Numerical investigation on behaviour of cylindrical steel tanks during mining tremors and moderate earthquakes

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Abstract. Cylindrical steel tanks are important components of industrial facilities. Their safety becomes a crucial issue since any failure may cause catastrophic consequences. The aim of the paper is to show the results of comprehensive FEM numerical investigation focused on the response of cylindrical steel tanks under mining tremors and moderate earthquakes. The effects of different levels of liquid filling, the influence of non-uniform seismic excitation as well as the aspects of diagnosis of structural damage have been investigated. The results of the modal analysis indicate that the level of liquid filling is really essential in the structural analysis leading to considerable changes in the shapes of vibration modes with a substantial reduction in the natural frequencies when the level of liquid increases. The results of seismic and paraseismic analysis indicate that the filling the tank with liquid leads to the substantial increase in the structural response underground motions. It has also been observed that the peak structural response values under mining tremors and moderate earthquakes can be comparable to each other. Moreover, the consideration of spatial effects related to seismic wave propagation leads to a considerable decrease in the structural response under non-uniform seismic excitation. Finally, the analysis of damage diagnosis in steel tanks shows that different types of damage may induce changes in the free vibration modes and values of natural frequencies.

Keywords: cylindrical steel tanks; numerical analysis; mining tremors; moderate earthquakes; non-uniform excitation; damage diagnosis

1. Introduction

Cylindrical steel tanks are often used to store a variety of liquids, including water, oil, chemicals or liquefied natural gas. They are critical elements of many industrial facilities, such as refineries or chemical factories (see, for example, Ziółko 1986, DiGrado and Thorp 1995 or Godoy 1996). Their safety and reliability are fundamental issues for engineers and researchers. A number of studies have recently been conducted so as to verify different methods of minimizing the causes of damages in steel tanks because any failure may have an influence on considerable economic losses or even ecological disaster. Among different excitations taken into account in these studies, earthquakes have been considered as the most dangerous and also the most unpredictable dynamic loads acting on steel tanks (Niwa and Clough 1982, Manos and Clough 1985 or Cooper 1997). Meanwhile, a lot of areas where mining activity of human being is conducted, mining tremors take place and this type of rockburst-induced ground motions can also be very dangerous to civil engineering structures (see Zembaty 2004, Maciag *et al.* 2016).

The behaviour of different types of steel tanks during Earthquakes has been intensively studied by many researchers. The development of seismic response theories of liquid storage tanks considered the structure to be rigid and the investigation was focused on the dynamic response of the contained liquid. One of the earliest of these studies, conducted by Hoskins and Jacobsen (1934), described the results of analytical and experimental investigations of the hydrodynamic pressure developed in rectangular tanks subjected to horizontal ground motions. Later, Jacobsen (1949) analysed the dynamic behaviour of rigid cylindrical tank. Historically, mechanical models were firstly developed for tanks with rigid walls by Housner (Housner 1954, 1957, 1963). He proposed simplified mechanical models for circular and rectangular rigid tanks. The mechanical model of Housner is still widely used with certain modifications. Wozniak and Mitchell (1978) generalized Housner's model for short and slender tanks. An analytical approach to the analysis of flexible containers was developed by Veletsos (1974). He presented a simple procedure for evaluating hydrodynamic forces induced in flexible liquid-filled tanks. Later, Veletsos and Yang (1977) used different approaches to propose a similar type of a mechanical model for circular rigid tanks. The first comprehensive numerical analysis concerning the behaviour of steel tanks under earthquake excitation was completed by Edwards (1969). He employed the FEM and a refined shell theory to predict seismic stresses and displacements in a vertical cylindrical tank. The interaction between the elastic wall of the tank and its liquid content

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was taken into account in the study. Fenves and Vargas-Loli (1988) used a mixed displacement-fluid pressure formulation for the liquid. In that analysis, the pressure was defined independently of the fluid displacements and a standard displacement finite-element formulation was used for the structure. Furthermore, the equations of motions were solved by a fully implicit time integration method. A mechanical model, which takes into account the deformability of the tank wall, was proposed by Haroun and Housner (1981) and widely applied because the previous models were either too complicated to be used in the design or too simple to yield accurate results. The other model of a flexible tank was developed by Veletsos (1984). After further simplifications of the model, proposed by Malhotra *et al*. (2000), the simplified procedure for analysis of liquid-storage tanks was adopted in Eurocode 8. Several investigators used the finite element method combined with the boundary element method (see, for example, Hwang and Ting 1989, Lay 1993 or Kim *et al*. 2002). Cho and Cho (2007) proposed a general numerical algorithm for the analysis of the seismic responses of cylindrical steel liquid storage tanks. To overcome the limitations of the finite and boundary element methods, elements for the structure and the liquid were coupled using equilibrium and compatibility conditions. Recently, many researchers have focused their studies on better description of fluid-structure interaction during earthquakes (see, for example, Bayraktar *et al*. 2010, Ozdemir *et al*. 2010 or Buratti and Tavano 2014). A number of researchers have also analysed the influence of different base-isolation systems on the dynamic and seismic behaviour of cylindrical liquid storage tanks (see, for example, Shekari *et al*. 2010, Seleemah and El-Sharkawy 2011, Moeindarbari *et al*. 2014, Shahrjerdi and Bayat 2018, Sun *et al*. 2018). Moreover, some investigations have concerned seismic design of liquid tanks, including the aspects of soil flexibility (see, for example, Minoglou *et al*. 2013, Spritzer and Guzey 2017, Shekari 2018, Shekari *et al*. 2019). Other studies have been focused on the numerical evaluation of standard provisions. For example, Hosseinzadeh *et al*. (2013) conducted numerical verification of API650-2008 standard, while Djermane *et al*. (2014) studied dynamic buckling resistance of liquid storage tanks subjected to seismic excitation.

On the contrary to seismic events, the effects of mining tremors on steel tanks have not been really studied so far (see the results of the experimental study for two scaled models of real structures at Burkacki and Jankowski 2019). Meanwhile, the effects of mining tremors on civil engineering structures can be similarly destructive as the effects of moderate earthquakes (see Zembaty 2004, Maciag *et al*. 2016).

The aim of the present paper is to show the results of comprehensive numerical investigation focused on the response of cylindrical steel tanks under mining tremors and moderate earthquakes, including the effects of different levels of liquid filling, the influence of non-uniform seismic excitation and the aspects of diagnosis of structural damage. In particular, the objective concerns the investigation on dynamic behaviour of real steel tanks conducted for a number of different cases related to space and time correlation of the earthquake field. The created numerical

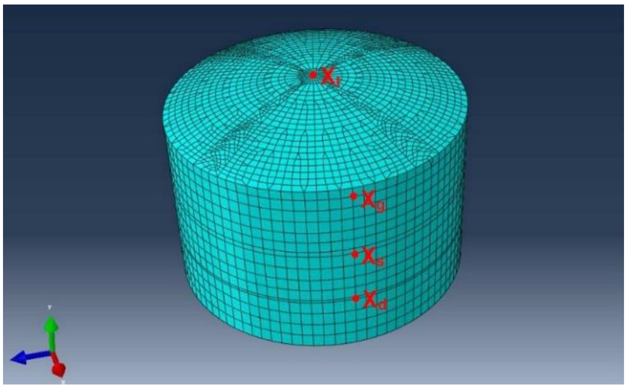


Fig. 1 FE model of steel tank with V=10,000 m^3

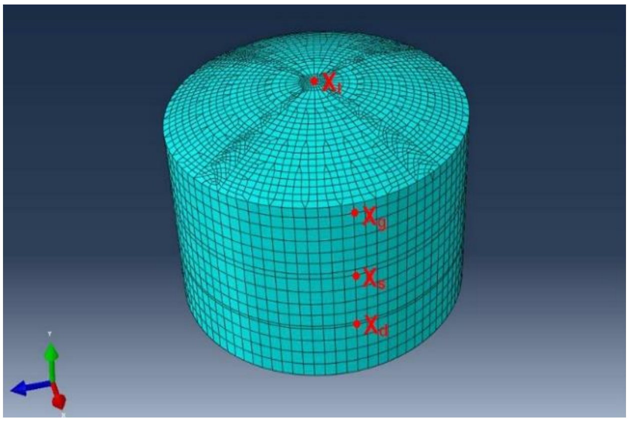


Fig. 2 FE model of steel tank with V=32,000 m^3

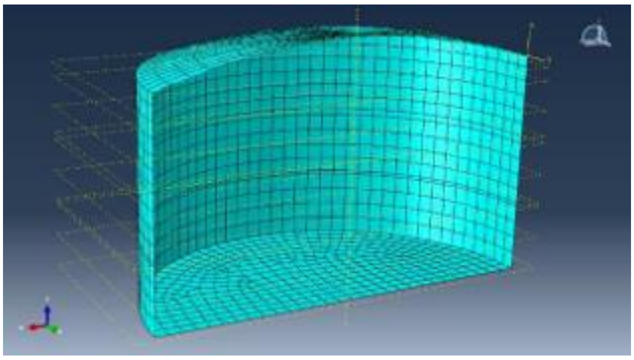
models of structures have been analysed using the FEM.

The modal analysis has been firstly conducted. Then, the structures have been subjected to the uniform ground motions for different levels of liquid filling (empty tanks, tanks partly filled, tanks fully filled). In the next stage of the study, the effects of the non-uniform earthquake excitation on the response of steel tanks have been analysed. Finally, the structures have been analysed after introducing different types of damages, so as to verify numerically the effectiveness of a method of damage diagnosis in cylindrical steel tanks.

