



# Evaluating the Spectral Acceleration Amplification Effects on the Seismic Response of Elevated Steel Water Tanks

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## ABSTRACT

Water Tanks are amongst the most important structures which are used for storage and providing the water needed on the pick usage time in water supply networks. The Seismic behaviour of such special structures is the main objective of current research, which was motivated by raising demands for design and construction of elevated water tanks. Hence, two structural models of steel elevated water tanks in Armenia, with capacities of 134m<sup>3</sup> and 160m<sup>3</sup>, demonstrating a height of 24m and 30m respectively are selected as shown in Figure 1. Each model is considered to be empty, 50% and 100% full and is designed according to Armenian SNIP II-6.02 seismic code for all filling strategies, taking into account the spectral acceleration level equal to  $S_a=0.40g$ . On each model, the information of Convective mass, Impulsive mass and the spring stiffness of the convective and impulsive masses are added, due to the Housner's Equivalent Mass-Spring theory, considering Soil-Structure Interaction (SSI) effects at the meantime. Earthquake Analysis procedures of the whole fluid-tank systems are completed by the means of Time History Analysis method, using 3 horizontal components of selected accelerograms, recorded on soil categories of Rock, Dense Soil and Loose Soil respectively, scaled to spectral acceleration levels of  $S_a=0.2g \sim 1.0g$ . Finally, the seismic response is computed for the filling strategy of Empty, 50% full and 100% full conditions for both models.

## Keywords:

Soil-Structure Interaction, Time History Analysis, Mass-Spring Theory, Water Tanks, Spectral Acceleration.



## 1. Introduction

Elevated water tanks are heavy structures which contain most of their weight is concentrated on a higher level than the level of its supports. According to fluid-structure interaction, the seismic behavior of the structural system is related to seismic load specifications. Elevated water tanks should be designed in such a way that could be able to maintain serviceable after an earthquake. Due to this, accurate analysis of these types of structures, according to modal displacements of contained fluid is recommended. Intensive research, taking into account additional mass model and soil-structure interaction is carried out by Haroun. Preliminary applied method for dynamic analysis of tanks is presented by Housner (1957). Researcher proposed a simple method for estimating the dynamic effects of fluid in solid cylindrical and rectangular tanks during an earthquake. He divided the hydrodynamic pressure into two parts: Impulsive mass and Convective mass. The main goal of Housner was to simplify the fluid behavior in order to propose an equivalent mass-spring dynamic model. He also applied a simple dynamic analysis for elevated tanks by the means of the equivalent mass-spring theory, based on response spectrum. Structures designed to resist moderate and frequently occurring earthquakes must have sufficient stiffness and strength to control deflection and to prevent any possible damage. Selecting a good structural system requires understanding seismic behavior of the systems available. Since stiffness and ductility are generally two opposing properties, it is desirable to devise a structural system that combines these properties in the most effective manner without excessive increase in the cost. For the seismic analysis of overground and underground structures, consideration of the soil-structure interaction becomes extremely important when the soil or the foundation medium is not very firm. During earthquake excitation, the structure interacts with the surrounding soil imposing soil deformations. These deformations, in turn, cause the motion of the supports or the interface region of the soil and the structure to be different to that of the free field ground motion. These interactions substantially change the response of the structure. For very stiff soil, this change is extremely small and can be neglected. Therefore, consideration of base fixity remains a valid assumption for overground structures constructed on firm soil. Similarly, the effect of soil-structure interaction on long buried structures, such as pipelines, within firm soil is negligible as it takes the same profile as that of the soil during the earthquake motion. In order to understand the soil-structure interaction problem properly, it is necessary to have some knowledge of the earthquake wave propagation through the soil medium for two main reasons. Firstly, the dynamic characteristics of the input ground motion to the structure depend upon the modification of the bedrock motion as it propagates through the soil. Thus, the knowledge of wave propagation through the soil medium is essential to understand ground motion modifications due to soil properties. Secondly, the knowledge of the vibration characteristics of the soil medium due to wave propagation is important in relation to the determination of the soil impedance functions and fixing the boundaries for a semi-infinite soil medium, when the wave propagation analysis is performed by numerical techniques. In this research, fluid-structure interaction is taken into account by the use of Housner's equivalent mass-spring theory and the soil-structure interaction is modeled by using spring dashpot theory.



## 2. Housner's Equivalent Mass – Spring Theory

If the fluid fulfills the reservoir completely so that the vertical movement of the fluid is prevented, the complete could be assumed as a whole body demonstrating a single degree of freedom system.

