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SEISMIC ANALYSIS OF A HISTORIC WATER TOWER: A FLUID-STRUCTURE-SOIL INTERACTION PROBLEM

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Abstract. *The dynamic analysis of a historic water is attempted taking into consideration the fluid-structure-soil interaction. The water tank is cylindrical with a concentric manhole and rests on a relatively flexible structure and a ring of surface foundations. A FEM model of the tower and the structure is developed preserving all the details of the original structure. Extensive parametric studies, undertaken in the context of this work, resulted in a discrete model for the hollow water tank along the lines of the convective-impulsive mass concept. Related non-dimensional charts are shown herein. In addition, a discrete spring-mass-damper model is used for the simulation of soil-structure interaction. The full model of the water tower is subjected to seismic excitation and the results obtained by this rigorous numerical model are compared to other simplified approaches.*

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1 INTRODUCTION

The water tower under investigation was designed by the famous Italian engineer Pier Luigi Nervi for the Santa Maria Novella Station in Florence, introducing several innovations in comparison to other similar structures of the same era. It was constructed in 1930 and is still in use. Figure 1 shows a view of the structure and representative plans [1,2].

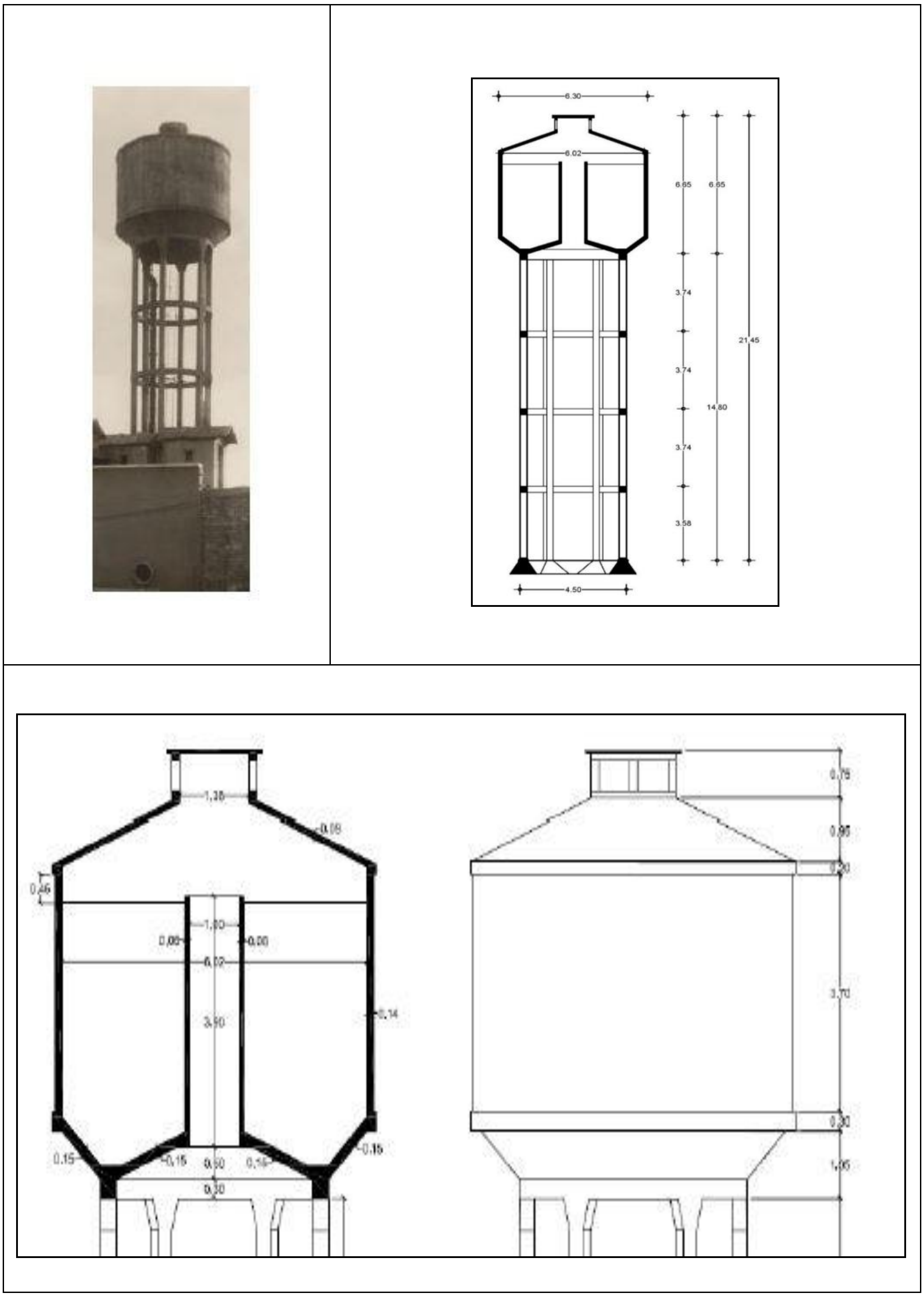

Figure 1. View and plans of the water tower at Santa Maria Novella Station in Florence [1,2].

