Feasibility Study of Structural Health Monitoring for Pressurized Spherical Tank in Liquified Petroleum Gas Storage

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Summary

This feasibility has for objective to investigate the dynamic behaviour of a liquified petroleum gas (LPG) storage tank in response to external hazards, primarily earthquakes in an area characterized by a high seismic hazard. The objective is to find the frequencies at which the tank tends to vibrate naturally to ensure structural stability, predict potential weaknesses, and understand how the structure will behave during a strong earthquake.

This work illustrates a workflow aimed at monitoring structural health of civil engineering structures for energy industry using passive ambient noise analysis, operational modal analysis and finite element structure modelling. The results from data analysis and modelling indicate a 1st mode at 1.4 Hz for a tank filled at 2%.

This work focused on the integrity of the supporting frame of the pressurized spherical vessels. The aspect of soil-structure interactions can be integrated into the workflow, including additional passive and active geophysical measurements. Such complementary analysis would help to understand the energy transfer from soil to structure.

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Introduction

The scope of this feasibility is to investigate the dynamic behaviour of a liquified petroleum gas (LPG) storage tank in response to external hazards, primarily earthquakes in an area characterized by a high seismic hazard. The objective is to find the frequencies at which the tank tends to vibrate naturally to ensure structural stability, predict potential weaknesses, and understand how the structure will behave during a strong earthquake.

Dynamic behaviours of pressurized spherical vessels or tanks have been investigated to analyse their resistance to major earthquakes (Zama et al., 2012; Ohno et al., 2015; Sivy and Musil, 2018; Fiore et al., 2018). Structural integrity problems resulting from earthquakes to pressurized vessels, such as spherical storage tanks have three main controlling factors,

a. Soil-structure interactions, including site amplification effects and soil liquefaction;

b. Failure of the supporting structure due to the forces resulting from ground shaking and acting on the structure, such as failure of the braces and buckling of the columns;

c. Sloshing effects, that may amplify the forces acting on the structure, creating larger stresses on the structural elements but also decrease of the eigen period of the structure, resulting in a stabilizing effect in certain situations.

This feasibility work focuses on the failure of supporting structure for a spherical vessel using passive ambient noise analysis, operational modal analysis and finite element structure modelling. Most technical and scientific literature available on spherical tanks draws considerations on the dynamic behaviour of these structures from numerical models not tested against reality. The objective of this work is to collect a dataset to infer the experimental dynamic properties of the spherical tanks and compare with an agile numerical model, with intermediate complexity, that can be easily run and updated.

Data Acquisition

The data acquisition was designed and done at one refilling facility in Kocaeli in Turkey with (Fig.1):

- 3 accelerometers of 2 components placed on the structure to characterize vibrational behaviours of the structure and to provide input for the operational modal analysis technique;
    1. SM051 at the tank equator at N45°W,
    2. SM053 at the tank equator at N10°E,
    3. SM047 at the top centre point of the tank.
- 1 velocimeter of 3 components, EB692, placed on the concrete floor at the south west corner at the base of the tank to evaluate the seismic input intensity and spectra and eventually the peak ground velocity (PGV).

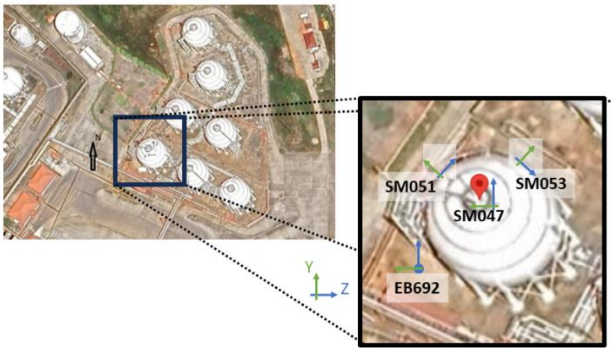

***Fig.1:** Map View of the accelerometers (SM047, SM051 and SM053) and velocimeter (EB692) positions and orientations relative to the gas tank.*

During the acquisition, the tank capacity went through a cycle of capacity:

- a decrease in the tank filling from 80% to 2% of its capacity from Nov. 11th to 13th,
- an increase back to the initial state of 80% as tank filling from Nov. 17th to 19th.

Ambient Noise Analysis

The quality of the data is impacted by many factors: equipment, installation conditions, ambient noise, self-noise of the equipment, data filters and so on. Ambient noise analysis was performed computing a root mean square (RMS) of the Fourier Transform of the stacked data recorded at each sensor, over 30 min of data and on a sliding window every 15 min. Such analysis, showing variation in data amplitude every 15 min considering 30 min of data, shows how repetitive the ambient noise is over the recording period. The ambient noise varies with work cycles, alternating high and low activities on site. High activities are recognized with high ambient noise from 07:00 during working hours. A break of activities can be seen in midday and after 19:00 (Fig. 2).