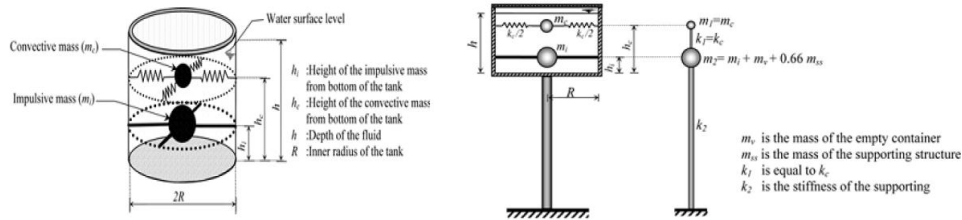


Figure 1. Two mass model and equivalent Mass-Spring

The mentioned assumption is often unreal and during the sloshing mode of the fluid, the behavior of the whole reservoir will vary to an extent. One of the well-known analysis methods of reservoirs by taking into account the sloshing mode of the fluid is proposed by Housner, illustrated in Figure 1. As could be observed in Figure 1,  $m_1$  is the convective mass of the sloshing fluid and  $m_2$  is the total mass of fluid + empty reservoir + partial mass of the supporting structure. The analysis method by the means of Housner's method is completed using equations 1~5:

$$M_i = M_w th(1.74R/H)/(1.74R/H) \quad (1)$$

$$h_i = (3/8)H \quad (2)$$

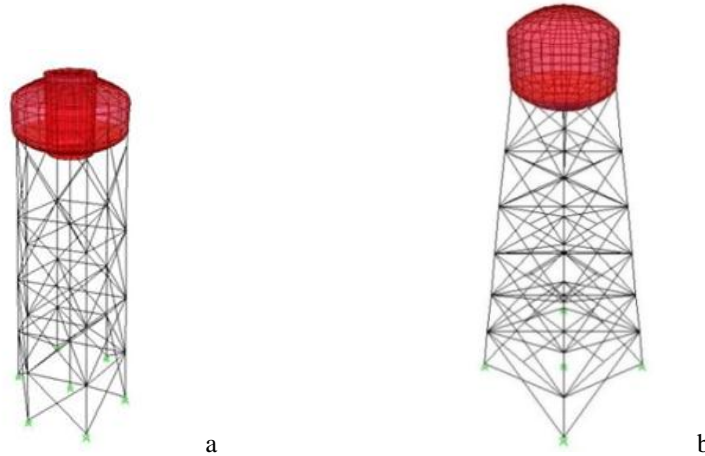
$$M_c = (0.318M_w R/H) th(1.84H/R) \quad (3)$$

$$K_c = (1.84M_c g/H) th(1.84H/R) \quad (4)$$

$$h_c = \left[ 1 - \frac{\text{Cosh}(1.84H/R) - 1}{1.84H/R \text{ Sinh}(1.84H/R)} \right] H \quad (5)$$

## 3. Tank-Liquid Finite Element Computational Models

In this research three elevated water tanks with braced supporting steel structure, containing values of 134 & 160 cubic meters are proposed. Dimensions and elevations of the proposed models are as Figure 2:



**Figure 2.** Proposed models a: 134m<sup>3</sup> tank & b: 160m<sup>3</sup> tank

- a- 134m<sup>3</sup> tank: Diameter=7.27m, Reservoir height=4.20m, Reservoir Level=24.0m
- b- 160m<sup>3</sup> tank: Diameter=7.00m, Reservoir height=6.60m, Reservoir Level=30.0m

Pipe sections are used for supporting steel structures. Vertical Bracings and horizontal beams are of pipe sections too. Models are designed due to 1,2, & 3 soil specifications and  $S_a=0.40g$  spectral accelerations, taking into account Empty, 0.50 full and 100% full conditions. When calculating the equivalent stiffness and damping of soil, the Rocking and Torsional movements are neglected, since the radiation damping of them are less than 2%. Soil stiffness and damping ratios are computed according to Spring-dashpot theory and is summarized in Table 1.

**Table 1. Soil Stiffness and Damping for 200x200 footings.**

	$K_v$ (kg/m)	$C_v$ (kg-sec/m)	$K_h$ (kg/m)	$C_h$ (kg-sec/m)
<b>Rock</b>	8.83e6	9.46e6	7.06e6	5.80e6
<b>Dense Soil</b>	2.22e6	4.62e6	1.78e6	2.83e6
<b>Loose Soil</b>	6.00e5	2.35e6	4.80e5	1.44e6

#### 4. Time History Analyses

In order to perform the time history analyses, 3 pair of accelerograms of earthquakes listed in Table2. Accelerograms are recorded on each soil type, according to Armenian SNIP II - 6.02 code, then scaled to spectral acceleration level of  $S_a= 0.20g \sim 1.0g$  respectively. Later the scaled records were applied to the finite element models due to the soil type and spectral acceleration level. For Time history analyses, the “Direct Integration” technique was used and for both models were completed using Newmark –  $\beta$  method, using  $\gamma = 0.5$  &  $\beta = 0.25$ . Due to structural characteristics, the damping ratio was determined equal to 0.05 for the first two modes of vibrations.

