Seismic Response of Conventional and Base-isolated Liquid Storage Tanks

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ABSTRACT:
Seismic excited liquid filled tanks are subjected to extreme loading due to hydrodynamic pressures, which can lead to nonlinear stability failure of the thin-walled cylindrical tanks, as it is known from past earthquakes. A significant reduction of the seismically induced loads can be obtained by the application of base isolation systems, which have to be designed carefully with respect to the modified hydrodynamic behavior of the tank in interaction with the liquid. For this reason a highly sophisticated fluid-structure interaction model has to be applied for a realistic simulation of the overall dynamic system. In the following, such a model is presented and compared with the results of simplified mathematical models for rigidly supported tanks. Finally, it is examined to what extent a simple mechanical model can represent the behavior of a base isolated tank in case of seismic excitation.

Keywords: Liquid-filled tanks, base isolation, fluid-structure-interaction, LS-DYNA

1. INTRODUCTION

Tanks are preferably designed as cylindrical shells, because the geometry is able to carry the hydrostatic pressure from the liquid filling by activating membrane stresses with a minimum of material. In combination with the high strength of steel this leads to thin-walled constructions, which are highly vulnerable to stability failures caused by additional axial and shear forces in case of seismic excitation. However, an earthquake-resistant design of rigid supported tanks for high seismic loading requires unrealistic und uneconomic wall thicknesses. Compared to increasing the wall thickness an earthquake protection system can be a much more cost-effective alternative. Especially a base isolation with elastomeric bearings offers advantages in terms of an earthquake-friendly tank design. But the calculation capabilities of base-isolated, liquid-filled tanks are quite limited because of the complex interaction of the seismic isolation behavior and the combined modes of vibrations of tank and fluid. Generally accepted calculation approaches are only available for rigid supported tanks (Meskouris et al. 2011). To capture the hydrodynamic loading of isolated tanks, a complete modeling of the fluid-structure interaction including the behavior of the seismic isolation is presented in the following.

2. CALCULATION OF ANCHORED LIQUID STORAGE TANKS

2.1 Seismically induced load components of liquid filled tanks

As a result of seismic excitation hydrodynamic pressure components, produced by the movement of the fluid, appear and has to be superimposed with the hydrostatic pressure. Since the oscillation periods of the individual seismically induced pressure components are far apart, each mode of oscillation with its associated pressure distribution can be determined individually. In case of a horizontal seismic excitation the convective part of sloshing vibrations, the impulsive rigid pressure component of the rigid-body motion as well as the impulsive flexible pressure component caused by the combined interaction vibration mode of tank and liquid must be considered (Fig.1).

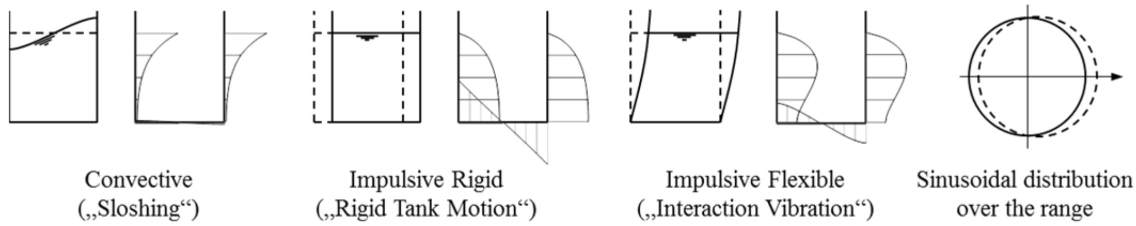


Figure 1. Horizontal seismic action: Modes of vibrations and pressure distributions (Meskouris et al. 2011)

Furthermore the vertical seismic excitation must be taken into account, which leads to two additional modes of vibrations and corresponding pressure distributions. The impulsive rigid pressure is activated by the rigid-body motion of the tank and the flexible pressure component is caused by the flexibility of the tank shell (Fig. 2).

