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DESIGN OF THE SPHERICAL LIQUID STORAGE TANKS FOR EARTHQUAKE RESISTANCE

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Abstract: Tanks of different shapes and sizes are installed in almost each section of industry and are used as storage for various types of liquids. Therefore, liquid storage tanks should be properly designed to withstand different types of loadings. One of them is the investigation of structures subjected to a seismic excitation. A specific interaction between the tank and the liquid occurs during a seismic loading. It can be determined as a vibration of the tank, its walls and contained liquid (i.e. impulsive and convective liquid portions). Standards for seismic resistance include procedures for calculation of seismic characteristics of tanks with shapes and cross-sections of elementary geometry (e.g. circular, rectangular cross-section). These codes are based on simplified mechanical models. However, there are several different shaped tanks (e.g. spherical, truncated conical, etc.) that do not have simplified models. Also, the procedures for the seismic design of individual different shaped tanks are not covered by standards for earthquake resistance. The article deals with the seismic analysis of a spherical liquid storage tank intended to compute the dynamic responses of the tank-liquid system to a seismic event using analytical methods (such as general principles for structural design, analytical studies) and numerical computations based on the finite element method in software ANSYS.
Keywords: spherical liquid storage tank, impulsive vibration, sloshing effect, seismic vulnerability, seismic design

1. INTRODUCTION

Large capacity tanks or vessels of different sizes, shapes and orientations are essential components in transmission, distribution and processing systems, e.g. reservoirs, pressure vessels, heat exchangers, evaporators, cooling and drying devices (more described in [1]). These devices are used for storing of various liquids from non-flammable, non-toxic liquids to dangerous flammable or toxic chemicals with explosive nature (e.g. chemicals, liquefied natural gas, oil, etc.) and are installed almost in each sector of contemporary industry such as nuclear, energy, chemical, food, etc.

During ordinary operation, the liquid storage tanks can be subjected to loadings of different nature which may have negative effects on the behaviour of the system. Therefore, a failure-free operation and ensuring of safety are required. On the one hand, the structure-liquid system can be influenced directly by the operational processes (such as by unfavourable oscillations of liquid, e.g. in distillation column [2]). Therefore, quantitative and qualitative methods in a hazard identification should be applied to prevent large industrial accidents. On the other hand, the systems must withstand external loadings (static, dynamic) as well. One of the most critical events affecting safety and operation efficiency of systems is a seismic loading.

Requirements for the suppression of a possible loading in a future operation must be reflected in the design process of the devices which are mostly included in various international, national or company standards and/or guidelines.

Computational analyses of the liquid storage tanks with the aim to evaluate hydrodynamic forces induced by the lateral ground motion require a certain amount of effort due to a problem involving the definition of the fluid-structure interaction.

Based on various analytical and experimental studies published by Housner [3], Haroun [4], Veletsos [5], Malhotra [6] and others, procedures for the evaluation of hydrodynamic effects of liquid storage tanks subjected to earthquake loading were formulated. There were proposed equivalent mechanical models for rigid and flexible tanks which simplify the procedure of the solution of the investigated tank-liquid systems and are more comprehensible for engineers engaged in designing of these structures.

The proposed simple mechanical models were adopted in various international codes aimed at the structural design for seismic resistance. While very detailed and specific seismic design rules for storage tanks of cross-sections of elementary geometry (circular, rectangular) are provided by several codes (e.g. Eurocode 8 – part 4 [7]), these rules are missing for different shaped tanks (such as spherical). Wieschollek [8] presented the results of his survey on the existing European and American codes regarding their applicability to spherical liquid storage tanks and provides a comparison of the design outcomes in accordance with these codes.