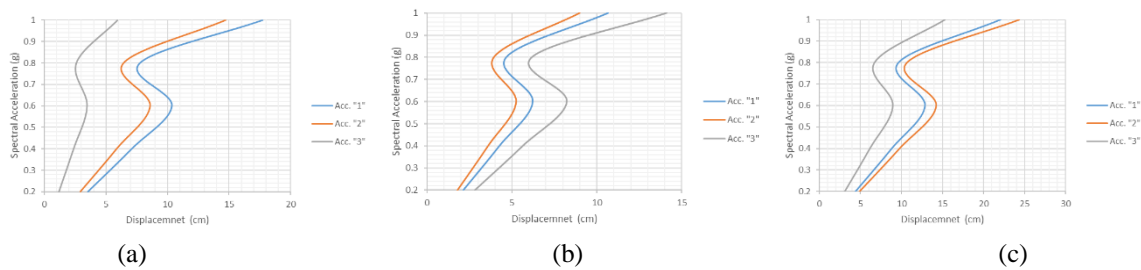


**Table 2. Characteristics of used Earthquake Records.**

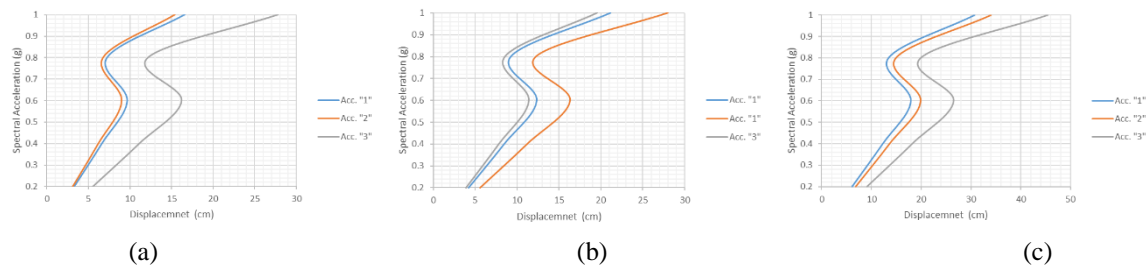
Event	Year	Mag.	Mechanism
Irpinia-Italy	1980	6.9	Normal
Tabas-Iran	1978	7.35	Reverse
Loma Prieta	1989	6.93	Reverse-Oblique
Northridge	1994	6.69	Reverse
San Fernando	1971	6.61	Reverse
Landers	1992	7.28	Strike-Slip
Hector Mine	1999	7.13	Strike-Slip
Westmorland	1981	5.9	Strike-Slip
Imperial Valley	1979	6.53	Strike-Slip

## 5. Numerical Results

The numerical analysis results of the tank-reservoir system are based on filling strategy. For the results of the analyses to be apparent, they are converted into diagrams of base shear force versus percent of filling. The mentioned diagrams are shown in Figure 3~8.



**Figure 3.** Diagrams of Spectral Acceleration versus Displacement for Filling Strategy of 0% for soil categories of: a) Rock, b) Dense Soil and c) Loose Soil for model "a".



**Figure 4.** Diagrams of Spectral Acceleration versus Displacement for Filling Strategy of 50% for soil categories of: a) Rock, b) Dense Soil and c) Loose Soil for model "a".

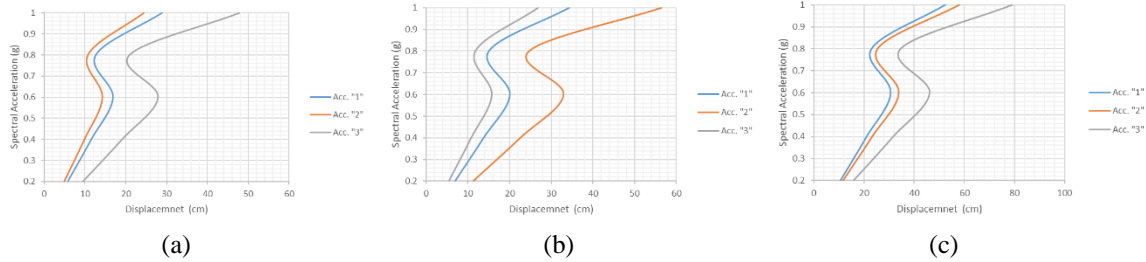


Figure 5. Diagrams of Spectral Acceleration versus Displacement for Filling Strategy of 100% for soil categories of: a) Rock, b) Dense Soil and c) Loose Soil for model “a”.

