Earthquakes and Structures, *Vol. 17, No. 2 (2019) 175-189*
DOI: https://doi.org/10.12989/eas.2019.17.2.175

Experimental study on models of cylindrical steel tanks under mining tremors and moderate earthquakes

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(Received November 29, 2018, Revised March 26, 2019, Accepted June 3, 2019)

Abstract. The aim of the study is to show the results of complex shaking table experimental investigation focused on the response of two models of cylindrical steel tanks under mining tremors and moderate earthquakes, including the aspects of diagnosis of structural damage. Firstly, the impact and the sweep-sine tests have been carried out, so as to determine the dynamic properties of models filled with different levels of liquid. Then, the models have been subjected to seismic and paraseismic excitations. Finally, one fully filled structure has been tested after introducing two different types of damages, so as to verify the method of damage diagnosis. The results of the impact and the sweep-sine tests show that filling the models with liquid leads to substantial reduction in natural frequencies, due to gradually increasing overall mass. Moreover, the results of sweep-sine tests clearly indicate that the increase in the liquid level results in significant increase in the damping structural ratio, which is the effect of damping properties of liquid due to its sloshing. The results of seismic and paraseismic tests indicate that filling the tank with liquid leads initially to considerable reduction in values of acceleration (damping effect of liquid sloshing); however, beyond a certain level of water filling, this regularity is inverted and acceleration values increase (effect of increasing total mass of the structure). Moreover, comparison of the responses under mining tremors and moderate earthquakes indicate that the power amplification factor of the mining tremors may be larger than the seismic power amplification factor. Finally, the results of damage diagnosis of fully filled steel tank model indicate that the forms of the Fourier spectra, together with the frequency and power spectral density values, can be directly related to the specific type of structural damage. They show a decrease in the natural frequencies for the model with unscrewed support bolts (global type of damage), while cutting the welds (local type of damage) has resulted in significant increase in values of the power spectral density for higher vibration modes.

Keywords: cylindrical steel tanks; experimental investigation; shaking table; mining tremors; moderate earthquakes; damage diagnosis

1. Introduction

Cylindrical steel tanks are among the most commonly constructed structures used to store petroleum and chemical products (see, for example, DiGrado and Thorp 2004, Godoy 1996, Ziółko 1986). The aspects of safety and reliability of such objects are very import since even a minor damage may lead to substantial material losses causing environmental pollution or ecological disaster. The most dangerous and, at the same time, the most unpredictable loads acting on steel tanks are related to earthquakes and mining tremors.

The behaviour of different steel tanks under earthquake excitations has been studied for more than eight decades now. One of the earliest studies, conducted by Hoskins and Jacobsen (1934), concerned the hydrodynamic pressure developed in rectangular tanks subjected to horizontal ground motions. Later on, Jacobsen (1949) analysed the dynamic behaviour of rigid cylindrical tank. The first mechanical models for circular and rectangular rigid tanks were developed by Housner (see Housner 1954, Housner 1957, Housner 1963). Wozniak and Mitchell (1978) generalized Housner’s models for short and slender tanks. An analytical approach to the analysis of flexible containers was presented by Veletsos (1974). He proposed a simple procedure for evaluating hydrodynamic forces induced in flexible liquid-filled tanks. Veletsos and Yang (1977) used different approach to propose a similar type of a mechanical model for circular rigid tanks. Haroun and Housner (1981) derived the mechanical model which takes into account the deformability of the tank wall. The model was widely applied because previous formulations were either too complicated to be used in the design or too simple to yield accurate results. Different approach was employed by Edwards (1969) who used the finite element method and a refined shell theory to predict seismic stresses and displacements in a vertical cylindrical tank. The study included coupled interaction between the elastic wall of the tank and its liquid content. Fenves and Vargas-Loli (1988) applied a mixed displacement-fluid pressure formulation for the liquid. Another model of a flexible tank was developed by Veletsos (1984). After further improvements of the model, proposed by Malhotra *et al.* (2000), the simplified procedure for analysis of liquid-storage tanks has been adopted in Eurocode 8. A number of researchers used also

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http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