This contribution describes the results of the investigation on a model of a spherical liquid storage tank. The aim of this article is to compare available analytical methods for seismic design (especially for evaluation of natural frequencies and basic seismic characteristics) of spherical liquid storage tanks introduced in [9] or general rules for the seismic design of structures (Eurocode 8 – part 1 [10]) with a numerical approach based on finite elements in software ANSYS. This investigation is performed following the results obtained from seismic analyses of circular liquid storage tanks using Eurocode 8 [7] and their good correlation with results from FE analyses (ANSYS) which were given attention to in other author's publications (e.g. in [11, 12, 13]) Hence, finite element method in software ANSYS could be advantageous tool when designing structures for seismic resistance.

2. MODELLING OF TANKS CONTAINING LIQUID

The most used mechanical analogy is the one proposed by Housner [3] in which the tank and the liquid are substituted by spring-mass systems. The liquid in the tank is divided into two portions. The lower or impulsive liquid region moves in unison with the tank walls as a rigid body and induces impulsive hydrodynamic pressure on the tank walls and the bottom. A higher or convective portion of the liquid represents the free surface which undergoes sloshing motion and exerts convective hydrodynamic pressure on the tank walls and the bottom. Figure 1 shows modified Housner's model for spherical tanks containing liquid.

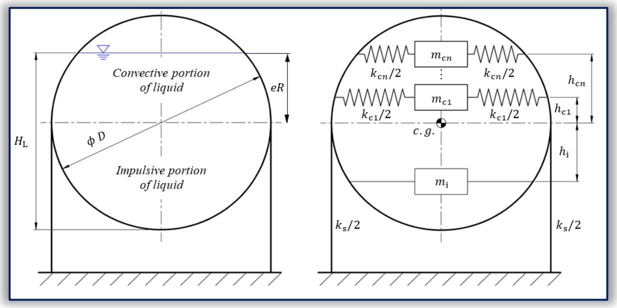

Figure 1: Mechanical model of a spherical tank containing liquid

In the simplified model, the impulsive liquid is replaced by respective impulsive mass m_i rigidly attached to the tank walls at a height h_i from the centre of gravity. The convective liquid is substituted by an infinite number of convective masses m_{cn} connected to the tank walls at height h_{cn} from the centre of gravity with springs of appropriate stiffness k_{cn}. Each convective mass represents the effective liquid mass that oscillates in respective slosh mode.

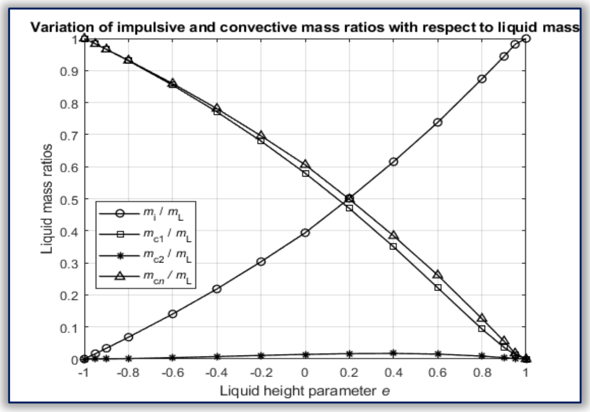

Figure 2: Variation of impulsive and convective mass ratios with respect to total liquid mass

Figure 2 (introduced by Karamanos [9]) presents the dependency or variation of the ratios of the impulsive and convective liquid masses to the total liquid mass contained in a spherical tank with respect to the liquid height parameter *e* (shown in Figure 1).

The mechanical model based on a system of springs and masses mentioned above can be advantageously employed when calculating basic seismic characteristics e.g., shear forces, overturning moments, hydrodynamic pressures, natural frequencies, etc. In these calculations, simplified expressions include the effects produced by the impulsive and the convective liquid.

In complex structures, when investigating the responses to seismic events, fatigue, the behaviour of selected tank equipment or accessories, simplified analytical methods could be insufficient and inaccurate. Therefore, numerical approaches could be employed. The most widely used is the method based on finite elements (FEM). Liquid storage tanks can be investigated by applying elements based on different formulation, such as the added mass concept, Lagrangian or Eulerian methods. When modelling liquid by acoustic elements, a definition of fluid-structure interaction (FSI) at the interface between structure and liquid is required to couple their displacements (coupled field problem).