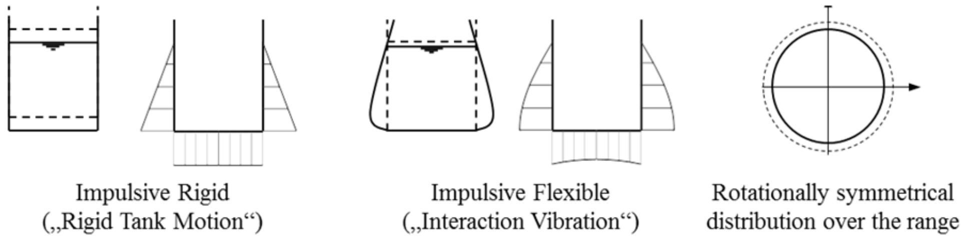


Figure 2. Vertical seismic action: Modes of vibrations and pressure distributions (Meskouris et al. 2011)

2.2 Computational models for seismic excited tank structures

In the literature different approaches for modeling and calculation of seismically excited tank structures can be found. On the one hand engineering-based analytical calculation approaches are used which are usually represented by simple mass oscillators. Most of these approaches are based on the findings of Housner (1963), who developed formulas for rigidly supported tanks with non-deformable walls to calculate the modes of vibrations and the corresponding dynamic pressure components. Based on these findings several approaches have been developed. A widely applied simplified method was developed by Veletsos (1974) for rigid supported tanks with flexible walls. This method is fast and easy to apply, but it delivers only the seismically induced shear force and the overturning moment at the bottom of the tank. An accurate calculation of the stress distribution is not possible using such simplified approaches. DIN EN 1998-4 (2006) proposes a more precise calculation that allows a three dimensional finite element analysis of the tank by applying the seismically induced pressure components as equivalent static loads on the dry shell. However, the approaches for calculating the individual seismically induced pressure components are based on the assumption of a rigid support at the tank bottom and they are not applicable to base isolated tanks. To gather the hydrodynamic loading of isolated tanks, a simulation model taking the fluid-structure interaction and the seismic isolation effects into account, is required. In the following the software LS-DYNA (2013) is used for the necessary fluid dynamics calculations.

2.3 Base isolation

A base isolation is aimed at a decoupling of the building and the ground motion. Elastomeric bearings are a widely used base isolation and can optionally be installed with or without reinforcement, often in combination with a lead core (Petersen et al. 2005). However an unreinforced execution is unusual nowadays, since elastomers are subjected to high deformations up to 25% under vertical loads. These deformations cause lateral strains, by which unwanted rocking motion in case of seismic excitation can occur. Reinforced bearings can be considered as quasi-rigid in the vertical direction, so they are suitable to transfer vertical loads. Under cyclic loading, elastomers behave almost like springs. They have – depending on the material properties – a certain stiffness which causes a reset of the bearing and thus of the entire system after the release. Through the use of high-damping elastomers (addition of oils, resins, extra fine carbon black and other fillers), or a lead core, the damping capacity of the bearings can be increased significantly. In case of a distortion of 100%, high damping elastomers have damping rates from 0.1 to 0.2 during normal elastomers from 0.04 to 0.06 (Petersen et al, 2005). The use of elastomeric bearings as earthquake protection systems for tanks has already been realized by Bachmann and Wenk (2000).

2.4 Example of calculation

The following calculations are carried out for a steel tank with constant wall thickness, firmly anchored to a reinforced concrete base plate. The geometry of the tank is illustrated in Figure 3. The base plate is supported on elastomeric bearings, which properties are taken from Baumann and Boehler (2001). The calculation model considers the horizontal stiffness of the elastomeric bearings, whereas a rigid behavior is assumed in vertical direction. The fluid is idealized as incompressible and friction-free. The material parameters of the tank and the isolation and the seismic hazard input parameter according to DIN EN 1998-1/NA (2010) are given in Table 1.