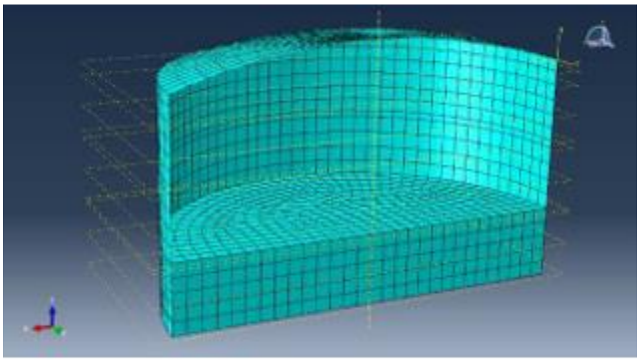
2. Numerical models

2.1 Models of steel tanks

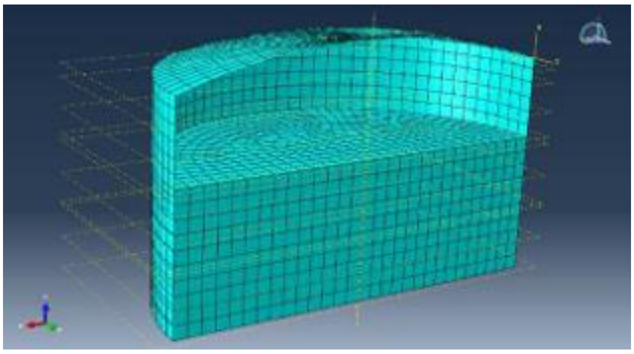
For the purpose of the analysis, two numerical models of real cylindrical steel tanks have been created. The first tank of the total volume capacity of V=10,000 m^3 is located in the fuel base Koluszki (middle part of Poland), nearby the Belchatow coal mine. Its diameter and the total height are equal to 28.36 m and 19.06 m, respectively. The bottom plate has a thickness of 9 mm. The thickness of the shell varies from 6 to 12 mm. The tank is equipped with the self-supported roof (see Virella *et al*. 2003) consisting of steel profiles: IPE270 (radial elements), C65, C80, C100, C120 (circumferential elements), L65×7 (wind bracings) and the roof sheeting with the thickness of 5 mm. The second tank



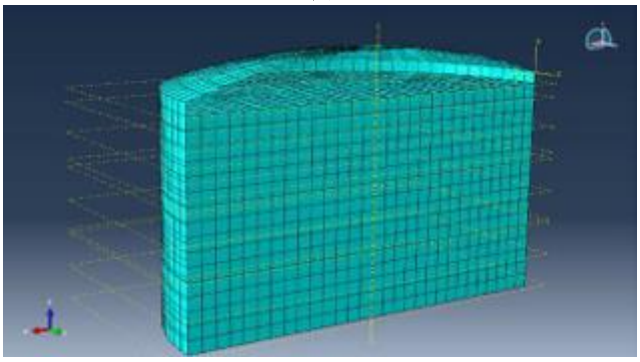
(a)



(b)

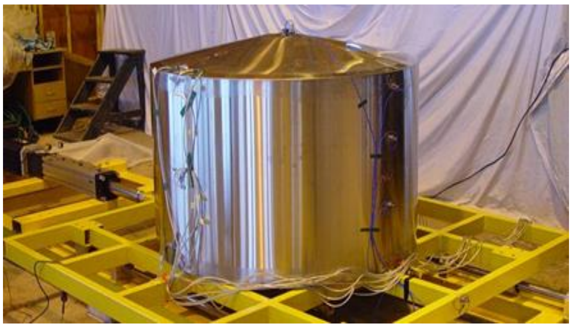


(c)

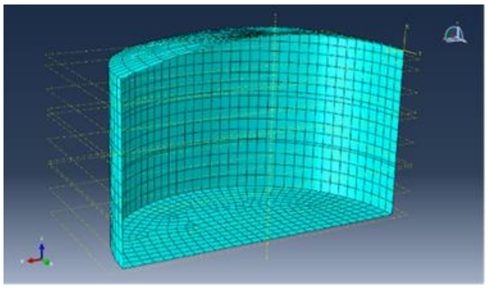


(d)

Fig. 3 Variants of liquid filling for tank with V=10,000 m^3



(a) Experimental model of tank (Burkacki and Jankowski 2019)

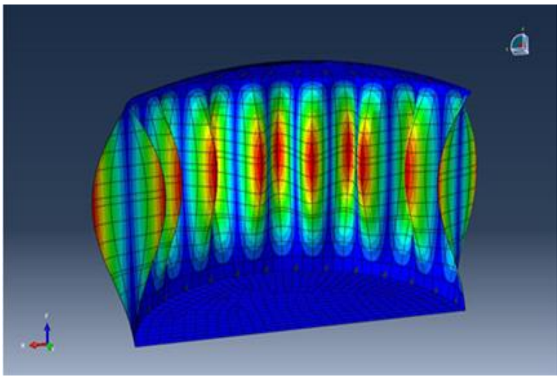


(b) FE model

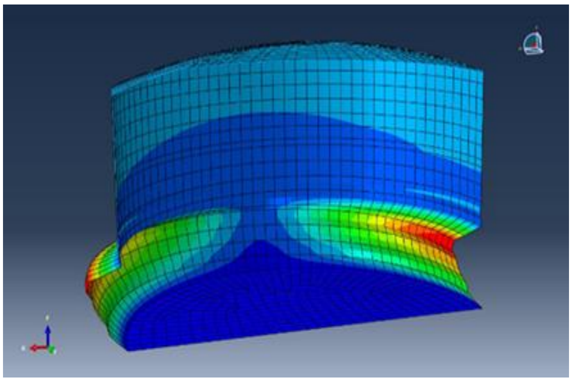
Fig. 4 Experimental model of tank with V=10,000 m^3 and its FE model

of the total volume capacity of V=32,000 m^3 is located in the oil refinery in Gdansk (northern Poland), in the region experienced by the moderate Kaliningrad earthquake in 2004. Its diameter and the total height are equal to 50 m and 23.33 m, respectively. The bottom plate has a thickness of 16 mm. The thickness of the shell varies from 8 to 22 mm. The tank is also equipped with the self-supported roof consisting of steel profiles: IPE360 (radial elements), C100, C120, C140 (circumferential elements), L65×6, L80×8, L100×8 (wind bracings) and the roof sheeting with the thickness of 5 mm.

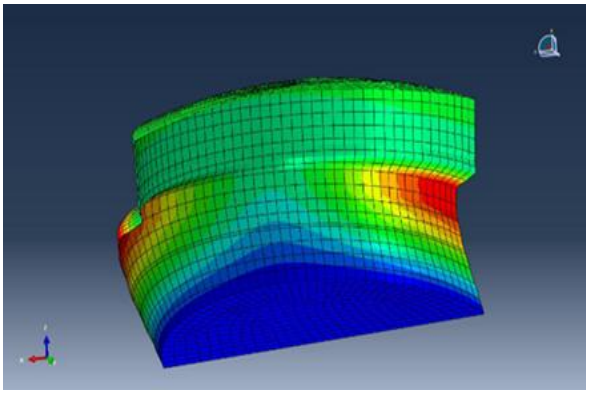
The numerical models of both tanks have been generated using the FEM commercial computer programme ABAQUS. Two types of FE elements (8-node shell element and 20-node solid element) have been used for this purpose. The structural supports at the bottom of steel tanks have been constrained. In the study, a model of sloshing of liquid considered by Virella *et al*. (2008) has been applied and the fluid-structure interaction has been modelled by the contact surfaces ('hard' contact – see ABAQUS 2011). This type of interaction is characterized by normal pressure-overclosure and tangential behaviour as hard and frictionless, respectively. It prevents from overlapping between the liquid and the shell of the tank allowing for smooth sloshing of the liquid inside the structure. The material of the tank structures is steel with Young's modulus E=210 GPa, Poisson's ratio ν=0.3 and mass density ρ=7850 kg/m^3. The material of liquid is petroleum with the bulk modulus K=1.30 GPa, Poisson's ratio ν = 0.4999 and mass density ρ=720 kg/m^3. The numerical models of both analysed tanks are shown in Fig. 1 and Fig. 2 (four locations marked in these figures represent reference nodes).



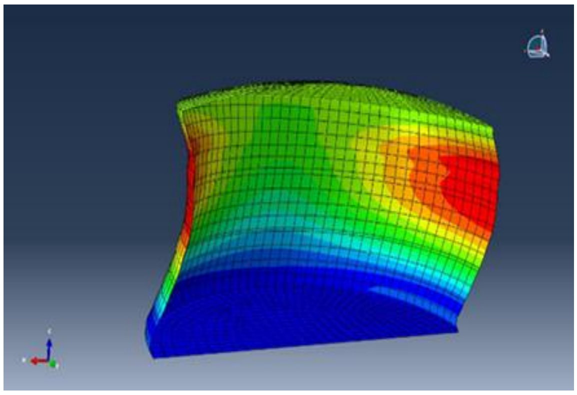
(a) Empty tank – *f* = 3.792 Hz



(b) Tank filled to 1/3 of allowable limit – *f* = 1.372 Hz

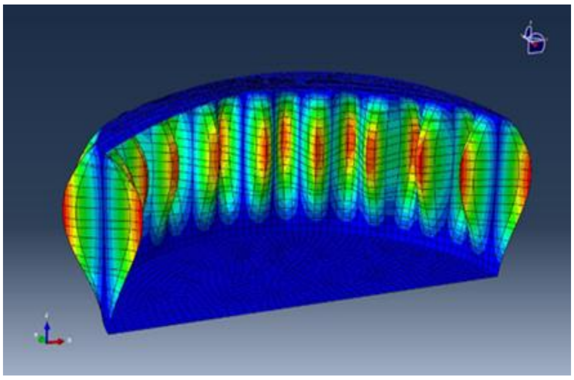


(c) Tank filled to 2/3 of allowable limit – *f* = 0.903 Hz

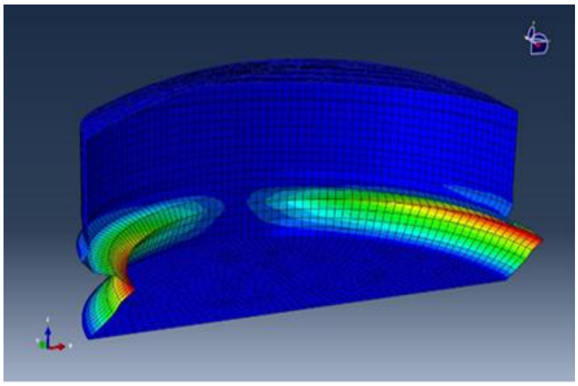


(d) Tank filled to allowable limit – *f* = 0.728 Hz

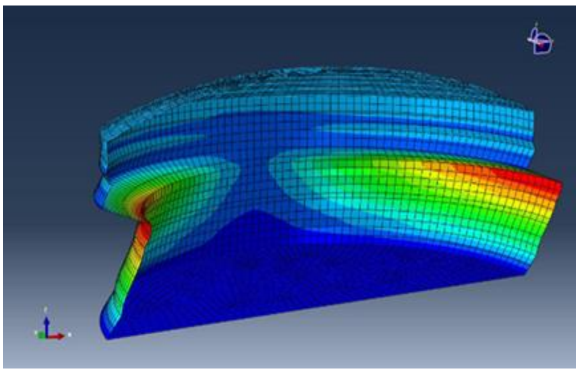
Fig. 5 First natural free vibration modes for tank with *V*=10,000 m^3 (visibility of liquid has been turned off due to clarity reasons)