3. SEISMIC RESPONSE OF THE SPHERICAL LIQUID STORAGE TANK

The presented seismic analysis is focused on a flexible (steel) spherical liquid storage tank fixed to the rigid foundation with the dimensions introduced in Figure 3. Investigated spherical tank is also included in the Design recommendation for storage tanks [14]. The model of the spherical tank is supported on the 12 vertical columns of circular cross-section (with radius R 304,5 mm) without additional bracings between them. Tank walls of a real structure consist of several courses of different thicknesses which varies from the bottom to the top. For tanks with non-uniform wall thickness, the equivalent uniform thickness of the tank wall is calculated by the weighted average method over the wetted height of the tank wall, as introduced by Malhotra [6]. The equivalent wall thickness t is set to 15 mm by weighted average. The spherical tank is filled with water with the free surface height $H_L$set to $8.96{\cdot}10^3$mm (e =0).

For calculations of seismic forces, design acceleration response spectrum in accordance with Eurocode 8 [10] as the seismic input is applied. For its representation, PGA of 2.5 m/sec^2 is used and ground type C with values of respective parameters for the base under the liquid storage tank is assumed. Behaviour factor q is not taken into an account at this point (i.e. q = 1). Figure 4 presents the design acceleration response spectrum for proportional damping of 0.5 % (liquid – water) and 2 % (steel structure – tank).

In the FE analysis, a spherical tank is modelled using structural shell elements (SHELL181); the liquid is represented by acoustics elements based on Eulerian's formulation (FLUID30). At the interface between structural and fluid elements, it is necessary to define the coupling of the tank and liquid displacements.

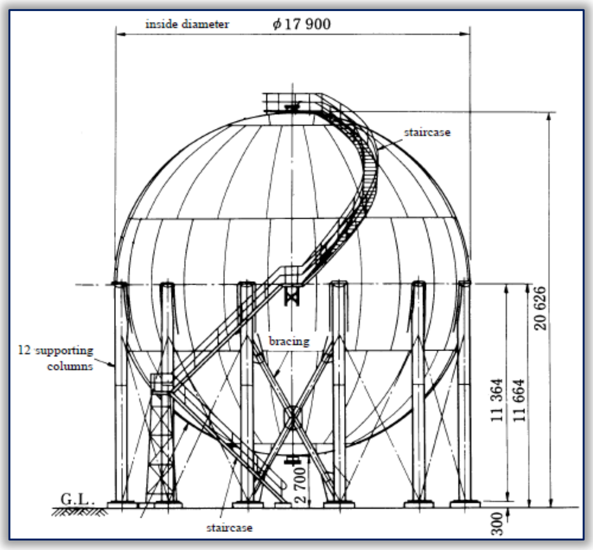

Figure 3: Investigated model of spherical liquid storage tank [14]

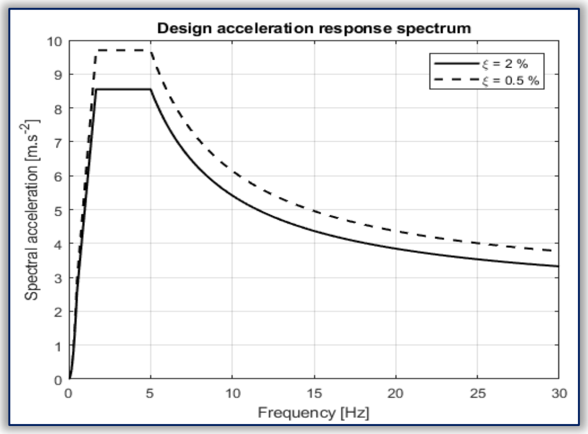

Figure 4: Design acceleration response spectrum according to Eurocode 8

Impulsive effects

Fundamental or impulsive natural mode of oscillation corresponds to the lateral mode of a tank-liquid system. This unfavourable response is described by the oscillation of the contained liquid which is in unison with the tank oscillation. Standards concerning to the earthquake resistance usually contain the procedure for calculation of the impulsive natural frequency f_i at which the respective lateral mode of the oscillation occurs.