The motivation for this study comes from a similar work by Sorace, Terenzi & Mori [2] and the particular way they model the circular water tank with the coaxial manhole, although this was not the focus of their work. They based their model on the discrete impulsive-convective Housner [3,4] approach for circular tanks, without manhole. To this, they added some arbitrary modifications, i.e. subtracting the volume of the manhole from the total water volume and, thus, calculating an equivalent water mass corresponding to an idealized circular tank of reduced water content. Although this approximation appears, more or less, adequate for the geometry and water level of the particular structure, it certainly violates the intrinsic hydrodynamic characteristics of such structures, in general, since the physical presence of the manhole is ignored. With this in mind, the authors of this work set out to perform a parametric study for water tanks with coaxial manholes based on a rigorous FEM model. The results of this study are compared to those obtained in [2] and some interesting conclusions are drawn. Finally, a complete analysis of the water tower at the Santa Maria Novella Station is presented (a) using a rigorous FEM model for the structure and the water-structure interaction and (b) taking in addition into account the interaction of the above system with the soil. The results of this analyses are also compared to those obtained using the approximate approach presented in [2].

2 DYNAMIC ANALYSIS OF CIRCULAR TANKS WITH COAXIAL MANHOLES

The geometry and a FEM model of a circular, full water tower with a manhole are shown in figure 2. In all cases examined in this eigenanalysis, the concrete walls of the outside and the inside (manhole) shells are considered rigid and, for the purposes of this parametric study aiming at computing the dynamic characteristics of the liquid content, of negligible mass.