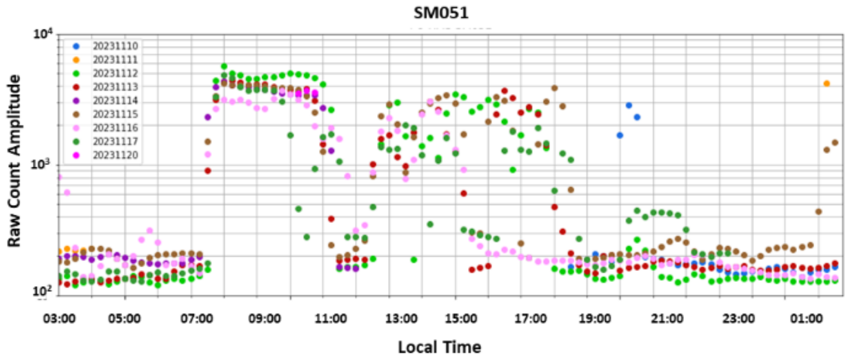

Fig.2: Ambient noise analyses on site indicates daily repetitive patterns .

Operational Modal Analysis (OMA)

The Operational Modal Analysis (OMA) is a data-driven approach used to check integrity and reliability of structures. OMA technique assumes that ambient seismic noise, i.e. vibrations generated by natural and anthropogenic sources, are able to excite the structure in such a way that starts vibrating following its natural modes (Ranieri and Fabbrocino, 2014; Brincker and Ventura, 2015). This requires that the seismic noise has sufficient energy to induce vibrations in the structure, but the frequency content is such that there is no dominant frequency (harmonic), i.e. the noise is white and broadband. This is clearly not always the case (rather, the opposite!) in an industrial context, where during working hours several devices (pumps, engines, etc) and machines (vehicles, cranes, etc) are in operation. Actions have therefore to be taken to characterize the ambient noise and reduce spurious effects.

Comparison of the experimental data with simulations performed using a dynamic finite element model of the structure is used to derive the structure characteristics, calibrate model parameters and subsequently evaluate their response in case of large earthquakes, when possible.

The modal analysis is done by using the method known as frequency domain decomposition, used extensively in civil engineering to analyse the dynamic behaviour of structures, such as bridges, buildings, and dams. A Singular Value Decomposition is performed on the energy spectra of recorded data, and the resulting singular values are used to identify the modes, if the peaks can be identified with sufficient accuracy and the noise contamination is effectively reduced or eliminated. The identified frequencies and corresponding mode shapes then can be extracted from the fitted complex exponentials. Each frequency represents a natural frequency of the structure, while the associated mode shape shows how the structure deforms or vibrates at that frequency. Additional parameters like damping ratios and modal participation factors are derived from the identified modes. These parameters provide crucial insights into structural dynamics.

From the frequency domain decomposition done over the data recorded on the 12th and the 13th of November, several consistent peaks appear in the frequency range between 1 Hz and 2 Hz (Fig.3).

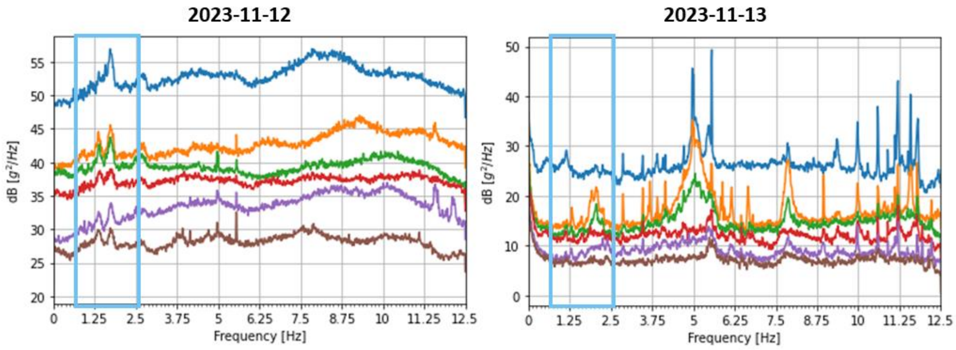

Fig. 3: Decomposition in frequency domain of the data recorded on 2 days on the 12th (left) and 13th (right).

Inspection of the PSDs (Power Spectral Densities) of all days suggest that background noise levels strongly affect peak identification (Fig.4). During noisy periods, peaks corresponding to the fundamental mode are hidden by other harmonics resulting from noise sources (Fig. 4 left). Vice-versa, during the night, with very low background noise, the peaks completely disappear, most likely because the energy in the vibrations is not sufficient to excite the structure (Fig. 4 right). The best period for extracting the fundamental frequency appears to be in the evening, when activities on site are reduced but still there is enough energy to trigger the fundamental mode (Fig. 4 middle).