Since the expression for determining the fundamental frequency of a spherical liquid storage tank is not contained in any standard for seismic resistance, it may be calculated by using classical mechanics. Due to large differences between impulsive and convective effects, the tank-liquid system can be treated as two uncoupled mechanical spring-mass systems, each of one degree of freedom. The fundamental impulsive natural frequency is calculated as follows

$$f_\mathrm{i} = \frac{1}{2\pi}\sqrt{\frac{k_\mathrm{s}}{m_\mathrm{i}}} \quad (1)$$

where k_s represents the stiffness of the staging which acts like a lateral spring and can be calculated as

$$k_\mathrm{s} = \sum_{j=1}^{n} \frac{12EI}{h_\mathrm{s}^3} \quad (2)$$

where E is a modulus of elasticity, I is a moment of inertia of a single column in a supporting structure and h_s is its height. In (1), the mass m_i is defined as the sum of the lower liquid portion mass and the mass of the tank and supporting structure (without convective effects)

$$m_\mathrm{i} = m_\mathrm{total} - \sum_{j=1}^{n} m_{cn} \quad (3)$$

Applying (1), the impulsive natural frequency of the tank-liquid system occurs at 2.02 Hz. The impulsive natural frequency from modal analysis using software ANSYS is 2.05 Hz and respective natural mode of oscillation is presented in Figure 5.

Convective effects

The upper or convective portion of the liquid in the tank does not move as a rigid body with the tank walls but tends to slosh. The sloshing natural frequencies of the liquid are essentially lower in comparison with the impulsive portion of the liquid whose modes of oscillation are characterized by higher frequencies. In the following, the sloshing response of spherical tanks is examined.

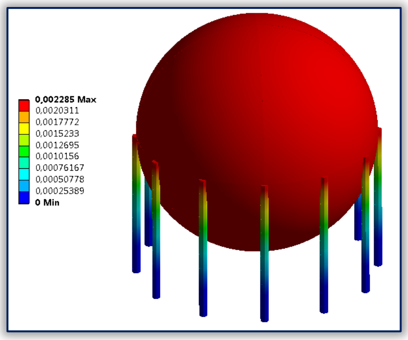

Figure 5: Impulsive mode of oscillation

In international standards such as Eurocode 8 [7], procedures for calculation of convective natural frequencies for horizontal and vertical liquid storage tanks of circular cross-section are introduced. For spherical storage tanks containing liquid, Karamanos [9] introduced expression (4) for calculation of convective natural frequencies whose respective natural modes of oscillation are antisymmetric (i.e. characterized by the Bessel function of the first order). Using correspondent wave numbers λ_n, convective frequency is calculated as

$$f_{cn} = \frac{1}{2\pi}\sqrt{\frac{\lambda_n\, g}{R}} \tag{4}$$

where R is a tank radius and g represents the gravitational acceleration.

In Figure 6, numerical results are introduced for the normalized sloshing frequencies $(\lambda_n = \omega_{cn}^2 R/g)$ of a spherical tank containing the liquid with respect to the liquid height parameter e.