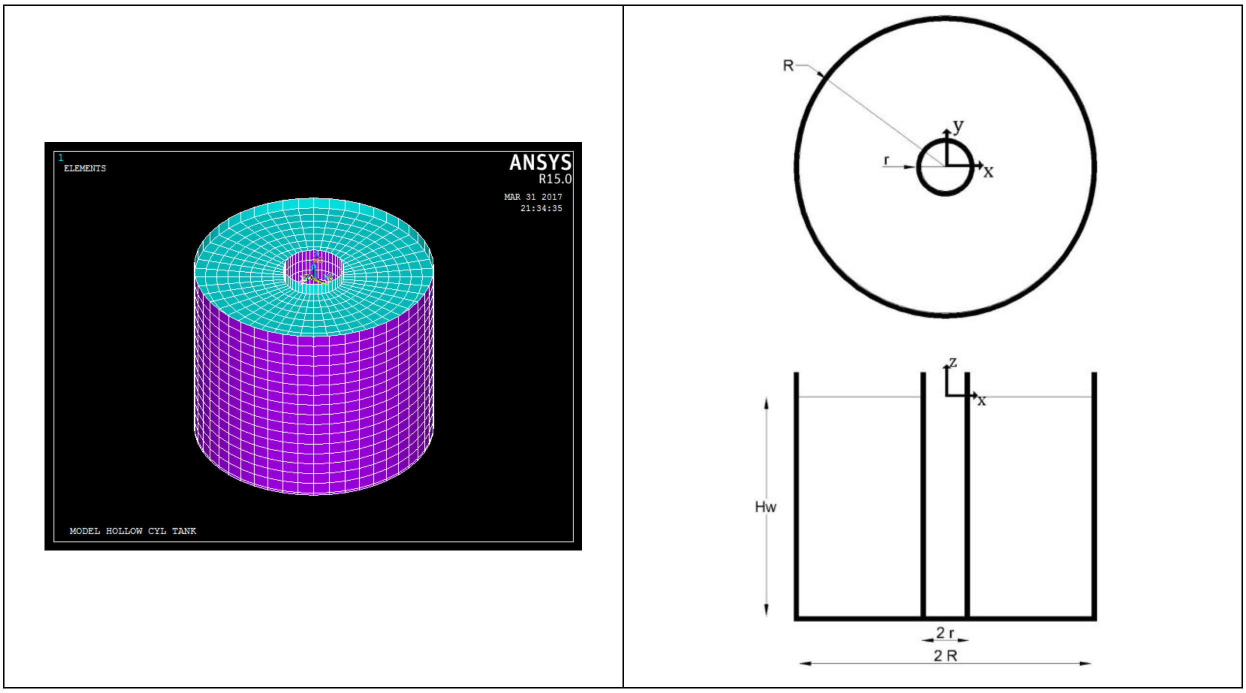

Figure 2. Geometry and FEM model of circular water tank with manhole.

The results of the modal analysis of the tank are shown in figure 3, where (a) the 1st eigenfrequency of the water, (b) the 1stconvective mass M_1, and (c) the corresponding convective mass height H_1 are plotted in a non-dimensional form versus the ratio r/R, i.e. the radius of the manhole to the that of the tank, as shown in figure 2. In all cases, g is the acceleration of gravity, M_w is the total mass of water and H_w the total height of water in the tank. The results obtained by the rigorous FEM model are plotted along with those of the approximate approach used in [2]. In an effort to verify the accuracy of the above solutions, results for r=0, i.e. a cylindrical tank without a manhole, as obtained from the analytic solution provided in Ref. [5], are also shown in figure 3, for all ratios of H_w/R.