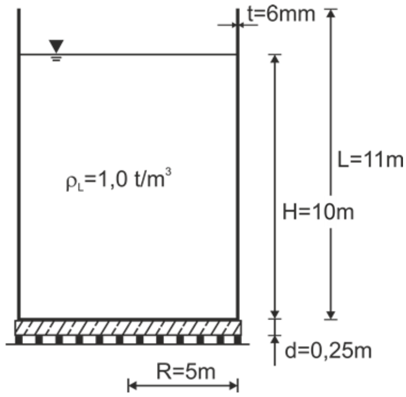


Figure 3. System of the isolated tank with elastomeric bearings

Table 1. Input parameter for the calculation

Location		Material		Base isolation	
PGA:	0,6 m/s^2	Shell:	S 235	Number:	20
Subsoil class:	AR/CS	Foundation:	C 50/60	Stiffness:	700 kN/m
Importance Factor:	1,2			Damping:	15 %

3. FLUID-STRUCTURE INTERACTION MODEL

The software LS-DYNA (2013) is used for the simulation of the fluid-structure interaction of the liquid-filled tank. The software provides an explicit solver, which offers advantages especially for the solution of short-term dynamic problems. In addition, LS-DYNA provides formulations for the modeling of fluids and standardized contact formulations, which are able to represent the interaction of the tank shell and the fluid during a seismic excitation. Details of the following material, element and contact formulations can be found at the LS-DYNA manuals (LS-DYNA 2012).

3.1 Material formulation

Basically both, elastic and plastic approaches are applicable for the tank shell. Since the focus is set on the reduction of the seismic loading by applying a base isolation, an elastic behavior of the tank shell is assumed (MAT_ELASTIC). For the base plate the concrete material model MAT_CSCM is used, which is applied with the default settings. Two material formulations are investigated for the fluid: a linear (MAT_ELASTIC_FLUID) and a non-linear (MAT_NULL). In the linear formulation, only the gross density as well as the bulk modulus of the fluid is needed for the calculation. The change in the hydrostatic pressure fraction $\dot{p}$ is described by the bulk modulus K and the strain rate $\dot{\varepsilon}_{ii}$ in the main directions of the material:

$$\dot{p} = -K \cdot \dot{\varepsilon}_{ii} \tag{3.1}$$

The shear modulus is set to zero. The deviatoric stress component S_{ik}^{n+1} is given by:

$$S_{ik}^{n+1} = VC \cdot \Delta L \cdot a \cdot \rho_L \cdot \dot{\varepsilon}_{ik}^{'} \tag{3.2}$$

Herein, VC is a tensor viscosity coefficient, ΔL is the characteristic element length, a is the fluid bulk sound speed, ρ_L is the fluid density, and $\dot{\varepsilon}_{ik}^{'}$ is the deviatoric strain rate. The linear material formulation is suitable for the use of an implicit calculation in the form of a modal analysis, but cannot - unlike as the nonlinear material formulation – image the change of the stiffness of the material due to cavitation or a failure of the material by erosion. The nonlinear material formulation uses an equation of state to calculate the hydrostatic stress component. Here, the Grüneisen-equation is used, which distinguishes between the calculation of the hydrostatic pressure p for the compressed and the expanded state:

$$p_{compressed} = \frac{\rho_L \cdot C^2 \cdot \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right) \mu - \frac{a}{2} \mu^2\right]}{\left[1 - (S_1 - 1)\,\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2}\right]^2} + (\gamma_0 + a \cdot \mu) \cdot E \tag{3.3}$$

