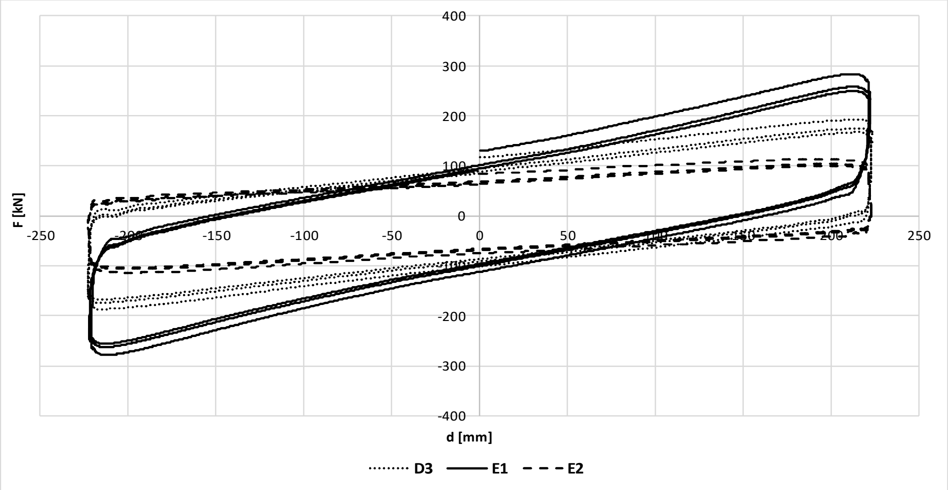


Fig. 12 – Compression load effect

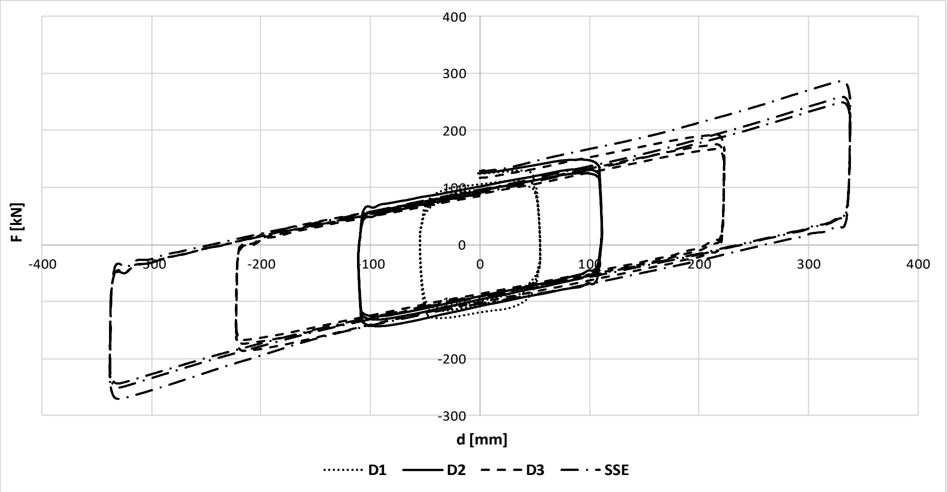


Fig. 13 – Displacement effect

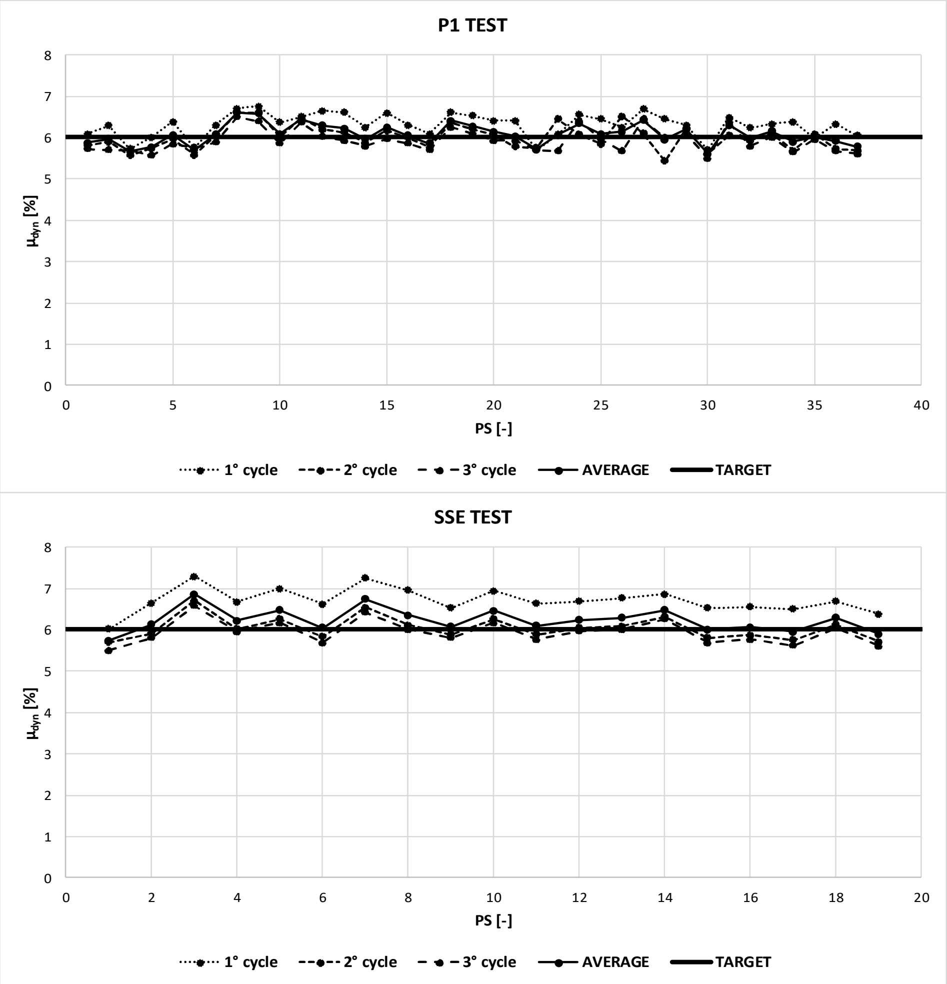


Fig. 14 – Cyclic effect: P1 test (top) and SSE test (bottom)

Fig. 15 shows different parts of the device before assembly, while in Fig. 16 the isolators are ready to be packaged and then shipped.

Fig. 15 – Sliding plates (top) and final quality control checks of the assembled device (down)

Fig. 16 – ISOSISM® PS 3300/700 before packing for shipping

The CSS devices provided by Freyssinet are proven to fully-comply the design specification as well as the European Standard and all the devices were therefore CE-marked. Type Tests and Factory Production Control Tests have given positive results, thus compliant with design performances and respecting the acceptance criteria requested by EN 15129:2009, thanks to high quality production process of all the isolator components. At the time of writing this paper, foundation piles and RC columns have already been built and the ant-seismic devices will be installed in the incoming months of 2020.

5. Conclusions

This paper described the isolation system implemented for 2 elevated LNG tanks, each one with a full working capacity of 10130 m^3. These tanks are under construction at the Corsini port of Ravenna, Italy, a seismic prone area characterized by medium earthquake activity. In fact, base isolation is one of the most widely used techniques for mitigation and control of the seismic response of tanks, especially when raised on short RC columns which therefore do not have a natural capacity to filter the seismic action. Each tank consists of an inner steel tank, containing the LNG, and an outer prestressed concrete one, supported by curved surface sliders, characterized by high lateral flexibility and high friction coefficient to effectively decouple the motion of the ground from that of the structure and dissipate the part of the seismic energy that cannot be filtered.

For this project, Freyssinet Group designed and supplied 182 ISOSISM® PS anti-seismic devices, of which 40% tested in ISOLAB, the advanced internal testing laboratory of the Company, based in Italy. The isolators were designed and tested according to EN 15129:2009 and NCT 2018, providing hence CE certification.

The paper illustrated the details of the complex testing protocol of the devices, as well as the stability of the dynamic response even when the isolators are subjected to the extreme seismic demand; this is made possible thanks to high quality manufacturing with internal severe controlled process and survey to guarantee the constancy of performances.