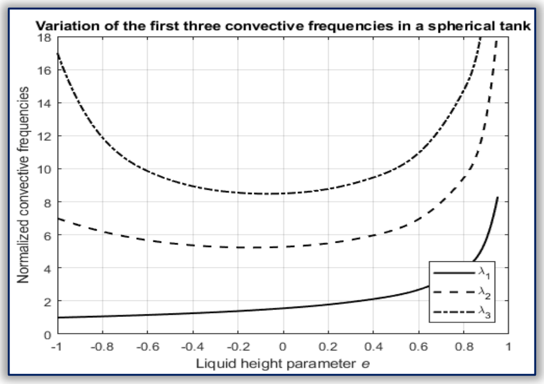

Figure 6: Variation of the first convective frequencies for liquid height parameter e

Using (4) and considering the respective wave numbers λ_n, convective natural frequencies of the investigated liquid storage tank are calculated. Table 1 presents analytically calculated convective frequencies which are compared with those obtained from FE analysis. Natural frequencies show good correlation between analytical and numerical calculations. Figures 7, 8 and 9 show respective first three slosh modes of oscillation computed in ANSYS.

Table 1. First three convective modes of oscillation for 50 % of liquid volume

Convective mode of oscillation *n*	Wave number λ_n	Analytical computation	FE analysis (ANSYS)
1st	1.5602	0.21 Hz	0.21 Hz
2nd	5.2756	0.38 Hz	0.39 Hz
3rd	8.5045	0.49 Hz	0.49 Hz

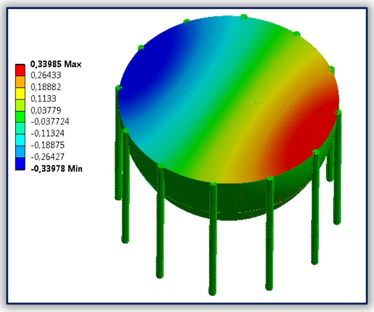

Figure 7: First convective mode of oscillation

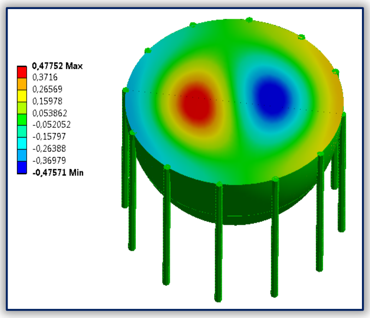

Figure 8: Second convective mode of oscillation

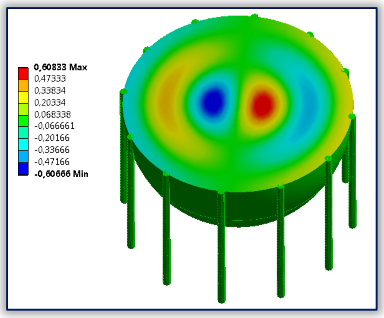

Figure 9: Third convective mode of oscillation

Figure 10 presents the variation of first three convective natural frequencies in investigated tank model as a function of different liquid heights. Analytically calculated frequencies are compared with those obtained by FE analysis in ANSYS. Results between each solution represented good conformity.

Seismic lateral force

In the following, the calculation of the seismic lateral force is described by lateral force method according to Eurocode 8 part 1 [10] and by the combination of the impulsive and convective contributions [9] using mechanical model for the spherical liquid storage tank (Figure 1).

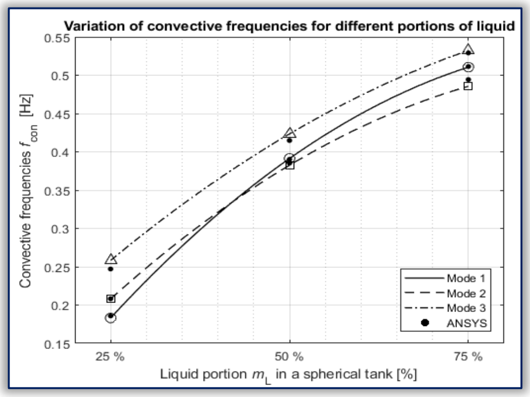

Figure 10: Variation of convective frequencies for different liquid heights

For calculation of seismic effects such as maximum seismic forces and overturning moments, the tank-liquid system is subjected to design acceleration response spectrum in horizontal direction introduced in Figure 4.