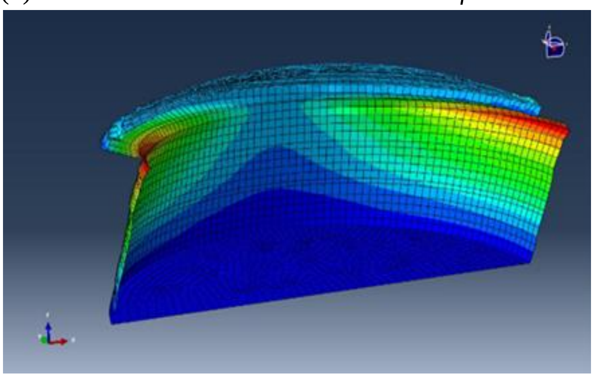
(a) Empty tank – *f* = 3.431 Hz



(b) Tank filled to 1/3 of allowable limit − *f* = 1.209 Hz

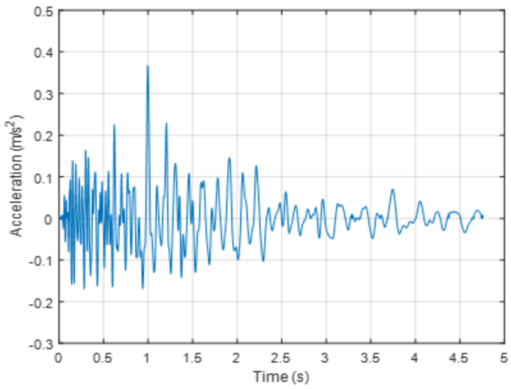


(c) Tank filled to 2/3 of allowable limit − *f* = 0.702 Hz

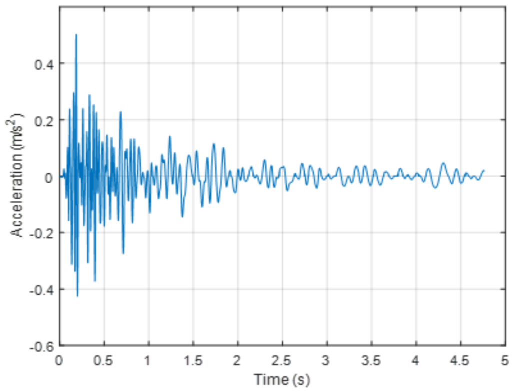


(d) Tank filled to allowable limit – *f* = 0.556 Hz

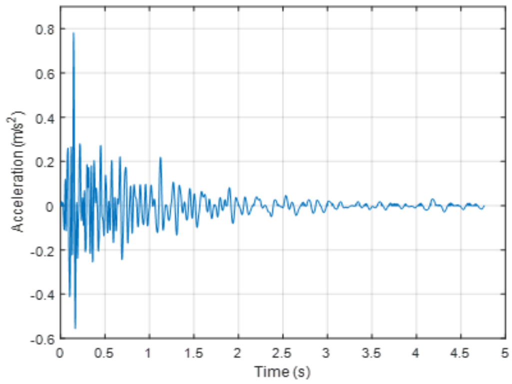
Fig. 6 First natural free vibration modes for tank with *V*=32,000 m^3 (visibility of liquid has been turned off due to clarity reasons)



(a) NS component

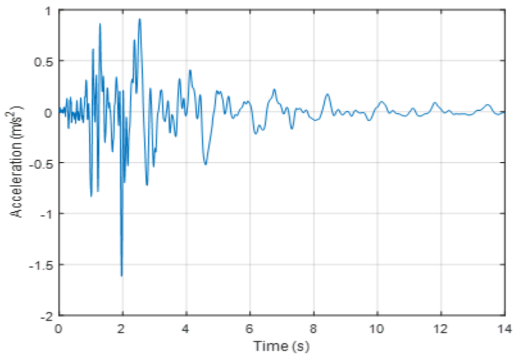


(b) EW component

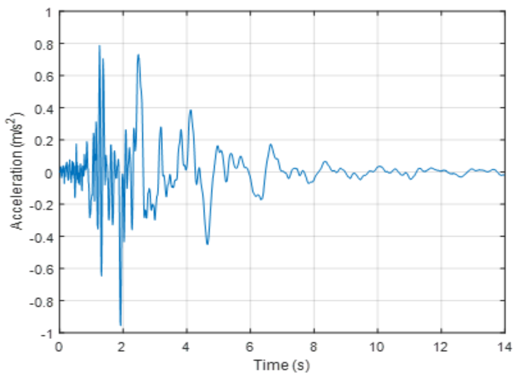


(c) UD component

Fig. 7 Polkowice 2001 mining tremor time histories



(a) NS component



(b) EW component

Fig. 8 Polkowice 2002 mining tremor time histories

2.2 Levels of liquid filling

The numerical analysis has been conducted for four variants of liquid level (Fig. 3):

a) Empty tank,

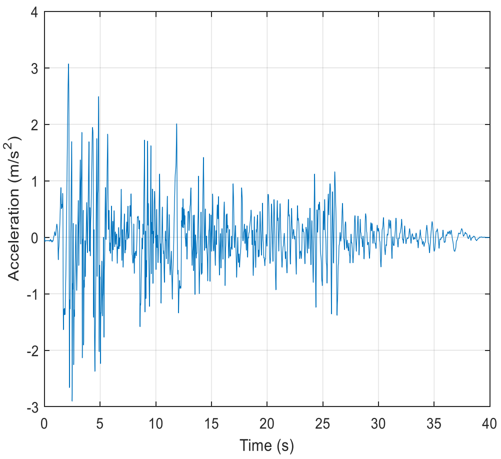
b) Tank filled to 1/3 of allowable height limit (5.24 m for tank with V=10,000 m^3, 5.4 m for tank with V=32,000 m^3),

c) Tank filled to 2/3 of allowable height limit (10.48 m for tank with V=10,000 m^3, 10.8 m for tank with V=32,000 m^3),

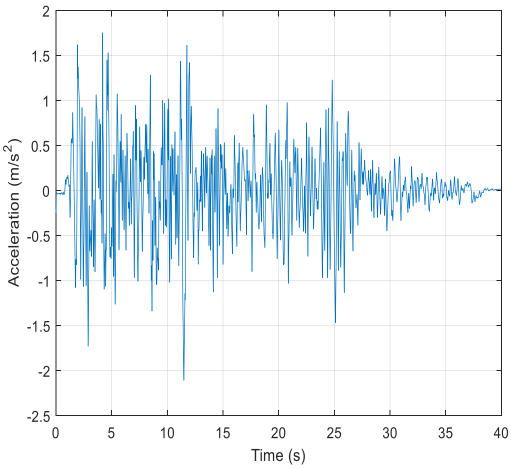
d) Tank filled to allowable height limit (15.72 m for tank with V=10,000 m^3, 16.2 m for tank with V=32,000 m^3).

2.3 Validation of numerical models

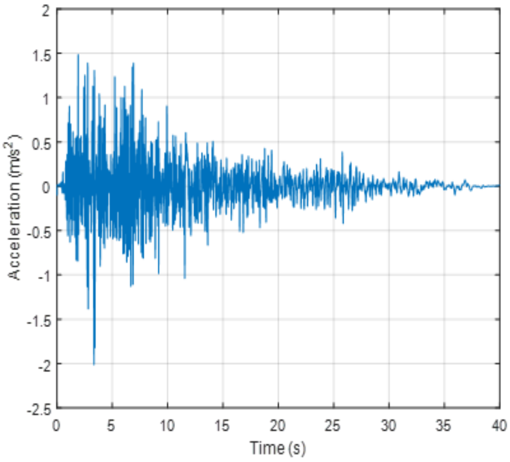
Verification of the accuracy of FE models of real tanks is complicated because these structures are important elements of existing industrial facilities; they are always in use, so it is difficult to conduct the tests for different, assumed levels of petroleum. For that reason, validation of numerical models has been conducted based on the results



(a) NS component



(b) EW component



(c) UD component

Fig. 9 El Centro 1940 earthquake time histories

obtained for the scaled experimental models studied by Burkacki and Jankowski (2019). As the example, the experimental model of tank with capacity of 10,000 m^3 (characterized by scale equal to 1:22.69 and diameter of 1.25 m) and its FE model are presented in Fig. 4. For validation purposes, the value of the first natural frequency of the structure, as a result of the modal analysis, has been compared with the corresponding value obtained from the experiment. According to results of such comparison, the difference between frequencies for FE and experimental models was not larger than 5.0% for all different cases of liquid filling. Based on this verification, FE models of real tanks have been implemented in order to conduct further numerical study.

3. Modal analysis

Modal analysis has been firstly conducted in order to determine values of natural frequencies and corresponding free vibration modes for each of the structure. A number of results for both steel tanks with different levels of liquid filling have been obtained. The examples of the first natural frequencies, *f*, and the corresponding free vibration modes, for four variants of liquid filling are shown in Fig. 5 and Fig. 6 (behaviour of liquid has been turned off to ensure better visibility of structures). The results clearly indicate that filling the tank with petroleum leads to considerable changes in the shapes of vibration modes. It can be seen from Fig. 5 and Fig. 6 that the first natural free vibration mode of empty tank is solely related to the behaviour of the tank shell, whereas the free vibration modes of tank filled with petroleum depend on the interaction between the structure and liquid under sloshing. What is more, the filling of structures with petroleum has resulted in a substantial reduction in the natural frequencies. Fig. 5 shows that the value of the first natural frequency has been reduced by 63.8%, 76.2% and 80.8% by filling the tank with 5.24 m, 10.48 m and 15.72 m of liquid, respectively, as compared to the empty structure. The same tendency has occurred for the model with V=32,000 m^3, where reductions are equal to 64.8%, 79.5% and 83.8% after filling the tank with 5.4 m, 10.8 m and 16.2 m of petroleum, respectively.