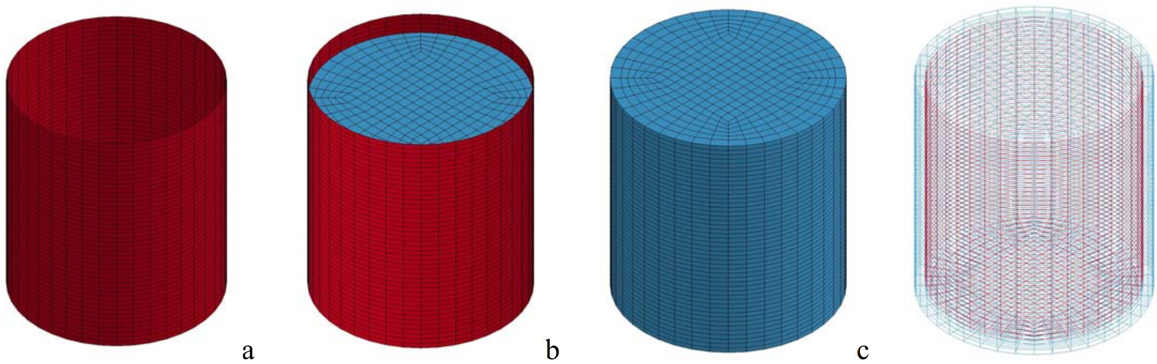
$$p_{expanded} = \rho_L \cdot C^2 \cdot \mu + (\gamma_0 + a \cdot \mu) \cdot E \tag{3.4}$$

Here, C is the axial section of the pressure-strain curve, S_1, S_2 and S_3 are coefficients of the inclination of the pressure-strain curve, γ_0 is a Grüneisen parameter, a is a volume correction parameter of first order and μ is a volumetric parameter as a measure of compression or expansion. A more detailed description of the Grüneisen-equation is given in LS-DYNA (2012) and Hallquist (2006). The deviatoric viscous stress σ'_{ik} only depends on the dynamic viscosity μ and the deviatoric strain rate $\dot{\varepsilon}_{ik}^{'}$:

$$\sigma_{ik}^{'} = 2 \cdot \mu \cdot \dot{\varepsilon}_{ik}^{'} \tag{3.5}$$

3.2 Element formulation

The tank wall and the tank bottom are idealized by Belytschko-Lin-Tsay shell elements with reduced integration, which are characterized by a high efficiency in terms of computing power required for explicit analysis (Hallquist, 2006). The foundation plate is idealized by 8-node solid elements and the fluid is represented by an Arbitrary-Lagrangian-Eulerian finite element formulation (ALE). This element formulation can be combined with both material models, but it cannot be used for an implicit calculation (modal analysis). When using the ALE formulation extra volume elements are generated within the scope of the freeboard up to the top edge of the tank wall, so the fluid surface can move freely (sloshing). Also, the ALE mesh must enclose the Lagrange mesh. For this reason a series of elements at the top and bottom of the tank, below the base plate and outside of the tank wall are generated (Fig. 4). The elements are assigned to the vacuum material MAT_VACUUM, which has no physical meaning, but merely represents a region within the ALE mesh in which the fluid can move.



a b c d

Figure 4. a: tank shell with foundation plate; b: fluid filled tank; c and d: enclosing ALE-mesh

3.3 Contact formulation

The interaction between the tank shell and the fluid represents an important aspect of modelling. If a contact of the two parts appears, compression stresses are transferred while the transfer of tensile and shear stresses is disregarded. LS-DYNA provides essentially two different contact formulations for coupling the tank shell (Lagrange) and the fluid (ALE) with each other: ALE_FSI_PROTECTION (AFP) and CONSTRAINED_LAGRANGE_IN_SOLID (CLIS). Both formulations are well suited for fluid-structure interaction, but the latter formulation offers more configuration options, for example a separate specification of damping. Furthermore the formulation allows the evaluation of the contact forces as a result of the hydrostatic and hydrodynamic pressures on the tank shell.

3.4 Base isolation

The base isolation is simply idealized by linear spring and damper elements, which are integrated in the model between the supporting nodes and the nodes of the base plate. The elements exhibit a corresponding equivalent stiffness and damping representing the behavior of the base isolation. The stiffness and damping values are given in Table 1. The base isolation is acting in the direction of the seismic excitation, whereas in vertical and horizontally perpendicular direction fixed supports are applied.

3.5 Sequence of loading

In a first step the system is loaded with the acceleration of gravity. The load is linearly applied within a period of one second to avoid an excessive oscillation of the system. For the next half second the system is unloaded, so that the resulting oscillations subside. Then the seismic excitation is applied to the supporting nodes as a displacement-time history, artificially generated from the code spectrum according to DIN EN 1998-1/NA (2010).