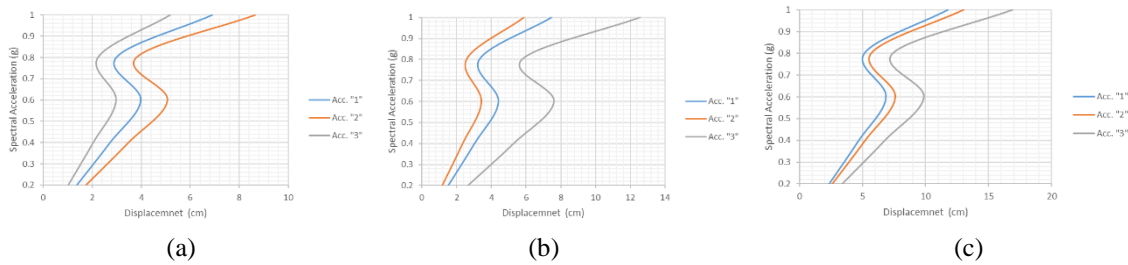


Figure 6. Diagrams of Spectral Acceleration versus Displacement for Filling Strategy of 0% for soil categories of: a) Rock, b) Dense Soil and c) Loose Soil for model “b”.

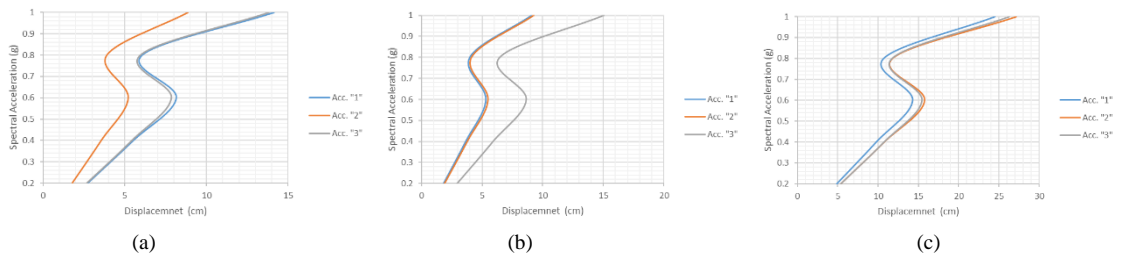


Figure 7. Diagrams of Spectral Acceleration versus Displacement for Filling Strategy of 50% for soil categories of: a) Rock, b) Dense Soil and c) Loose Soil for model “b”.

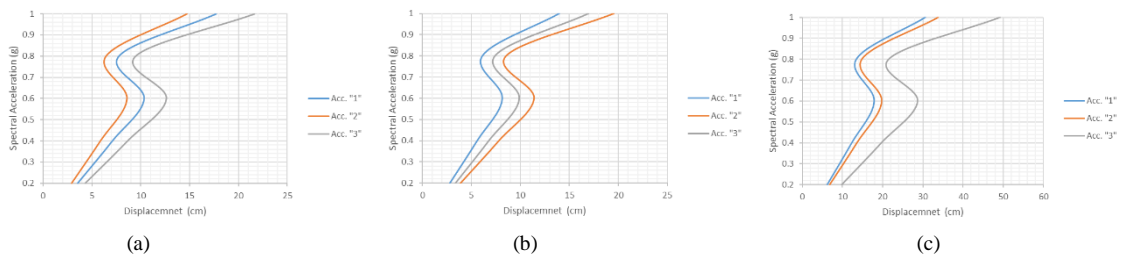


Figure 8. Diagrams of Spectral Acceleration versus Displacement for Filling Strategy of 100% for soil categories of: a) Rock, b) Dense Soil and c) Loose Soil for model “b”.



## 6. Conclusion

The computational results of FEM analysis of the whole Fluid-Soil-Structure system in Figures 3 to 8 illustrate that by degrading the soil category, the lateral displacement amplification due to filling percent of tanks converts to be nonlinear for all soil categories, regardless of the frequency content effects of the earthquake records. All diagrams of spectral acceleration versus displacement show two turning points at 0.60g and 0.78g. Generally, the randomness of results decrease while the soil category degrades containing a few exceptions, which demonstrates the lower effects of frequency content of the earthquake records. For the existing exceptions even, 2 accelerograms out of 3 are demonstrating low randomness, when the soil category degrades. The displacement amplification decreases due to soil degradation which illustrates the high filtering effect of convective mass sloshing modes in case of low frequency content of selected accelerograms. The SSI effect also causes the sloshing mode of convective mass to operate as a more powerful frequency filter, when the soil category degrades.

## 7. References

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