4. Seismic and paraseismic analysis

The next phase of the numerical study has been focused on seismic and paraseismic tests. The following three ground motions have been used in the study:

a) Polkowice mining tremor, 02.02.2001 (NS component with PGA=0.368 m/s^2, EW component with PGA=0.503 m/s^2, UD component with PGA=0.782 m/s^2) - see Fig. 7,

b) Polkowice mining tremor, 20.02.2002 (NS component with PGA=1.634 m/s^2, EW component with PGA=0.965 m/s^2) - see Fig. 8,

c) El Centro earthquake, 18.05.1940 (NS component with PGA=3.402 m/s^2, EW component with PGA=2.107 m/s^2, UD component with PGA=2.013 m/s^2)-see Fig. 9,

where PGA stands for the peak ground acceleration. The first two excitations are typical examples of mining-induced seismicity, whereas the last one can be somehow considered as the example of a moderate earthquake.

4.1 Uniform ground motions

The case of uniform ground motions has been firstly considered assuming that the acceleration time histories are identical for all structural supports. The representative examples of the results of the study are presented in Figs. 10-13. In particular, Fig. 10 and Fig. 11 show the displacement UX time histories in normal-to-wall direction (reference node X_t), as well as the extreme distributions of von Mises stresses, for the tank with V=10,000 m^3 for different levels of liquid filling under the uniform Polkowice 2002 mining tremor. On the other hand, the displacement UX time histories in normal-to-wall direction (reference node X_g), as well as the extreme distributions of von Mises stresses, for the tank with V=32,000 m^3 for different levels of liquid filling under the uniform El Centro earthquake are presented in Fig. 12 and Fig. 13. The obtained results clearly indicate that filling the tank with petroleum leads to a substantial increase in the structural response under uniform ground motions. For example, it can be seen from Fig. 10 that the peak value of displacement UX (reference node X_t) has increased under the Polkowice 2002 mining tremor by as much as 161.5%, 584.6% and 1184.6% by filling the first tank with 5.24 m, 10.48 m and 15.72 m of petroleum, respectively, as compared to the empty structure. The corresponding increases in the maximum value of von Mises stress are equal to 184.9%, 477.5% and 776.5%, respectively, for the same structure and seismic excitation (see Fig. 11). Similarly, it can also be observed from Fig. 12 that the peak value of displacement UX (reference node X_g) has increased under the El Centro earthquake by as much as 188.0%, 620.0% and 980.0% by filling the second tank with 5.4 m, 10.8 m and 16.2 m of liquid, respectively, as compared to the empty structure. The corresponding increases in maximum value of von Mises stress are equal to 191.0%, 462.8% and 517.1%, respectively, for the same structure and seismic excitation (see Fig. 13). The results of the study also indicate that the peak structural response values under mining tremors can be really comparable to the peak structural response values under moderate earthquakes. It can be seen from Fig. 11 and Fig. 13, for example, that the differences in von Mises stresses are not so large having in mind the fact that the PGA values for both excitations are much different (see the description at the beginning of section 4). Fortunately, the allowable level of stresses has not been exceeded in any case of ground motions for none of both steel tanks analysed in the study.

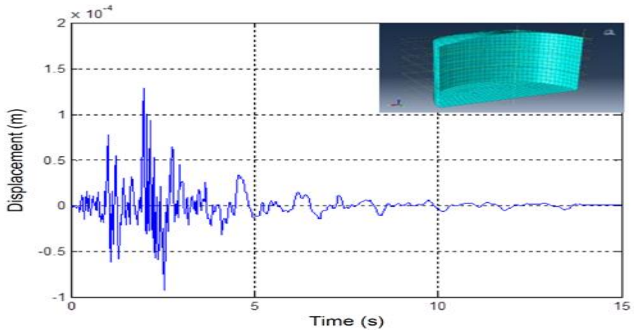
4.2 Non-uniform ground motions

It has been assumed in the analysis described in section 4.1 that the ground motions are uniform for all support locations of a steel tank. In reality, however, the ground motion differs from place to place due to spatial seismic effects related to the propagation of the seismic wave (see Der Kiureghian 1996, Zembaty and Rutenberg 2002). These effects include: difference in the arrival times of seismic wave at various locations (wave passage effect), loss of coherency of seismic wave due to scattering in the heterogeneous medium of the ground as well as due to differential superimposition of waves arriving from an extended source (incoherence effect) and spatially varying local soil conditions (site response effect) (Der Kiureghian 1996). Previous studies have indicated that the variation of ground motion in space and time can be visible even for the distance of tens of meters and it may considerably change the behaviour of structures (Harichandran *et al*. 1996). In earthquake engineering, the simulation of spatiotemporal variation of ground motion field can be successfully conducted (Harichandran and Vanmarcke 1986, Jankowski and Wilde 2000, Zhang *et al*. 2013). Therefore, in the next stage of the study, the case of non-uniform seismic excitation has been considered. For this purpose, a method of conditional stochastic simulation of ground motions for structures with extended foundations has been used (Jankowski 2012). The method is based on the spatiotemporal correlation function and it allows us to generate unknown acceleration time histories for different support locations of the structure. The spatiotemporal correlation function can be defined as (compare Jankowski 2012):

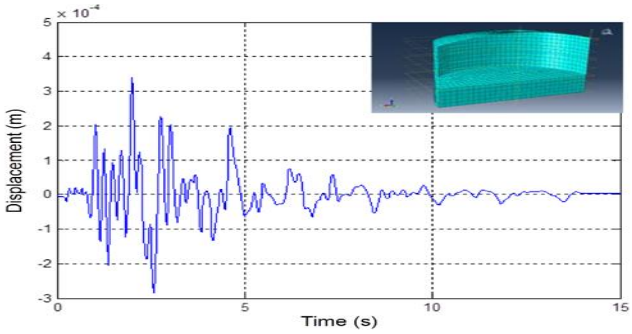
$$K(\mathbf{r}_{ij},\Delta t_{ij}) = \sigma^2 \exp\left(-\frac{\omega_d\left|\mathbf{r}_{ij}\right|}{2\pi v d}\right)\exp\left(-\beta\Delta t_{ij}\right) \quad (1)$$

where σ-standard deviation of the history record, ω_d-predominant frequency of the ground motion, $|\mathbf{r}_{ij}|$-distance between the structural support locations i, j, v-mean apparent seismic wave velocity in the ground, d-space scale parameter (d>0) depending on local ground conditions, Δt_{ij}-time lag between the values in the ground motion records for the support locations i, j and time scale parameter (β>0) describing the degree of time correlation.

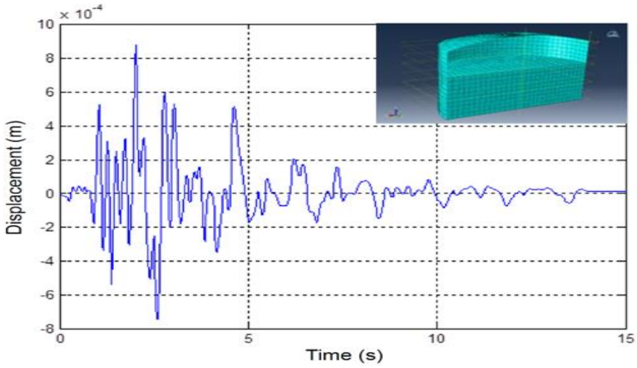
In the random fields theory, the ground motion acceleration record is usually treated as a set of measured values, which satisfy zero-mean Gaussian distribution (see Jankowski and Wilde 2000). A formula for the probability density of Gaussian conditional distribution can be written as (Jankowski and Walukiewicz 1997):



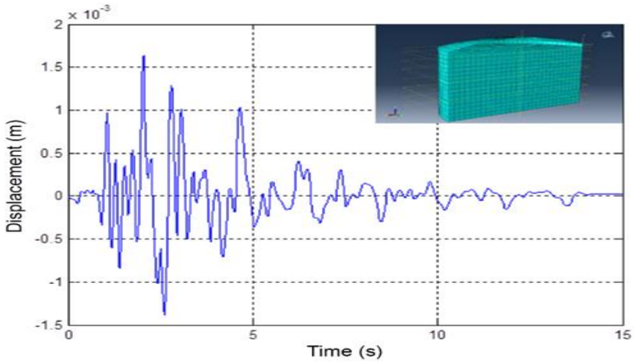
(a) Empty tank (peak value: $1.30 \cdot 10^{-4}$ m)



(b) Tank filled to 1/3 of allowable limit (peak value: $3.40 \cdot 10^{-4}$ m)

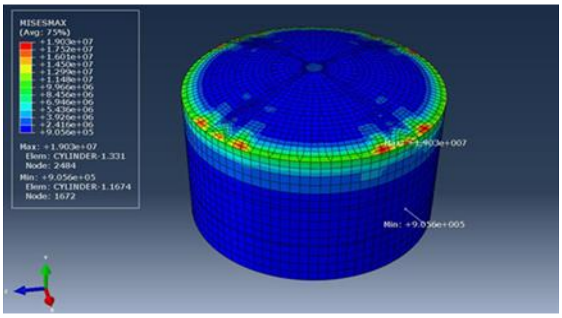


(c) Tank filled to 2/3 of allowable limit (peak value: $8.90 \cdot 10^{-4}$ m)

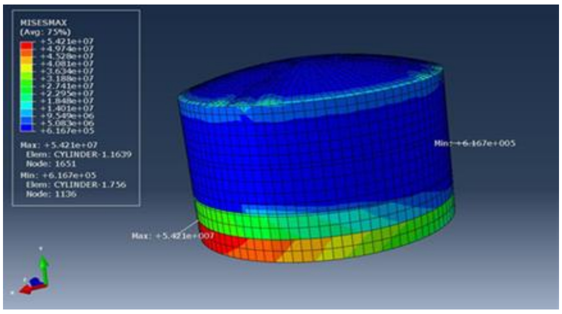


(d) Tank filled to allowable limit (peak value: $1.67 \cdot 10^{-3}$ m)