1st eigenmode

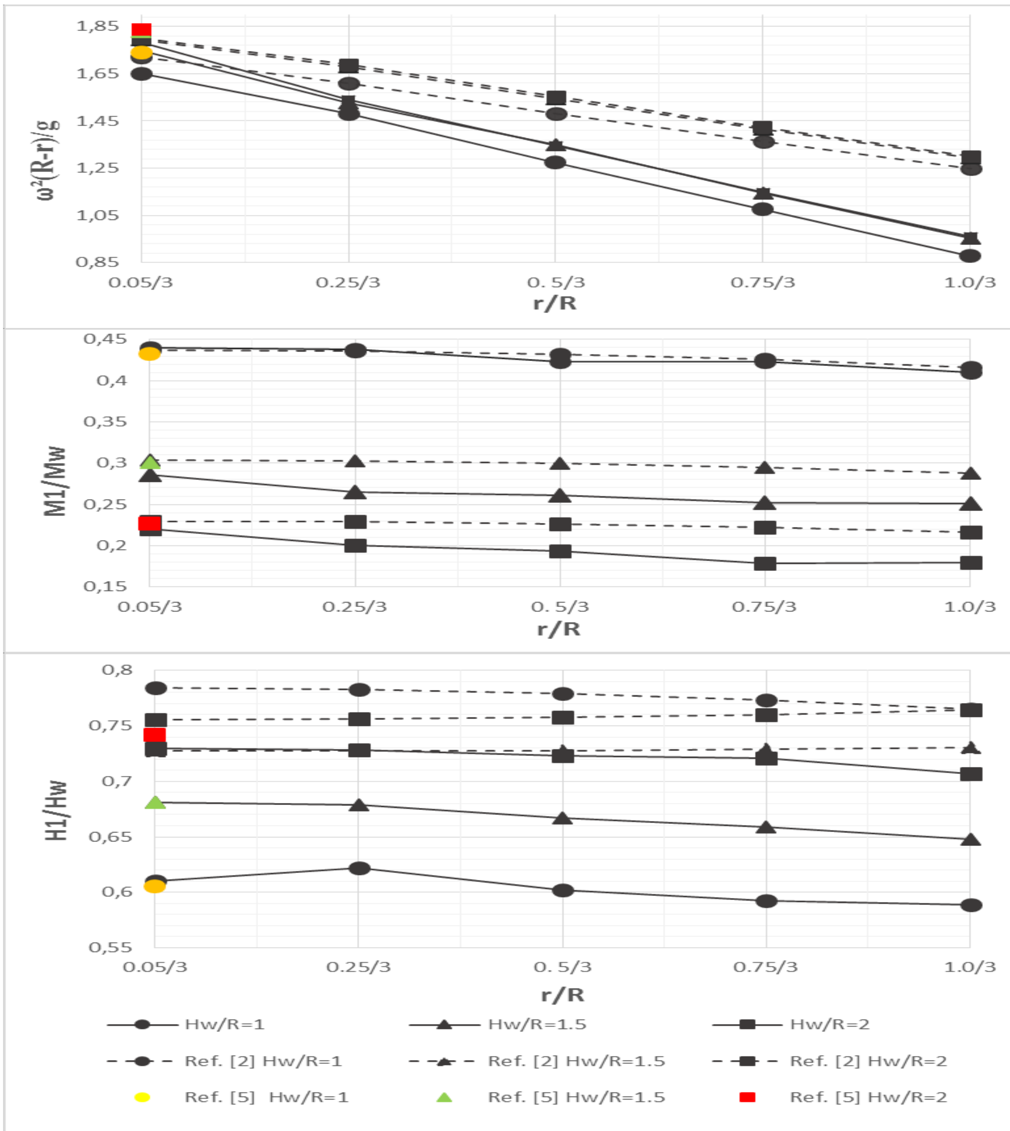

Figure 3. Non-dimesional of 1st eigenfrequency and corresponding convective mass and convective mass height versus the ratio of r/R for several values of H_w/R.

On the basis of the results shown in figure 3 it is concluded that (a) as it should be expected, the difference between the rigorous FEM model and the approach adopted in Ref. [2] increases as the ratio r/R increases, (b) the differences between the two approaches also increase as the height H_w of the water increases in comparison to the radius R of the tank. These differences are in all cases substantial, except for $H_w/R=1$ where a good agreement between the ratio M_1/M_w appears for all values of r/R. Of course, both approaches converge well at the limit value of r/R=0.05/3 to those provided in Ref. [5] for simple cylindrical tanks. However, for the particular water tank resting on the tower at the Santa Maria Novella Station, where r/R=0.5/3 and $H_w/R=1.2$ (approximately) the approximate approach of Ref. [2] presents an error, as compared to the rigorous FEM model, of about 23% with respect to the 1st eigenfrequency, 15% with respect to the ratio M_1/M_w, and 10% as far as the ratio H_1/H_w is concerned.

3 SEISMIC RESPONSE OF WATER TOWER AT SANTA MARIA NOVELLA STATION

As a first step towards a practical seismic analysis, the entire water tower at Santa Maria Novella Station, actual structure and full water tank, is subjected to a horizontal seismic excitation. The seismic record chosen is an artificial accelerogram compatible with the design spectrum of Eurocode 8 for soil category C and damping 5%, with PGA=0.4g and duration 20sec. The fitting of the artificial accelerogram to the target spectrum is made via the iterative procedure introduced in [6]. A 6% of critical damping is assumed for the concrete structure. The analysis is performed using (a) a full FEM model, including the fluid in the tank, and (b) a FEM model for the concrete structure and the approximate discrete model proposed in [2] for the fluid. The 1st period of the structure is computed at 2.87sec using the FEM model and 2.58 sec using the approach in Ref. [2]. Certainly the high value of the 1st period is attributed to the convective fluid mass which accounts for about 30% of the total water mass, and the remaining impulsive mass, since the 1st period of the rather flexible concrete structure, with an empty tank, is 0.94sec. The response versus time of the water tower, in terms of displacement at the top of the structure and base shear, is shown in figure 4.