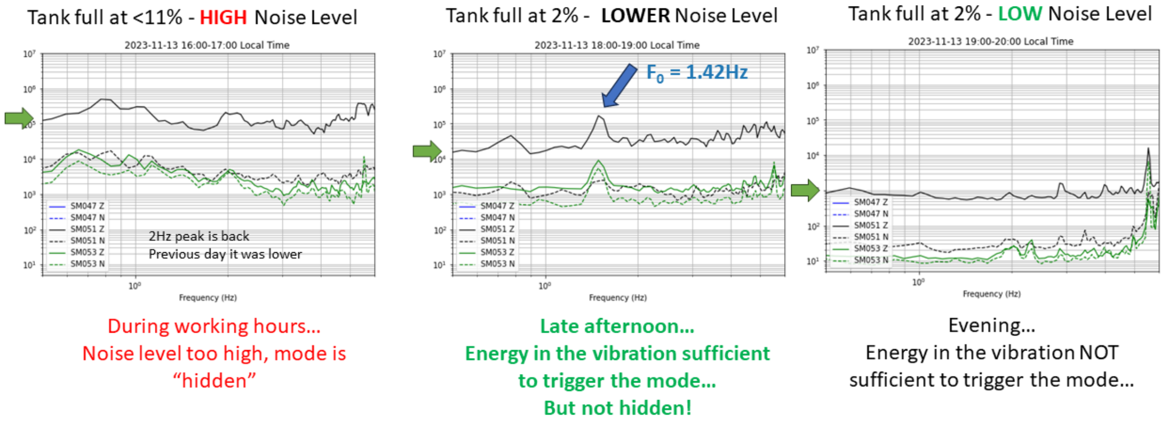

Fig. 4: Observation at low frequencies between 1 Hz and 2 Hz for various times during the day during high noise level (left), lower noise level (medium) and too low noise level (right).

Finite Element Analysis and Structure Modelling

For the modelling of the structure using Finite Element Analysis, the structure was assumed to be composed of 12 columns of 12 m height with in-between braces, composed of the same material (Fig. 5). The lumped mass method, a structural analysis approach, is used to monitor the structural health. Its advantage is in its simplification of complex structures into simpler systems by considering the mass of the structure as concentrated at specific points or nodes. In this present case of the spherical gas tank, one lumped mass was placed at the centroid of a rigid diaphragm at the column tops, with 3 degrees of freedom: 2 on the horizonal plane and 1 rotation around the vertical axis.

For the finite element analysis, the software NextFEM was used with Open System for Earthquake Engineering Simulation as a solver for the simulation of the performance of structures subjected to natural hazards. The modelling was run and calibrated using the results from the OMA analysis above. In particular, the data show that the fundamental mode has a frequency of about 1.5 Hz for an almost-empty tank. The model was also used to compute the first three modes (Fig. 5 – right side). To calibrate the model, the material properties were adjusted setting the Young modulus to 290 GPa and Poisson’s ratio to 0.3 for pillars and braces. This results in a frequency of the fundamental mode of 1.44Hz, in accordance with the measured data.

Note that fundamental modes are expecting to decrease with the mass of fluid contained in the tank, as the tank is getting full. With a filling going from 2% to 90%, the fundamental frequency is estimated to be 1.41 Hz and 0.76Hz, respectively.

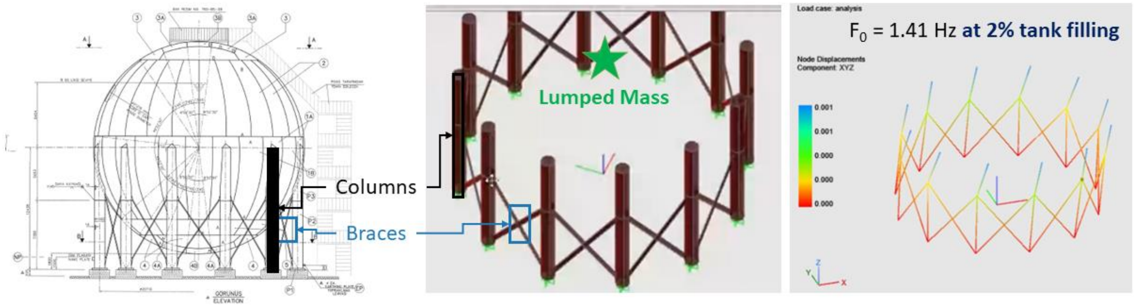

***Fig. 5:** Gas Tank Drawing (left), Lumped Mass Modelling with columns, braces and lumped mass (medium) with modelling results with 1st mode at 1.4 Hz for tank filling at 2% (right).*

Conclusions

This feasibility illustrates a workflow to monitor health of civil engineering structures for energy industry. The proposed workflow includes ambient noise analysis, operational modal analysis and finite element modelling as a lumped mass model. The results from data analysis and modelling indicate a 1st mode at 1.4 Hz for a tank filled at 2%.

This work focused on the integrity of the supporting frame of the pressurized spherical vessels. The aspect of soil-structure interactions can be integrated into the workflow, including additional passive and active geophysical measurements. Such complementary analysis would help to understand the energy transfer from soil to structure.

As well, understanding sloshing effects can be performed extending the modelling approach. This would require a much more detailed FE model, with a significant increase in computational complexity. Finally, different structures could be compared to classify structures and their various health conditions.

Acknowledgements

The authors would like to thank Petrol Ofisi and ISAMGEO for the permission to publish these data and results. The authors would also like to acknowledge Lunitek as provider for sensors as well as the software used for this study: PyOMA (Pasca et al., 2022), NextFEm and Berkeley OpenSees.

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