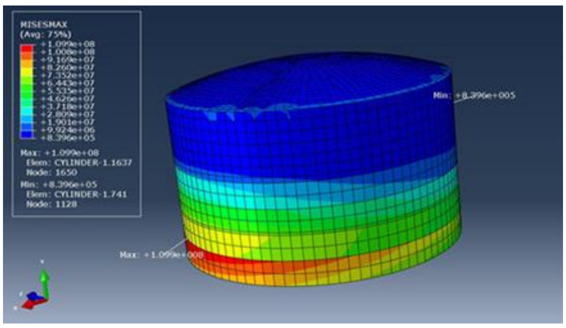
Fig. 10 Displacement UX time histories for tank with V=10,000 m^3 under the uniform Polkowice 2002 mining tremor – reference node X_t



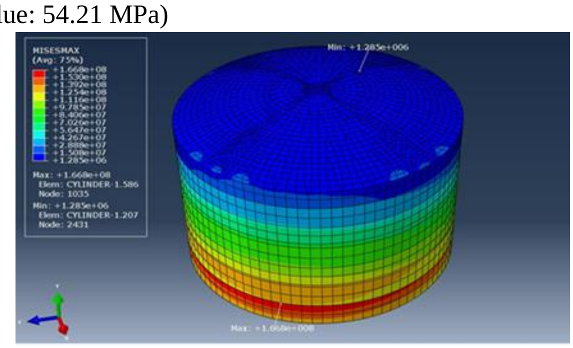
(a) Empty tank – t=1.41 s (max value: 19.03 MPa)



(b) Tank filled to 1/3 of allowable limit – t=2.01 s (max value: 54.21 MPa)

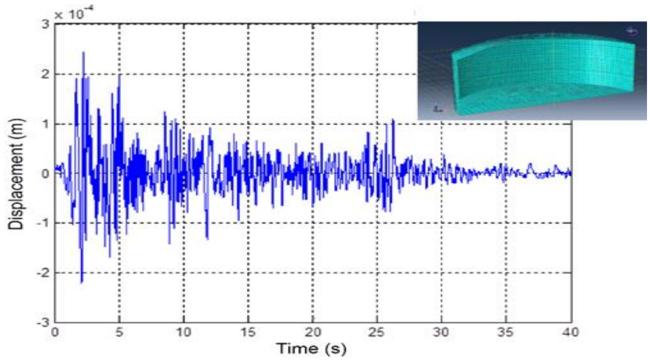


(c) Tank filled to 2/3 of allowable limit – t=2.01 s (max value: 109.90 MPa)

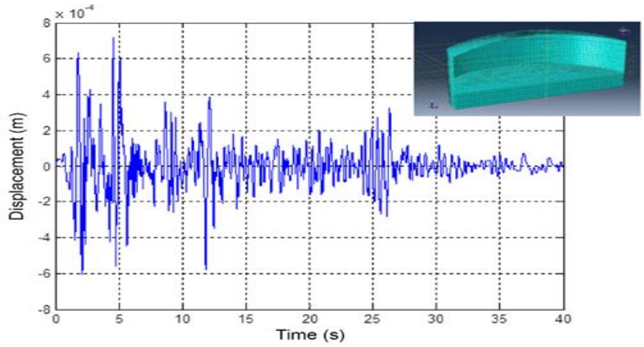


(d) Tank filled to allowable limit – t=2.01 s (max value: 166.80 MPa)

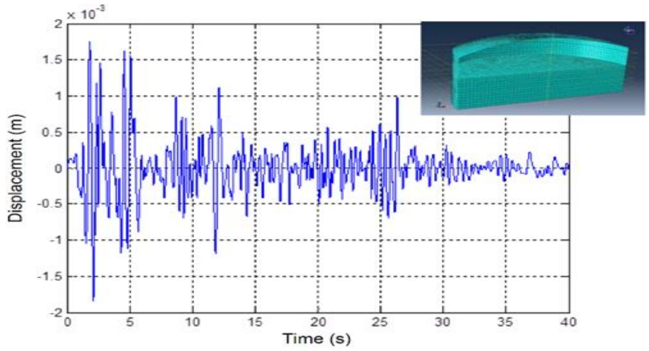
Fig. 11 Extreme distributions of von Mises stresses for tank with V = 10,000 m^3 under the uniform Polkowice 2002 mining tremor



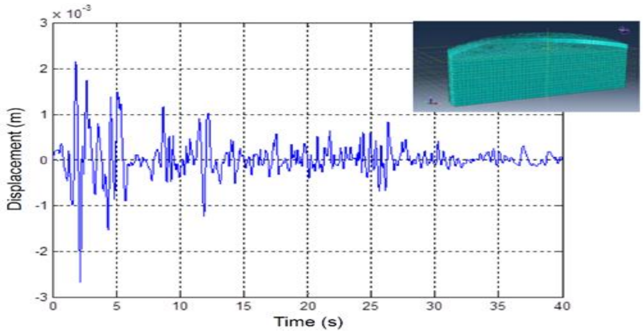
(a) Empty tank (peak value: $2.50 \cdot 10^{-4}$ m)



(b) Tank filled to 1/3 of allowable limit (peak value: $7.20 \cdot 10^{-4}$ m)

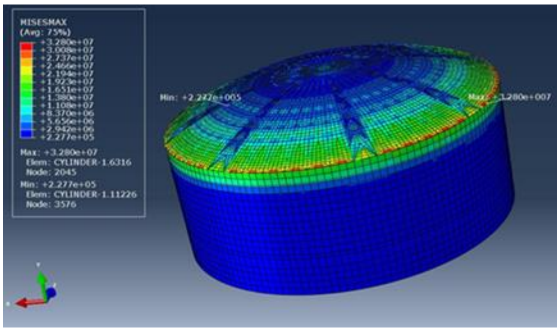


(c) Tank filled to 2/3 of allowable limit (peak value: $1.80 \cdot 10^{-3}$ m)

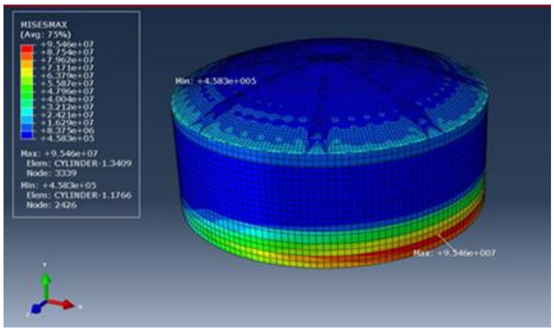


(d) Tank filled to allowable limit (peak value: $2.70 \cdot 10^{-3}$ m)

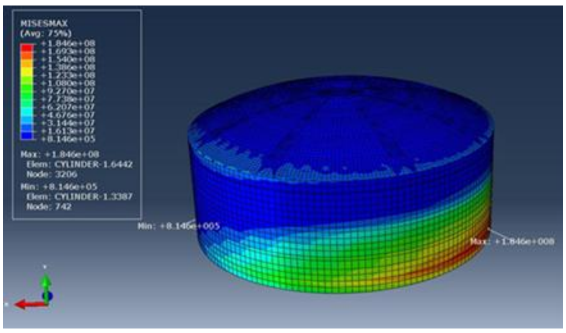
Fig. 12 Displacement UX time histories for tank with V = 32,000 m^3 under the uniform El Centro earthquake – reference node X_g



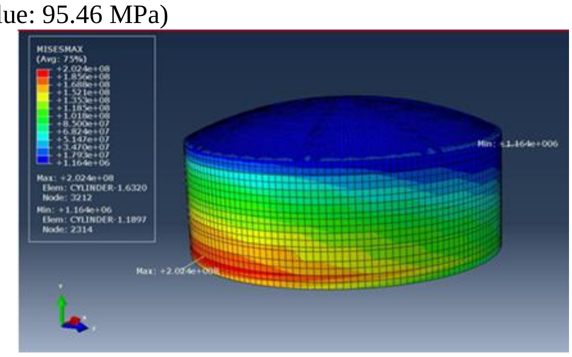
(a) Empty tank – t = 3.21 s (max value: 32.80 MPa)



(b) Tank filled to 1/3 of allowable limit − t = 1.80 s (max value: 95.46 MPa)



(c) Tank filled to 2/3 of allowable limit − t = 2.16 s (max value: 184.60 MPa)



(d) Tank filled to allowable limit − t = 2.16 s (max value: 202.40 MPa)

Fig. 13 Extreme distributions of von Mises stresses for tank with V = 32,000 m^3 under the uniform El Centro earthquake

$$f(\mathbf{x}|\mathbf{y}) = \left(\det \mathbf{K}_c\right)^{-\frac{1}{2}} \cdot (2\pi)^{-\frac{n}{2}} \cdot \exp\left(-\frac{1}{2}\left(\mathbf{x}-\mathbf{m}_c\right)^T \mathbf{K}_c^{-1}\left(\mathbf{x}-\mathbf{m}_c\right)\right) \quad (2)$$

where $\mathbf{x} = [x_1, x_2, \cdots, x_n]^T$ is n-dimensional vector of unknown values, $\mathbf{y} = [y_1, y_2, \cdots, y_{n'}]^T$ is n'-dimensional vector of known values and $\mathbf{K}_c$ is a conditional covariance matrix:

$$\mathbf{K}_c = \mathbf{K}_{11} - \mathbf{K}_{12}\mathbf{K}_{22}^{-1}\mathbf{K}_{21} \quad (3)$$

and $\mathbf{m}_c$ is a vector of conditional mean values:

$$\mathbf{m}_c = \mathbf{K}_{12}\mathbf{K}_{22}^{-1}\mathbf{y} \quad (4)$$

where $\mathbf{K}_{11}$, $\mathbf{K}_{12}$, $\mathbf{K}_{21}$ and $\mathbf{K}_{22}$ are the elements of the covariance matrix, **K**, determined for all (known and unknown) values assuming the correlation function defined by Eq. (1). Matrix **K** can be expressed as:

$$\mathbf{K} = \begin{bmatrix} \mathbf{K}_{11}\mathbf{K}_{12} \\ \mathbf{K}_{21}\mathbf{K}_{22} \end{bmatrix} \quad (5)$$

For the simulation purposes of ground motion records, the following algorithm, based on the acceptance-rejection theorem, has been used (compare Jankowski 2012):

1) Determination of the spatiotemporal correlation function defined by Eq. (1).