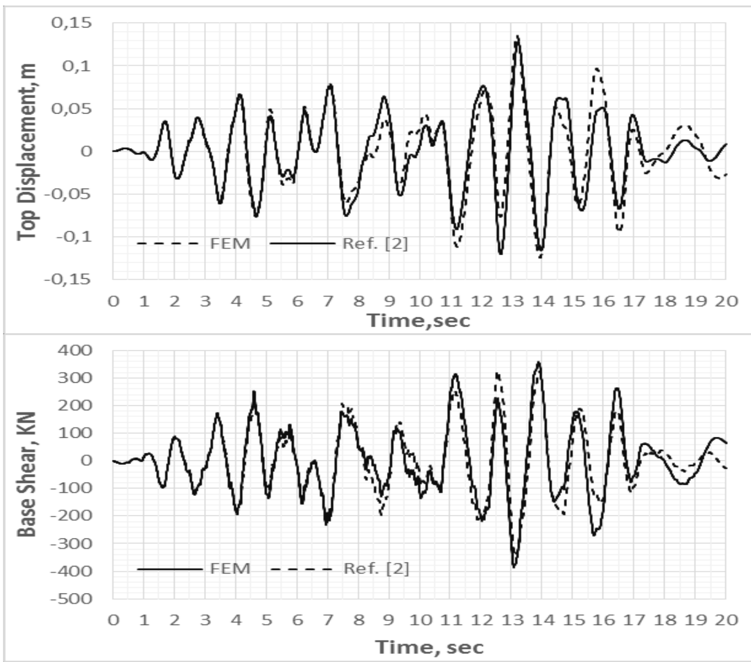

Figure 4. Displacement at the top and base shear of the water tower at Santa Maria Novella Station versus time due to a seismic excitation compatible with the design spectra of EC-8.

Although for this structure, the differences in peak absolute values in terms of displacements and base shear do not seem large, the differences in the dynamic characteristics used by the two approaches (see discussion in previous section) become evident. Of course, the FEM model takes effectively into consideration all eigenmodes of the sloshing fluid (at least those "allowed" by the particular choice of time step) while in the approximate discrete model of Ref. [2] only the 1st mode is included. As it is shown in the literature, e.g. Refs [5,7], the 2nd and higher sloshing modes are of negligible importance and can safely be ignored for all practical purposes.

In a second step, the effect of soil-structure interaction is considered. To this extend, a discrete spring-mass system is introduced at the base of the foundation of the FEM model. The water tower under investigation is supported by 6 footings, at the base of each column, closely arranged and connected rigidly at their top by circular beam. For the purposes of this study, the foundation is simulated as a rigid circular ring resting on a soil medium with shear wave velocity around 280m/sec (an arbitrary guess for the actual soil conditions). The spring and damping constants are computed following the approach proposed in Ref. [8]. Further details for the FEM simulation of the structure and the foundation model can be found in Ref. [9]. The same artificial accelerogram is used as in the previous paragraph. As it is expected, a relative increase in the top displacement and a decrease in the base shear, as compared to fixed base conditions, are observed when the SSI phenomenon is taken into account.