6. References

[1] Gregoriou VP, Tsinopoulos SV, Karabalis DL (2006): Base isolated LNG tanks: seismic analysis and comparison studies. *1st European Conference on Earthquake Engineering and Seismology,* Geneva, Switzerland.

[2] EN 15129 (2009): Anti-Seismic Devices, Comitè Europèen de Normalisation, Brussels.

[3] MIT NTC (2018): D.M. del Ministero delle Infrastrutture e dei trasporti del 17/01/2018. Aggiornamento delle Norme Tecniche per le Costruzioni.

[4] Paolacci F, Giannini R, Uckan E, Akbas B, Corritore D (2014): Seismic response of elevated tanks by HDRB and FPS isolation systems. *2nd European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey.

[5] Bakalis K, Fragiadakis M, Vmvatsikos D (2015): Seismic response of elevated tanks by HDRB and FPS isolation systems. *5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Crete Island, Greece.

[6] Sezen H, Livaoğlu R, Doğangun A (2008): Dynamic analysis and seismic performance evaluation of above-ground liquid-containing tanks. *Engineering Structures*, **30**, 794-803.

[7] Seleemah AA, El-Sharkawy M (2011): Seismic response of base isolated liquid storage ground tanks. *Ain Shams Engineering Journal*, **2**, 33-42.

[8] Shrimali MK, Jangid RS (2004): Seismic analysis of base-isolated liquid storage tanks. *Journal of Sound and Vibration*, **275** (1-2), 59-75.

[9] Tsipianitis A, Tsompanakis Y (2017): Seismic vulnerability assessment of base-isolated liquid fuels tanks. *12th International Conference on Structural Safety and Reliability*, Vienna, Austria.

[10] EN 1998-4 (2006): Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines.

[11] Malhotra PK (1997): Method for seismic base isolation of liquid-storage tanks. *Journal of Structural Engineering*, **123**.

[12] Sartori M, Barone S, Camossi G, Zivanovic I (2019): Seismic isolation and post-tensioning: a complete solution for the new Trieste harbor logistic. *16th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*, St. Petersburg, Russia.

[13] Barone S, Calvi GM, Pavese A (2019): Experimental dynamic response of spherical friction-based isolation devices. *Journal of Earthquake Engineering*, **23** (9), 1465-1484.

[14] Barone S, Pavese A, Calvi GM (2017): Characterization of frictional properties of different sliding materials for curved surface sliders. *7th International Conference on Advances in Experimental Structural Engineering*, Pavia, Italy.