2) Determination of the covariance matrix, **K**, according to Eq. (5).

3) Calculation of the conditional covariance matrix, $\mathbf{K}_c$, from Eq. (3).

Points 4-7 are repeated for all time steps in the ground motion record:

4) Generation of an unknown vector **x**, $x_i=-a_{max} + 2a_{max}\cdot r_d$ where a_{max} is a peak ground acceleration and r_d is a uniform random variable from interval <0,1>.

5) Calculation of the vector of conditional mean values, $\mathbf{m}_c$, according to Eq. (4), and the value of conditional density function, $f(\mathbf{x}|\mathbf{y})$, defined by Eq. (2).

6) Generation of a random value, R

$$R = \left(\det \mathbf{K}_c\right)^{-\frac{1}{2}} \cdot (2\pi)^{-\frac{n}{2}} \cdot r_d \quad (6)$$

7) Verification of the condition (von Neumann elimination)

$$R \le f(\mathbf{x}|\mathbf{y}) \quad (7)$$

If this condition holds, vector **x** is accepted and the simulation for the next time step in undertaken. If not, the calculation returns to point 4 and the generation of another vector **x** is conducted.

The described above algorithm of conditional stochastic modelling has been used to generate the ground motion records for different locations based on a specified acceleration time history. The base plate of each steel tank has been divided into eight regions. The example of the division for the structure with V=32,000 m^3 is presented in Fig. 14. It has been assumed in the analysis that the ground motion record for the structural support location no. 1 is specified and different acceleration time histories for other 7 locations have been generated. Simulations have been carried out for the apparent seismic wave velocity of v=1000 m/s and for the space and time scale parameters equal to d=1.0 and β=100, respectively (compare Jankowski 2012). Then, the input ground motion records have been applied to conduct a numerical dynamic analysis of the behaviour of steel tanks under non-uniform excitation. The representative results of the investigation, in the form of the displacement UX time history in normal-to-wall direction (reference node X_g) as well as the extreme distribution of von Mises stresses for the tank with V=32,000 m^3 filled with liquid to allowable limit under the non-uniform El Centro earthquake, are presented in Fig. 15 and Fig. 16, respectively. The obtained results clearly indicate that the consideration of spatial effects related to seismic wave propagation leads to a considerable decrease in the structural response during ground motions. For example, it can be seen comparing Fig. 15 with Fig. 12(d) that the peak value of UX displacement (reference node X_g) has decreased by 11.1% when the uniform El Centro excitation is replaced by the non-uniform one. Similarly, the comparison between Fig. 16 and Fig. 13(d) indicates that the decrease in value of the maximum von Mises stress is equal to 13.4% for the same structure and seismic excitation.

5. Damage diagnosis

The problem of damages in civil engineering structures have recently been intensively studied (see, for example, Falborski *et al*. 2012, 2017, Jankowski 2015, Jankowski and Mahmoud 2010, 2016, Elwardany *et al*. 2017). A number of different methods of damage diagnosis have been considered in various analyses. Among them, a

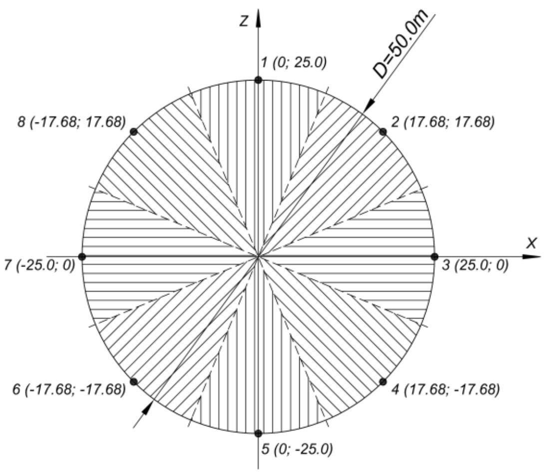


Fig. 14 Division of base plate of tank with V=32,000 m^3 for the purposes of generation of non-uniform excitation

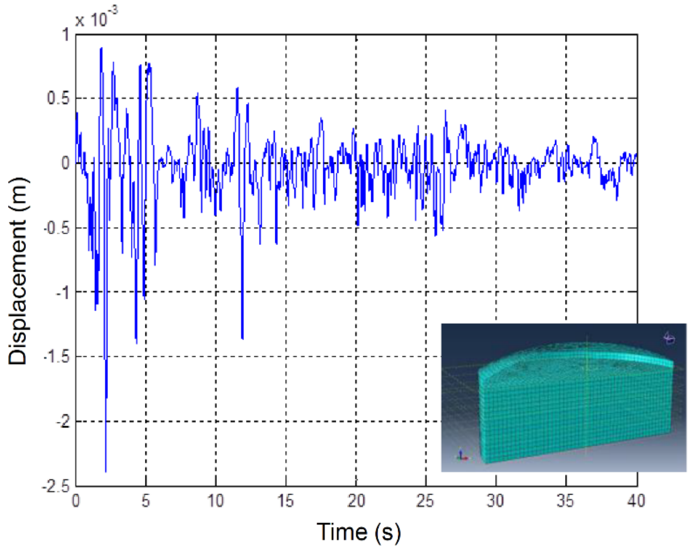


Fig. 15 Displacement UX time history for tank with V=32,000 m^3 filled to allowable limit under the non-uniform El Centro earthquake – reference node X_g (peak value: 2.40·10^{-3} m)

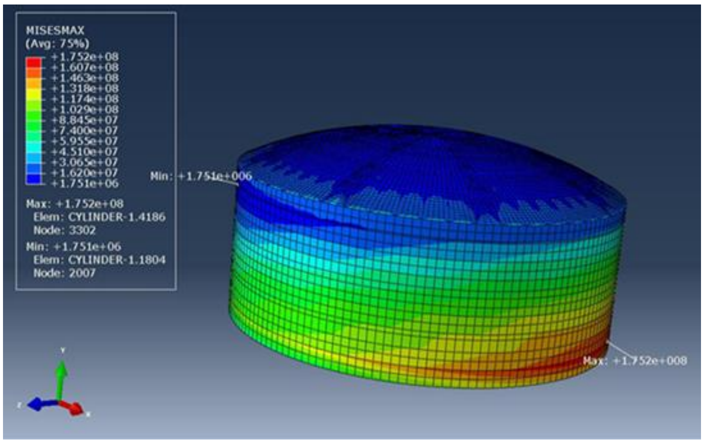
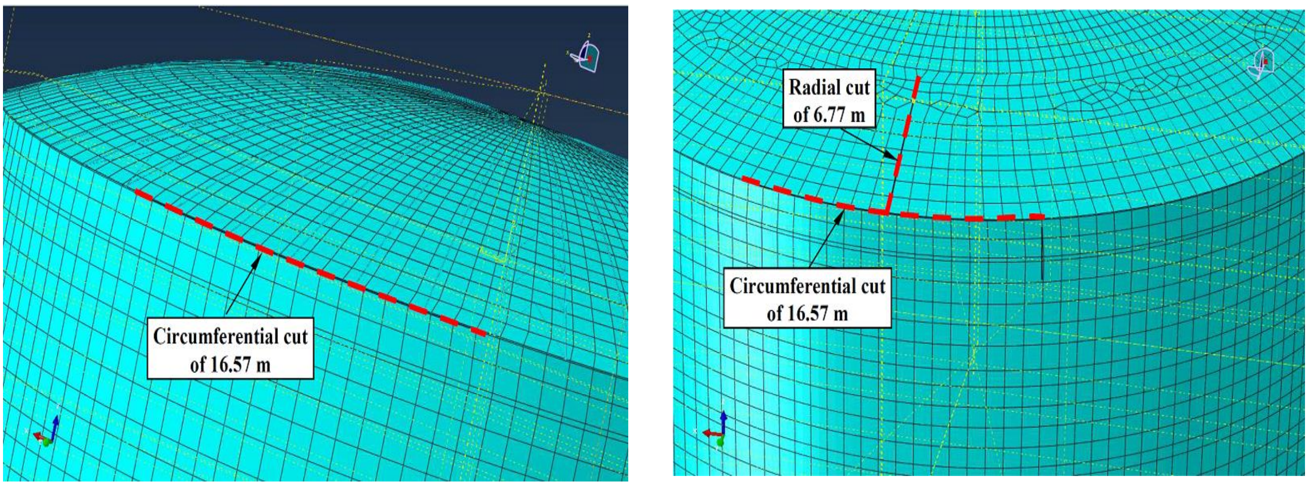


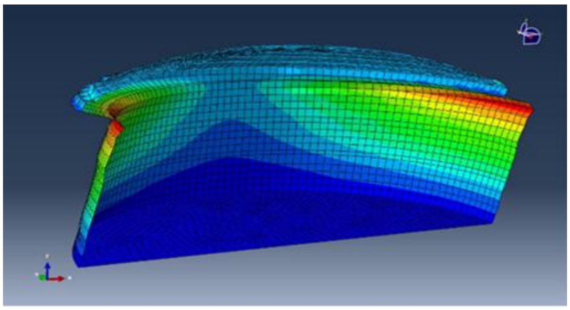
Fig. 16 Extreme distribution of von Mises stress for tank with V=32,000 m^3 filled to allowable limit under the non-uniform El Centro earthquake – t=2.19 s (max value: 175.20 MPa)