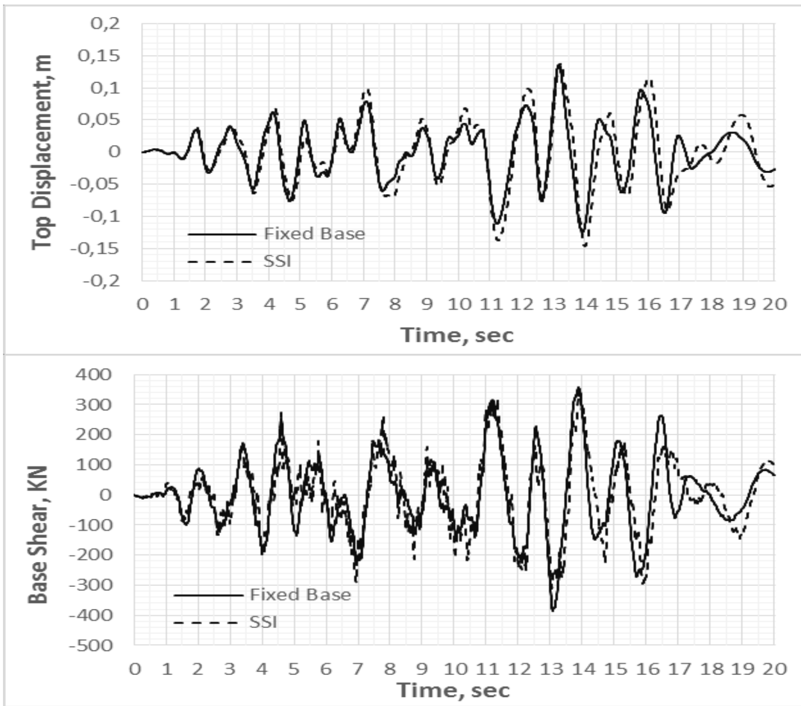

Figure 4. A comparison study between fixed base and SSI conditions in terms of displacement at the top and base shear of the water tower at Santa Maria Novella Station due to a seismic excitation compatible with the design spectra of EC-8.

4 CONCLUSIONS

A FEM rigorous model is developed for the study of the structure-fluid interaction of cylindrical tanks with a coaxial manhole. The results of these analyses are compared to those obtained by an approximate approach where the hydrodynamic effects due to structural geometry are ignored. The conclusions drawn on the basis of these parametric studies are as follows:

- The 1st eigenperiod of the tank increases monotonically as the radius of the manhole increases in comparison to that of the tank ratio (r/R), and it is almost independent of the water level H_W/R.
- The differences of eigenanalysis characteristics, i.e. 1st eigenfrequency and the corresponding convective mass and convective mass height, between the two approaches increase substantially as the radius of the manhole increases in comparison to that of the tank, for all levels of water fill.
- A seismic analysis of the historic water tower at Santa Maria Novella Station using both approaches results to minor differences between them. This is attributed to the particular geometric and structural characteristics of the tower under investigation.
- Hydrodynamic effects caused by a particular structural geometry, such as internal holes, should not be ignored, in general, for structures in which a large portion of the vibrating mass is in fluid form and is located at a high elevation with respect to the rest of the structure, e.g. water towers.
- Approximate approaches ignoring hydrodynamic effects are not in a position to consider certain important effects related to sloshing, e.g. wave height and overspilling.
- SSI for structures with large fundamental period does not play an important role in their seismic response. However, it could become detrimental for seismic motions of low frequency and soft soil conditions.

REFERENCES

[1] S. Sorace, Private correspondence, 2015.

[2] S. Sorace, G. Terenzi, C. Mori, Passive energy dissipation-based retrofit strategies for R/C frame water towers, *Engineering Structures,* **106**, 385-398, *2016.*

[3] G.W. Housner, Dynamic behavior of water tanks, *Bulletin of the Seismological Society of America,* **53(2)**, 381-387, 1963.

[4] M.A. Haroun, G.W. Housner, Seismic design of liquid storage tanks, ASCE Journal of Technical Councils, **107(1)**, 191-207, 1981.

[5] A.S. Veletsos, P. Shivakumar, Tanks containing liquids or solids, Chapter 15, D.E. Beskos, S.A. Anagnostopoulos eds., *Computer Analysis and Design of Earthquake Resistant Structures A Handbook*, Advances in Earthquake Engineering, Computational Mechanics Publications, Southampton, 1997.

[6] D.L. Karabalis, G.J. Cokkinides, D.C. Rizos, J.S. Mulliken, Simulation of earthquake ground motions by a deterministic approach, *Advances in Engineering Software*, **31**, 329-338, 2000.

[7] G.C. Drosos, A.A. Dimas, D.L. Karabalis, Discrete models for seismic analysis of liquid storage tanks of arbitrary shape and fill height, *Journal of Pressure Vessel Technology*, **130**, 1-12, 2008.

[8] T. L. Karavasilis, D.C Rizos, D.L. Karabalis, Seismic analysis of spherical tanks including fluid-structure-soil interaction, *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, August 1-6, 2004.

[9] A. Zanni, Dynamic analysis of a water tower including soil-structure interaction, Diploma Thesis, Department of Civil Engineering, University of Patras, Greece, 2016.