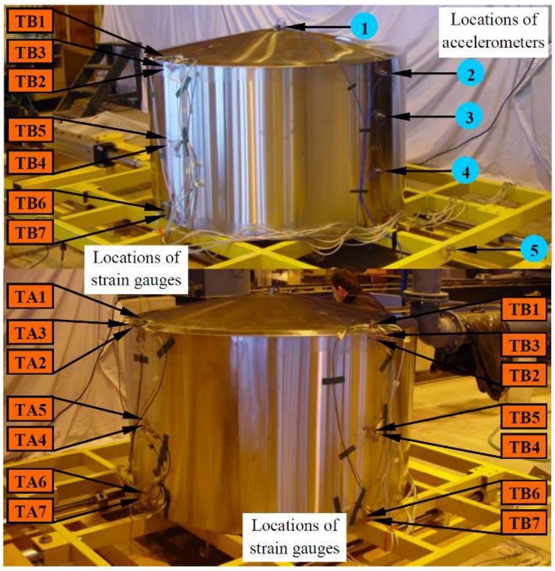


Fig. 1 Experimental setup for the model with diameter D=1.25 m

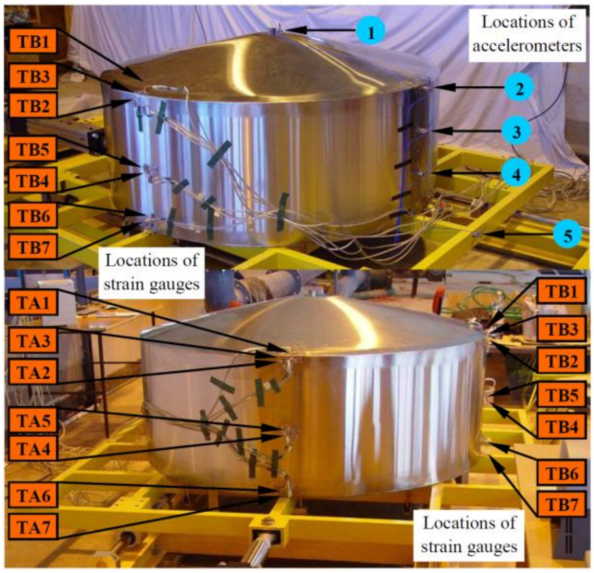


Fig. 2 Experimental setup for the model with diameter D=1.5 m

the Finite Element Method (FEM) combined with the boundary element method (see, for example, Hwang and Ting 1989, Lay 1993, Kim *et al.* 2002). Cho and Cho (2007) proposed a general FEM numerical algorithm for the analysis of the seismic responses of cylindrical steel liquid storage tanks, in which finite elements for the structure and for the liquid are coupled, using equilibrium and compatibility conditions. Virella *et al.* (2003) analysed the influence of the roof on the natural periods of empty steel tanks using the general purpose FEM package ABAQUS. Numerical structural and vibrational analysis of liquid storage tanks was conducted using the ADINA software by Dong and Redekop (2007). More recently, Maraveas (2011), Hosseinzadeh *et al.* (2013) and Djermane *et al.* (2014) focused their studies on numerical verification of provisions of different building codes, with relation to the aspects dealing with the behaviour of steel tanks under earthquake loading. Besides, Buratti and Tavano (2014) investigated the effects of fluid-structure interaction during seismic excitations. 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, Seleemah and El-Sharkawy 2011, Moeindarbari *et al.* 2014, Shahrjerdi and Bayat 2018, Sun *et al.* 2018).

In contrast to the analytical and numerical approaches, the results of experimental investigations on steel tanks under earthquake excitations are quite limited. Chen *et al.* (2007) conducted small-scale model experiments on rectangular and cylindrical liquid tanks subjected to harmonic and seismic excitations. The shaking table experimental investigation on the seismic response of a model of base-isolated tank equipped with a floating roof was carried out by De Angelis *et al.* (2010). Ormeño *et al.* (2014) compared different approaches of defining the seismic loadings using experimental tests. Also, Ormeño *et al.* (2015) examined the influence of seismic uplift on the behaviour of liquid-storage tanks.

On the contrary to seismic events, the effects of mining tremors on steel tanks have not been really studied so far, nor numerically nor experimentally. Meanwhile, the influence of mining tremors, as dynamic excitations similar to earthquakes but directly associated with mining activity of human being, can also be very dangerous to civil engineering structures (see Zembaty 2004, Maciag *et al.* 2016).

The aim of the present paper is to show the results of the detailed shaking table experimental study focused on the response of two models of cylindrical steel tanks under mining tremors and moderate earthquakes, including the aspects of diagnosis of structural damage. The first phase of the investigation concerns the determination of dynamic properties of the experimental models by using the impact tests and the sweep-sine tests. In the next phase, the models of cylindrical steel tanks have been subjected to dynamic loading related to seismic and paraseismic excitations. The models have been tested for different levels of liquid filling (empty tanks, tanks partly filled with liquid, tanks fully filled with liquid). Finally, one fully filled model has been tested experimentally after introducing two different types of damages, so as to verify the method of diagnosis of damages possible to occur in the case of cylindrical steel tanks.