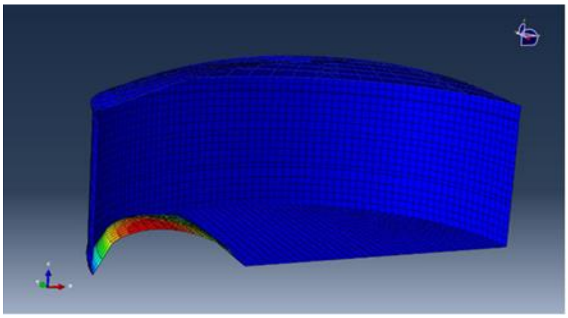
(a) Cut of weld between shell and roof

(b) Cut of weld between shell and roof and radial cut of weld in the roof

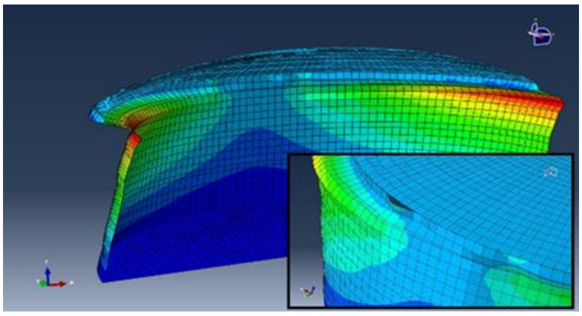
Fig. 17 Cases of damage in the form of weld cuts



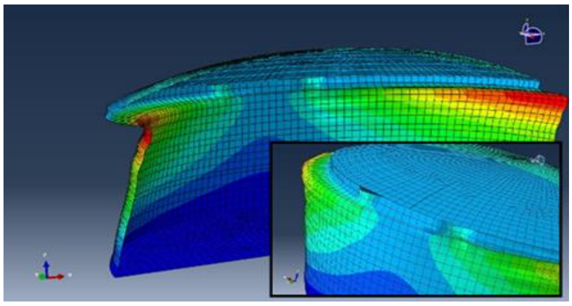
(a) Undamaged tank – f=0.556 Hz



(b) Tank with reduced stiffness of tank-foundation connection – f=0.504 Hz



(c) Tank with circumferential cut of weld between shell and roof – f=0.556 Hz



(d) Tank with circumferential cut of weld between shell and roof and with radial cut of weld in roof – f=0.556 Hz

Fig. 18 First natural free vibration modes for different types of damage for tank with V=32,000 m^3 fully filled with liquid (visibility of liquid has been turned off due to clarity reasons)

method of measuring the changes in natural frequencies of structures is one of the most popular (see Salawu 1997). However, its effectiveness, in the case of such structures as cylindrical steel tanks, still needs to be verified. Since the experimental investigations on real tanks are extremely difficult, the last part of the present study has been focused on numerical modal analysis of structures after introducing different types of damages.

The following cases of structural damage, which may somehow represent various types of damages typical for cylindrical steel tanks, have been taken into account at this stage of the study:

a) Undamaged tank

b) Tank with reduced stiffness of tank-foundation connection by taking off 30% of fixed supports (the effect of uplifting – see, for example, Ishida and Kobayashi 1988 or Malhotra and Veletsos 1994),

c) Tank with circumferential cut of weld between shell and roof – see Fig. 17(a),

d) Tank with circumferential cut of weld between shell and roof as well as with radial cut of weld in the roof – see Fig. 17(b).

A number of results for both steel tanks with different levels of liquid filling have been obtained. The representative examples in the form of the first natural free vibration modes for different types of damage for tank with V=32,000 m^3 fully filled with liquid are shown in Fig. 18 (behaviour of liquid has been turned off to ensure better visibility). The results of the investigation indicate that the changes in the free vibration modes, as well as in the natural frequencies, are related to the type of damage which has been introduced in the structure. A characteristic decrease in the natural frequencies has been observed for the steel tank with reduced stiffness of tank-foundation connection which results from the fact that this damage type can be classified as a global one. For example, in the case of the tank with V=32,000 m^3 fully filled with liquid, the decrease in the first natural frequency is as large as 9.4%, as compared to the undamaged structure (compare Fig. 18(b) with Fig. 18(a)).

On the other hand, the results of the numerical analysis for types of damage in the form of weld cuts, which can be classified as local types of damage, are much different. This time, the natural frequencies have not been altered compared to the undamaged tank for all the cases considered. However, the deformation of the shell of the structure has been observed in the vicinity of cuts (see Fig. 18(c) and Fig. 18(d)).

6. Conclusions

A comprehensive numerical study concerning the dynamic behaviour of cylindrical steel tanks under mining tremors and moderate earthquakes has been conducted and described in this paper. The effects of different levels of liquid filling (empty tanks, tanks partly filled, tanks fully filled), the influence of non-uniform seismic excitation, as well as the aspects of diagnosis of structural damage, have been investigated. The created numerical models of real structures have been analysed using the FEM.

The results of the modal analysis indicate that the level of liquid filling is really essential in the structural analysis leading to considerable changes in the shapes of vibration modes. They show that the natural free vibration modes of empty tank are related to the behaviour of the structure itself, whereas the vibration modes of the structure filled with petroleum depend on the interaction between the structure and liquid under sloshing. Moreover, the filling of the tank with liquid has resulted in a substantial reduction in the natural frequencies of the structure.

The results of seismic and paraseismic analyses show that that dynamic behaviour under mining tremors and moderate earthquakes is considerably different for different levels of liquid filling. They indicate that the filling the tank with petroleum leads to a substantial increase in the structural response underground motions. It has also been observed that the peak structural response values under mining tremors can be comparable to the peak structural response values under moderate earthquakes. Moreover, the results for the non-uniform seismic excitation clearly indicate that the consideration of spatial effects related to seismic wave propagation leads to a considerable decrease in the structural response.

Finally, the analysis of damage diagnosis in steel tanks shows that different types of damage may induce changes in the free vibration modes and values of natural frequencies. A characteristic decrease in the natural frequencies has been observed for the steel tank with reduced stiffness of tank-foundation connection which is characteristic for the global type of damage. On the other hand, for the case of weld cuts, which can be classified as the local type of damage, the natural frequencies have not been altered comparing to the undamaged tank, however, the deformation of the shell of the structure has been observed in the vicinity of cuts.

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References

ABAQUS (2011), Explicit version 6.11 User's Manual, Dassault Systèmes.

Bayraktar, A., Sevim, B., Altun, A.C. and Türker, T. (2010), "Effect of the model updating on the earthquake behavior of steel storage tanks", *J. Constr. Steel Res.*, **66**(3), 462-469. ttps://doi.org/10.1016/j.jcsr.2009.10.006.

Buratti, N. and Tavano, M. (2014), "Dynamic buckling and seismic fragility of anchored steel tanks by the added mass method", *Earthq. Eng. Struct. Dyn.*, **43**(1), 1-21. https://doi.org/10.1002/eqe.2326|.

Burkacki, D. and Jankowski, R. (2019), "Experimental study on models of cylindrical steel tanks under mining tremors and moderate earthquakes", *Earthq. Struct.*, **17**(2), 175-189. https://doi.org/10.12989/eas.2019.17.2.175.

Cho, K.H. and Cho, S.Y. (2007), "Seismic response of cylindrical steel tanks considering fluid-structure interaction", *Steel Struct.*, **7**(2), 147-152.

Cooper, T.W. (1997), "A Study of the Performance of Petroleum Storage Tanks During Earthquakes", 1933-1995, NIST No. GCR 97-720, U.S. Dept. of Commerce, National Institute of Standards and Technology, Gaithersburgh, Md., U.S.A.

Der Kiureghian, A. (1996), "A coherency model for spatially varying ground motions", *Earthq. Eng. Struct. Dyn.*, **25**(1), 99-111. https://doi.org/10.1002/(SICI)1096-9845(199601)25:1<99::AID-EQE540>3.0.CO;2-C|.

DiGrado, B.D. and Thorp, G.A. (1995), *The Aboveground Steel Storage Tank Handbook*, Van Nostrand Reinhold, New York, U.S.A.

Djermane, M., Zaoui, D., Labbaci, B. and Hammadi, F. (2014), "Dynamic buckling of steel tanks under seismic excitation: numerical evaluation of code provisions", *Eng. Struct.*, **70**(1), 181-196. ttps://doi.org/10.1016/j.engstruct.2014.03.037.

Edwards, N.W. (1969), A Procedure for the Analysis of the Dynamic of Thin-Walled Cylindrical Liquid Storage Tanks, Ph.D. Dissertation, University of Michigan, Ann Arbor, Michigan, U.S.A.

Elwardany, H., Seleemah, A. and Jankowski R. (2017), "Seismic pounding behavior of multi-story buildings in series considering the effect of infill panels", *Eng. Struct.*, **144**, 139-150. ttps://doi.org/10.1016/j.engstruct.2017.01.078.

Falborski, T. and Jankowski, R. (2017), "Experimental study on effectiveness of a prototype seismic isolation system made of polymeric bearings", *Appl. Sci.*, **7**(8), 808. https://doi.org/10.3390/app7080808.

Falborski, T., Jankowski, R. and Kwiecień, A. (2012), "Experimental study on polymer mass used to repair damaged structures", *Key Eng. Mater.*, **488-489**, 347-350. https://doi.org/10.4028/www.scientific.net/KEM.488-489.347

Fenves, G. and Vargas-Loli, L.M. (1988), "Nonlinear dynamic analysis of fluid-structure systems", *J. Eng. Mech.*, **114**(2), 219-240. https://doi.org/10.1061/(ASCE)0733-9399(1988)114:2(219).

Godoy, L.A. (1996), *Thin-Walled Structures with Structural Imperfections Analysis and Behaviour*, Pergamon Press-Elsevier, New York, U.S.A.

Harichandran, R.S. and Vanmarcke, E.H. (1986), "Stochastic variation of earthquake ground motion in space and time", *J. Eng. Mech.*, **112**(2), 154-174. ttps://doi.org/10.1061/(ASCE)0733-9399(1986)112:2(154)

Harichandran, R.S., Hawwari, A. and Sweidan, B.N. (1996), "Response of long-span bridges to spatially varying ground motion", *J. Struct. Eng.*, **122**(5), 476-484. https://doi.org/10.1061/(ASCE)0733-9445(1996)122:5(476).

Haroun, M.A. and Housner, G.W. (1981), "Seismic design of liquid storage tanks", *J. Tech. Councils*, SCE, **107**(1), 191-207.

Hoskins, L.M. and Jacobsen, L.S. (1934), "Water pressure in a tank caused by a simulated earthquakes", *Bull. Seismol. Soc. Am.*, **24**(1), 1-32.