The lateral force method is applicable for structures that respond to seismic action as SDOF system. This requirement is fulfilled if the structure satisfies the criteria for regularity in elevation introduced in [10] and if the fundamental natural frequency f_i is smaller than the following values

$$f_\mathrm{i} \leq \frac{4}{f_{c1}} \quad \text{and} \quad f_\mathrm{i} \geq 0.5 \tag{5}$$

When neglecting the influence of the sloshing, the seismic lateral force F_L is determined as follows

$$F_\mathrm{L} = \gamma \lambda m_\mathrm{i} S_\mathrm{ai}(f_\mathrm{i}) \tag{6}$$

where γ is an importance factor, λ is a correction factor (chapter 4.3.3.2.2 in [10]), $S_\mathrm{ai}(f_\mathrm{i})$ is a spectral acceleration corresponding to an impulsive natural frequency from a specific design acceleration response spectrum (Figure 4).

Applying (6), the seismic lateral force is $8.72 \cdot 10^6$ N (for $\gamma = 1.25$ and $\lambda = 1.0$). This force passes through the centre of gravity of the spherical tank which is located at the height 11.36 m from the ground (Figure 3). Thus, the overturning moment with respect to the ground level is $9.90 \cdot 10^7$ Nm.

Including sloshing effects, estimation of seismic design force can be defined as the sum of impulsive and convective contributions which are subsequently combined by the SRSS (i.e. square root of sum of the squares) rule as follows

$$F_\mathrm{D} = \sqrt{(m_\mathrm{i} S_\mathrm{ai}(f_\mathrm{i}))^2 + \left(\sum_{j=1}^{n} m_{cn} S_{acn}\,(f_{cn})\right)^2} \tag{7}$$

where $S_{cn}(f_{cn})$ is a spectral acceleration corresponding to a convective natural frequency from a specific design acceleration response spectrum (Figure 4).

Higher mode masses are generally much smaller than the first sloshing mass and, therefore, they may be neglected in calculations of the seismic design force. Considering only first convective mode mass and correspondent parameters, the expression (7) may be treated as

$$F_\mathrm{D} = \sqrt{(m_\mathrm{i} S_\mathrm{ai}(f_\mathrm{i}))^2 + (m_{c1} S_{ac1}(f_{c1}))^2} \tag{8}$$

Applying (8), the resultant seismic force is $1.02 \cdot 10^7$ N and overturning moment $1.16 \cdot 10^8$ Nm.

The comparison with seismic force obtained by lateral force method shows the necessity of consideration of the sloshing effect because it significantly increases the total earthquake load.

4. CONCLUSIONS

The spherical storage tanks are widely used for various types of liquids, including hazardous contents. Therefore, they must be adequately designed for seismic actions, especially in earthquake-prone regions.

The aim of this article was to perform a seismic analysis on a model of the spherical liquid storage tank. The spherical tank was chosen since different shaped structures are not covered with respective equivalent mechanical models in codes for seismic resistance. Finite element analysis in software ANSYS was used to compute dynamic properties (natural frequencies and respective modes of oscillation) of the investigated tank model and subsequently, the obtained results were compared with those from analytical approach (not covered in any standards). Natural frequencies showed good conformity between each solution.

Therefore, finite element method using software ANSYS could be advantageously used in designing of the different shaped storage tanks for seismic resistance which provides comparable results with analytical calculations. This method is also useful when evaluating only the responses of individual parts to seismic loading.

In the calculation of seismic lateral forces and overturning moments of the spherical tank model, general standard of seismic structural design and analytical approach not covered in any standard for earthquake resistance were compared. It can be concluded that the general procedures can be in a certain measure limited and conservative.

The introduced methodology offers an easy and efficient tool to compute a dynamic response to seismic actions in spherical tanks, it is compatible with the corresponding rules in existing specifications for vertical liquid storage tanks (e.g. [7]) and can be used for the seismic design of industrial storage tanks.

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