3.6 Results

To validate the fluid-structure interaction model the stress results of a rigidly supported tank are compared to those from an equivalent force analysis according to Eurocode 8, Part 4 (DIN EN 1998-4 2006). In case of the equivalent force analysis the seismic induced pressure components (Fig. 1) are calculated separately and then they are superimposed to the resulting hydrodynamic pressure using the SRSS-rule. Finally the resulting hydrodynamic pressure is applied as an equivalent static load to the dry tank wall. Afterwards the hydrodynamic pressure is combined with dead load and hydrostatic pressure. The calculations are carried out for the subsoil classes AR (rock) and CS (soft soil) according to DIN EN 1998-1/NA (2010). Figure 5 shows the circumferential, axial and shear stress distributions over the tank height for the two subsoil classes. It has to be pointed out, that the decisive stresses for the design appear at different circumferential angles θ: circumferential stresses ($\theta = 180°$), axial stresses ($\theta = 0°$) and shear stresses ($\theta = 90°$). According to DIN EN 1998-4 (2006) damping values of 2% for the tank shell and 0.5% for the fluid are applied for the rigidly-supported tank. By using these damping values the numerical simulation results of the rigidly-supported tank considering fluid-structure interaction effects show a good agreement with results according to DIN EN 1998-4 (2010) for both material formulations of the fluid. Generally the hoop stresses of the tank wall are dominated by tension stresses due to the hydrostatic pressure of the liquid. Except the upper edge of the tank wall with low hydrostatic pressures shows local compression stresses which can lead to stability problems of the thin steel sheet in the upper tank section. The axial and shear stresses comply qualitatively for both fluid material formulations with the results according to DIN EN 1998-4 (2010). For the subsoil class AR, the results of the nonlinear fluid formulation are consistent with the results according to DIN EN 1998-4 (2010), while the results of the linear fluid formulation are somewhat less than the results of the DIN EN 1998-4 (2010) calculation. This deviation lies in the range of up to 20%. For the subsoil class CS it is reversed: The stresses calculated with the nonlinear fluid material formulation are higher than those according to DIN EN 1998-4 (2010), whereas the results of the linear fluid material formulation show a good agreement.The calculations of the base isolated tank are carried out for an elastic behavior of the tank itself and a damping of the fluid of 0.5%. The results show a significant decrease of the axial and shear stresses for both subsoil classes, while the differences of the circumferential stresses are negligible because they are dominated by the tension stresses due to the hydrostatic pressure.