Hosseinzadeh, N., Kazem, H., Ghahremannejad, M., Ahmadi, E. and Kazem, N. (2013), "Comparison of API650-2008 provisions with FEM analyses for seismic assessment of existing steel oil storage tanks", *J. Loss Prevent. Process Industr.*, **26**(4), 666-675. https://doi.org/10.1016/j.jlp.2013.01.004.

Housner, G.W. (1954), "Earthquake pressures on fluid containers", Report No. 081-095 Eighth Technical Report under Office of Naval Research, Project Designation, California Institute of Technology, Pasadena, California, U.S.A.

Housner, G.W. (1957), "Dynamic pressure on accelerated fluid containers", *Bull. Seismol. Soc. Am.*, **47**(1), 15-35.

Housner, G.W. (1963), "The dynamic behaviour of water tanks", *Bull. Seismol. Soc. Am.*, **53**(2), 381-387.

Hwang, I.T. and Ting, K. (1989), "Boundary element method for fluid-structure interaction problems in liquid storage tanks", *J. Press. Ves. Technol.*, **3**(4), 435-440. ttps://doi.org/10.1115/1.3265701.

Ishida, K. and Kobayashi, N. (1988), "An effective method of analyzing rocking motion unanchored cylindrical tanks including uplift", *J. Press. Ves. Technol.*, **110**, 76-87. https://doi.org/10.1115/1.3265572.

Jacobsen, L.S. (1949), "Impulsive hydrodynamics of fluid inside a cylindrical tank and of fluid surrounding a cylindrical pier", *Bull. Seismol. Soc. Am.*, **39**(3), 189-203.

Jankowski, R. (2012), "Non-linear FEM analysis of pounding-involved response of buildings under non-uniform earthquake excitation", *Eng. Struct.*, **37**, 99-105. https://doi.org/10.1016/j.engstruct.2011.12.035.

Jankowski, R. (2015), "Pounding between superstructure segments in multi-supported elevated bridge with three-span continuous deck under 3D non-uniform earthquake excitation", *J. Earthq. Tsunami*, **9**(4), 1550012. https://doi.org/10.1142/S1793431115500128.

Jankowski, R. and Mahmoud, S. (2016), "Linking of adjacent three-storey buildings for mitigation of structural pounding during earthquakes", *Bull. Earthq. Eng.*, **14**(11), 3075-3097. https://doi.org/10.1007/s10518-016-9946-z.

Jankowski, R. and Walukiewicz, H. (1997), "Modeling of two-dimensional random fields", *Prob. Eng. Mech.*, **12**(2), 115-121. https://doi.org/10.1016/S0266-8920(96)00040-9.

Jankowski, R. and Wilde, K. (2000), "A simple method of conditional random field simulation of ground motions for long structures", *Eng. Struct.*, **22**(5), 552-561. https://doi.org/10.1016/S0141-0296(98)00125-4.

Kim, M.K., Lim, Y.M., Cho, S.Y. and Cho, K.H. (2002), "Seismic analysis of base-isolated liquid storage tanks using the BE-FE-BE coupling technique", *Soil Dyn. Earthq. Eng.*, **22**(9-12), 1151-1158. https://doi.org/10.1016/S0267-7261(02)00142-2.

Lay, K.S. (1993), "Seismic coupled modelling of axisymmetric tanks containing liquid", *J. Eng. Mech.*, **119**, 1747-1761. https://doi.org/10.1061/(ASCE)0733-9399(1993)119:9(1747).

Maciag, E., Kuzniar, K. and Tatara, T. (2016), "Response spectra of ground motions and building foundation vibrations excited by rockbursts in the LGC region", *Earthq. Spect.*, **32**, 1769-1791. https://doi.org/10.1193%2F020515EQS022M.

Mahmoud, S. and Jankowski, R. (2010), "Pounding-involved response of isolated and non-isolated buildings under earthquake excitation", *Earthq. Struct.*, **1**(3), 231-252. http://doi.org/10.12989/eas.2010.1.3.231.

Malhotra, P.K. and Veletsos, A.S. (1994), "Uplifting analysis of base plates in cylindrical tanks", *J. Struct. Eng.*, **120**(12), 3489-3505. https://doi.org/10.1061/(ASCE)0733-9445(1994)120:12(3489).

Malhotra, P.K., Wenk, T. and Wieland, M. (2000), "Simple procedure for seismic analysis of liquid storage tanks", *Struct. Eng.*, **10**(3), 197-201. https://doi.org/10.2749/101686600780481509.

Manos, G.C. and Clough, R.W. (1985), "Tank damage during the May 1983 Coalinga earthquake", *Earthq. Eng. Struct. Dyn.*, **13**(4), 449-466. https://doi.org/10.1002/eqe.4290130403.

Minoglou, M.K., Hatzigeorgiou, G.D. and Papagiannopoulos, G.A. (2013), "Heuristic optimization of cylindrical thin-walled steel tanks under seismic loads", *Thin Wall. Struct.*, **64**, 50-59. https://doi.org/10.1016/j.tws.2012.12.009.

Moeindarbari, H., Malekzadeh, M. and Taghikhany, T. (2014), "Probabilistic analysis of seismically isolated elevated liquid storage tank using multi-phase friction bearing", *Earthq. Struct.*, **6**(1), 111-125. http://doi.org/10.12989/eas.2014.6.1.111.

Niwa, A. and Clough, R.W. (1982), "Buckling of cylindrical liquid-storage tanks under earthquake loading", *Earthq. Eng. Struct. Dyn.*, **10**, 107-122. https://doi.org/10.1002/eqe.4290100108.

Ozdemir, Z., Souli, M. and Fahjan, Y.M. (2010), "Application of nonlinear fluid-structure interaction methods to seismic analysis of anchored and unanchored tanks", *Eng. Struct.*, **32**(2), 409-423. https://doi.org/10.1016/j.engstruct.2009.10.004.

Salawu, O.S. (1997), "Detection of structural damage through changes in frequency: a review", *Eng. Struct.*, **19**(9), 718-723. https://doi.org/10.1016/S0141-0296(96)00149-6.

Seleemah, A.A. and El-Sharkawy, M. (2011), "Seismic analysis and modeling of isolated elevated liquid storage tanks", *Earthq. Struct.*, **2**(4), 397-412. http://doi.org/10.12989/eas.2011.2.4.397.

Shahrjerdi, A. and Bayat, M. (2018), "The effect of composite-elastomer isolation system on the seismic response of liquid-storage tanks: Part I", *Earthq. Struct.*, **15**(5), 513-528. https://doi.org/10.12989/eas.2018.15.5.513.

Shekari, M.R. (2018). "A coupled BE–FE–BE study for investigating the effect of earthquake frequency content and predominant period on seismic behavior of base-isolated concrete rectangular liquid tanks", *J. Fluids Struct.*, **77**, 19-35. https://doi.org/10.1016/j.jfluidstructs.2017.11.003.

Shekari, M.R., Hekmatzadeh, A.A. and Amiri, S.M. (2019), "On the nonlinear dynamic analysis of base-isolated three-dimensional rectangular thin-walled steel tanks equipped with vertical baffle", *Thin Wall. Struct.*, **138**, 79-94. https://doi.org/10.1016/j.tws.2019.01.037.

Shekari, M.R., Khaji, N. and Ahmadi, M.T. (2010), "On the seismic behavior of cylindrical base-isolated liquid storage tanks excited by long-period ground motions", *Soil Dyn. Earthq. Eng.*, **30**, 968-980. https://doi.org/10.1016/j.soildyn.2010.04.008.

Spritzer, J.M. and Guzey, S. (2017), "Review of API 650 Annex E: Design of large steel welded aboveground storage tanks excited by seismic loads", *Thin Wall. Struct.*, **112**, 41-65. https://doi.org/10.1016/j.tws.2016.11.013.

Sun, J., Cui, L., Li, X., Wang, Z., Liu, W. and Lv, Y. (2018), "Vibration mode decomposition response analysis of large floating roof tank isolation considering swing effect", *Earthq. Struct.*, **15**(4), 411-417. https://doi.org/10.12989/eas.2018.15.4.411.

Veletsos, A.S. (1974), "Seismic effects in flexible liquid storage tanks", *Proceedings of the 5th World Conference on Earthquake Engineering*, Rome, Italy,

Veletsos, A.S. (1984), "Seismic response and design of liquid storage tank", Guidelines for Seismic Design of Oil and Gas Pipelines System, American Society of Civil Engineers, New York, U.S.A.,

Veletsos, A.S. and Yang, J.Y. (1977), "Earthquake response of liquid storage tanks", *Proceedings of the 2nd EMD Specialty Conference*, New York, U.S.A.

Virella, J.C., Godoy, L.A., Suárez, L.E. and Mander, J.B. (2003), "Influence of the roof on the natural periods of empty steel tanks", *Eng. Struct.*, **25**, 877-887. https://doi.org/10.1016/S0141-0296(03)00022-1.

Virella, J.C., Prato, C.A. and Godoy, L.A. (2008), "Linear and nonlinear 2D finite element analysis of sloshing modes and pressure in rectangular tanks subjected to horizontal harmonic motions", *J. Sound Vib.*, **312**(3), 442-460. https://doi.org/10.1016/j.jsv.2007.07.088.

Wozniak, R.S. and Mitchell, W.W. (1978), "Basis of seismic design provisions for welded steel oil storage tanks", *Proceedings of the Sessions on Advances in Storage Tank Design*, Toronto, Ontario, Canada, May.

Zembaty, Z. (2004), "Rockburst induced ground motion-a comparative study", *Soil Dyn. Earthq. Eng.*, **24**(1), 11-23. https://doi.org/10.1016/j.soildyn.2003.10.001.

Zembaty, Z. and Rutenberg, A. (2002), "Spatial response spectra and site amplification effects", *Eng. Struct.*, **24**(11), 1485-96. https://doi.org/10.1016/S0141-0296(02)00096-2.

Zhang, D.Y., Li, X., Yan, W.M., Xie, W.Ch. and Pandey, M.D. (2013), "Stochastic seismic analysis of a concrete-filled steel tubular (CFST) arch bridge under tridirectional multiple excitations", *Eng. Struct.*, **52**, 355-371. https://doi.org/10.1016/j.engstruct.2013.01.031.

Ziółko, J. (1986), *Steel Tanks for Liquids and Gases*, Arkady, Warszawa, Poland.

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