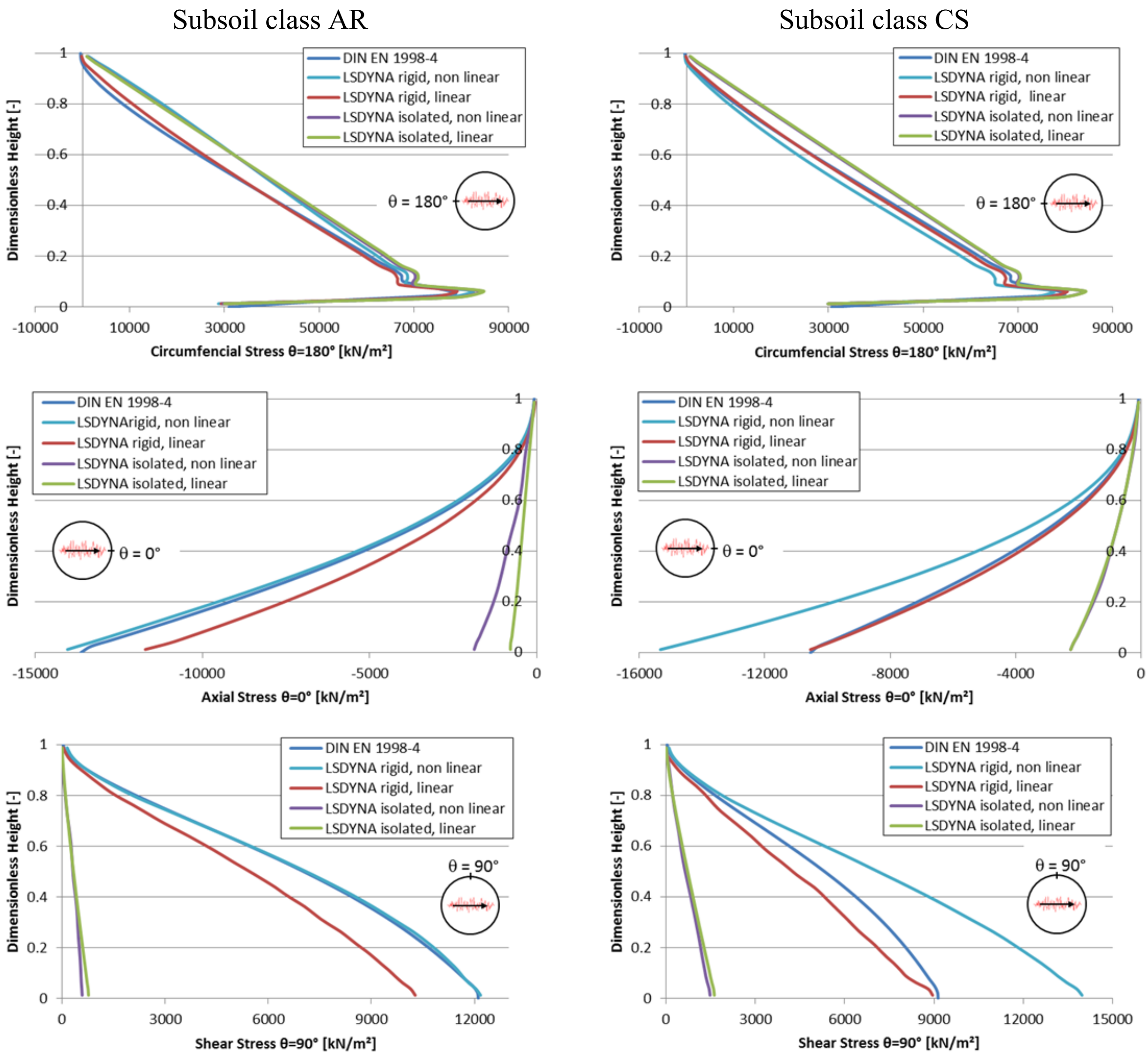


Figure 5. Stress distributions over the tank height for different subsoil classes

4. SIMPLIFIED MECHANICAL MODEL

The development of simplified mechanical models for isolated liquid-filled tanks has been studied in recent years and is particularly interesting in terms of practicality. For example, in Malhotra (1997), Christovasilis and Whittaker (2008) equivalent dynamic systems in the form of single-mass oscillators are derived. The base isolation is simply taken into account by introducing a horizontal degree of freedom at the base of the single-mass oscillator. In addition, the degree of freedom is combined with spring and damper elements, which reflect the characteristics of the corresponding protection system. The seismically induced pressure components are considered by single masses with certain lever arms. The masses and lengths of the lever arms correspond to those of rigidly-supported tanks, which is not really correct for the calculation of base-isolated tanks. The equivalent dynamic systems can be used for the calculation of the total shear force and the overturning moment, but they cannot be applied for the determination of the pressure distribution over the tank wall. Schäpertöns (1996) investigated the influence of soil-structure interaction effects for seismically excited tanks and noticed that the normalized impulsive pressure distribution over the tank height is not significantly affected by soil-structure interaction effects. Veletsos and Tang (1990) showed in their studies, that it is sufficient to consider the impulsive pressure components for the soil-structure interaction, since the changes of the convective pressure component is negligible small. These findings can be used to derive a simplified mechanical model for isolated liquid storage tanks. The starting point is the calculation of the pressure distributions for a rigidly supported tank according to DIN EN 1998-4 (2006). The integration of the impulsive flexible pressure $p_{if,h,rigid}$ normalized to the spectral acceleration of the first eigenperiod of the flexible vibration mode delivers the seismic mass in node 1 for an equivalent two-mass oscillator (Fig. 6):

$$m_{if,h} = \int_0^H \int_0^{2\pi} \left[p_{if,h,rigid}(\xi = 1, \zeta, \theta) \cdot \cos(\theta)\right] \cdot R \; d\theta \; dz \qquad (4.1)$$

Herein, ξ and ζ are the dimensionless coordinates for radius ($\xi = r/R$) and wetted height of the tank wall ($\zeta = z/H$) and θ is the peripheral angle. The integration assumes a sinusoidal pressure distribution in circumferential direction which is projected to the direction of excitation. With the mass $m_{if,h}$ and the natural period of the impulsive flexible vibration mode of the rigidly supported system, the stiffness k_{ifh} of the two-mass oscillator is calculated. The damping factor $c_{if,h}$ of the impulsive flexible vibration mode is set to 2,5%, as suggested in Meskouris et al. (2011). The mass of the foundation plate and the base isolation (m_{Bi}) is applied in node 2. The idealization of the base isolation is performed by a combined spring-damper element, which represents the damping and stiffness properties of the base isolation. The load a(t) is applied as a synthetically generated acceleration time history in node 3 of the system.

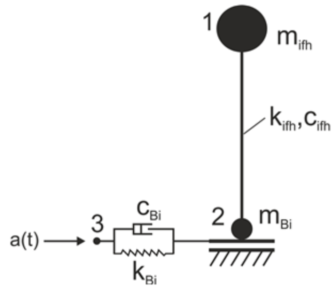


Figure 6. Simplified model of the isolated liquid storage tank

The needed result for the further calculation steps is the maximum response acceleration max $a_{if,h,iso}$ of the mass $m_{if,h}$ in node 1. This acceleration is used for scaling the normalized impulsive flexible pressure $p_{if,h,rigid}$ in Equation (4.1), which leads to the impulsive flexible pressure distribution corresponding to the isolated vibration mode:

$$p_{if,h,iso}(\xi{=}1, \zeta, \theta) = \max a_{if,h,iso} \cdot p_{if,h,rigid}(\xi{=}1, \zeta, \theta) \qquad (4.2)$$

For the calculation of the impulsive flexible pressure component in Equation (4.2), the horizontal response acceleration of the mass of $m_{if,h}$ relative to the ground has to be applied, because the impulsive rigid pressure component already includes the ground acceleration. The impulsive pressure component can be disregarded (Veletsos and Tang 1990), if the absolute acceleration is applied in Equation (4.2). In this case the resulting seismically induced pressure of the isolated tank can be calculated by superposition of the impulsive flexible pressure component of the isolated tank and the convective pressure component of the rigidly supported tank. The stress calculation is carried out according to DIN EN 1998-4 (2006).

4.1 Results

Figure 7 compares the axial and shear stress distributions over the tank height calculated with the simplified mechanical model and the fluid-structure interaction model with a linear and non-linear material approach for the fluid. The results show a good agreement for subsoil class CS, but it should be noted, that the results of the simplified model are more conservative.

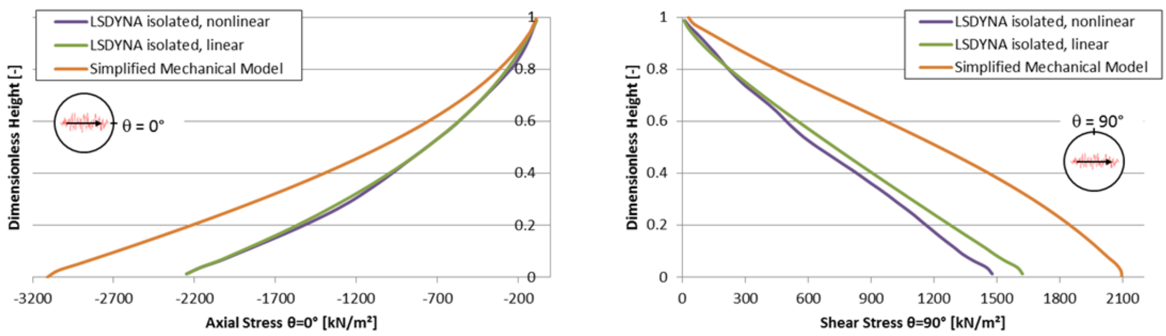


Figure 7. Axial and shear stress curve of the isolated tank (subsoil class CS)

5. CONCLUSION

The seismic excitation of rigidly supported liquid storage tanks activates hydrodynamic pressure components which lead to uneconomic wall thicknesses. A significant reduction of the seismic induced stresses can be obtained by the application of base isolations with elastomeric bearings. The paper introduced two calculation models for base-isolated tanks with different levels of accuracy. The simplified mechanical model is an equivalent two-mass oscillator, which is used for the calculation of modified impulsive pressure components for the base isolated tank. The more sophisticated simulation model is realized with LS-DYNA (2013) and takes the fluid-structure interaction into account. The results of both models show a satisfactory agreement with the analysis results according to DIN EN 1998-4 (2006). Although the obtained results with the developed models are very promising further investigations are needed for different slenderness ratios and isolation systems.

References

Bachmann, H., Wenk, T. (2000). Schwächen statt Verstärken bei der Erdbebensanierung. *Schweizer Ingenieur und Architekt*, **Band 118, Heft 3**, 18-23.

Baumann, T., Böhler, J. (2001). Seismic Design of Base-Isolated LNG-Storage-Tanks. *Structural Engineering International*, **Vol. 11, No. 2**, 139-144.

Christovasilis, I. P., Whittaker, A. S. (2008). Seismic Analysis of Conventional and Isolated LNG Tanks Using Mechanical Analogs. *Earthquake Spectra*, **Vol. 24, No. 3**, 599-616.

DIN EN 1998-1/NA (2010). Eurocode 8: Auslegung von Bauwerken gegen Erdbeben – Teil 1: Grundlagen, Erdbebeneinwirkungen und Regeln für Hochbauten; Nationaler Anhang, Deutsches Institut für Normung.

DIN EN 1998-4 (2006). Eurocode 8: Auslegung von Bauwerken gegen Erdbeben – Teil 4: Silos, Tankbauwerke und Rohrleitungen. Deutsches Institut für Normung.

Hallquist, J. O. (2006). LS-DYNA Theory Manual. Livermore Software Technology Corporation

Housner, G. W. (1963). The dynamic behavior of water tanks. *Bulletin of the Seismological Society of America,* **Vol. 53, No. 2**, 381-387.

LS-DYNA (2012). Keyword User's Manual Volume I and II. Version 971 R6.1.0. Livermore Software Technology Corporation.

LS-DYNA (2013). Livermore Software Technology Corporation (LSTC)

Malhotra, P. K. (1997). New Method for Seismic Isolation of Liquid-Storage Tanks. *Earthquake Engineering and Structural Dynamics*, **Vol. 26**, 839-847.

Meskouris, K., Hinzen, K.-G., Butenweg, C., Mistler, M. (2011). Bauwerke und Erdbeben. Vieweg und Teubner Verlag.

Petersen, C., Beutler, H. Braun, C., Mangering, I. (2005). Erdbebenschutzsysteme für den Hoch- und Brückenbau. In: Kuhlmann, U. (Hrsg.), Stahlbaukalender 2005; Ernst und Sohn.

Schäpertöns, B. (1996). Über die Wellenausbreitung im Baugrund und deren Einfluss auf das Tragverhalten von Flüssigkeitsgefüllten Behältern (Dissertation). Technische Universität München.

Veletsos, A. S. (1974). Seismic effects in flexible liquid storage tanks. *Proceedings of the 5th World Conference on Earthquake Engineering*; **Vol. 1**, 630-639.

Veletsos, A. S., Tang, Y. (1990). Soil structure interaction effects for laterally excited liquid storage tanks. *Earthquake Engineering and Structural Dynamics*, **Vol. 19**, 473-496.