2. Experimental setup

2.1 Experimental models of cylindrical steel tanks

Two experimental models of real cylindrical steel tanks with self-supported roofs have been prepared for the purpose of the study. The first model, shown in Fig. 1, is a scaled model (scale 1:22.69) of the steel tank of the total capacity of 10,000 m^3 which is located in the fuel base Koluszki, in the middle part of Poland, nearby the Belchatow coal mine. The real tank has the diameter and

Fig. 3 The method of filling experimental models with water and equipment to control the liquid level

the total height equal to 28.36 m and 19.06 m, respectively. Moreover, the bottom plate has the thickness of 9 mm and the thickness of the shell varies from 6 to 12 mm. The experimental model has the diameter and the total height equal to 1.25 m and 0.84 m, respectively. The empty experimental model has the total weight of 71.4 kg. The second model, presented in Fig. 2, is a scaled model (scale 1:33.33) of the steel tank of the capacity of 32,000 m^3 which is located in the oil refinery in Gdansk (northern Poland), in the region experienced by the moderate Kaliningrad earthquake in 2004. The real tank has the diameter and the total height equal to 50 m and 23.33 m, respectively. What is more, the bottom plate has the thickness of 16 mm and the thickness of the shell varies from 8 to 22 mm. The experimental model has the diameter and the total height equal to 1.5 m and 0.7 m, respectively. The empty model has the total weight equal to 86 kg. In the case of both experimental models, the thickness of the steel bottom plate, shell and roof is equal to 3 mm, 1.2 mm and 1.2 mm, respectively. The first tank has been fixed by fourteen M10 bolts to the platform of the shaking table, while eighteen M10 bolts have been used in the case of the second model.

2.2 Levels of liquid filling and measuring equipment

A unidirectional shaking table (see Falborski and Jankowski 2013, 2017, Jaroszewicz *et al.* 2016 for details concerning its parameters) located at the Gdansk University of Technology has been used in the experimental study. The models are symmetrical, and for this reason, the dynamic excitation has been implemented for only one horizontal direction, consistent with the movement of the shaking table platform. Due to technical difficulties and safety reasons related to the tests of different liquids filling the tank models, water has been chosen as the only possible option. The shaking table tests have been carried out for four variants of water level:

a) empty tank,
b) tank filled to 1/3 of allowable limit (for model with D=1.25 m – 231 mm, for model with D=1.5 m – 162 mm),
c)tank filled to 2/3 of allowable limit (for model with D=1.25 m – 462 mm, for model with D=1.5 m – 324 mm),
d) tank filled to allowable limit (for model with D=1.25 m – 693 mm, for model with D=1.5 m – 486 mm),

where the allowable limit has been taken as a scaled value from the real construction project. Fig. 3 shows the method of filling experimental models with water and the equipment to control the liquid level.

The following measuring equipment has been used to conduct the tests:

a) five single-axis accelerometers,
b) twelve-channel amplifier (five channels were active),
c) fourteen active unidirectional strain gauges,
d) fourteen compensatory unidirectional strain gauges,
e) sixty four-channel dynamic strain measuring system (twenty eight channels were active),
f) PC for recording all measurements.

Acceleration measurements have been conducted simultaneously in five points (four points located at the model and one additional, reference point located at the shaking table platform – see Figs. 1 and 2). On the other hand, strain measurements have been conducted simultaneously in fourteen points. They have included two points located at the model roof (for radial strains), six points located at the model shell (for longitudinal strains) and another six points located at the model shell (for circumferential strains). Detailed locations of strain gauges are presented in Figs. 1 and 2.

3. Determination of structural dynamic parameters

3.1 Impact tests

Firstly, the impact tests have been carried out, so as to determine the dynamic parameters of the experimental models of cylindrical steel tanks. The modal hammer with a flexible pad limiting the frequency excitation to 300 Hz has been used to apply impacts in four different locations (see Fig. 4). Based on the measured acceleration and force amplitudes, the inertance characteristics in the frequency domain and the modal parameters in the resonances for each location of accelerometer have been determined. Then, the natural frequencies and modes of free vibrations of considered structures have been obtained. The representative examples of the results (accelerometer no. 2) for the first natural frequency for different levels of water filling are summarized in Table 1. They clearly indicate that filling the tank with water leads to substantial reduction in natural frequencies, as the result of increasing the overall mass. In the case of the tank model with diameter D=1.25 m, the first natural frequency has been reduced by 26.4%, 43.0% and 65.0% after filling the tank with 231 mm, 462 mm and 693 mm of water, respectively. On the other hand, for the tank model with diameter D=1.5 m, the first natural frequency has been reduced by 24.7%, 32.8% and 42.3% after filling the tank with 162 mm, 324 mm and 486 mm of water, respectively.

3.2 Sweep-sine tests

In the second stage of the study, the harmonic tests with variable frequency (sweep-sine tests) have been conducted. The excitation frequency of the shaking table platform varied from 1.0 Hz to 60 Hz with the amplitude of

Fig. 4 Experimental setup for impact tests

Table 1 Summary of results of impact tests

Model of tank	Level of water filling (mm)	First natural frequency (Hz)
Model with *D*=1.25 m	0	62.34
	231	45.89
	462	35.53
	693	21.81
Model with *D*=1.5 m	0	43.64
	162	32.88
	324	29.32
	486	25.20

Table 2 Summary of results of sweep-sine tests

Model of tank	Level of water filling (mm)	First natural frequency (Hz)	Damping ratio (%)
Model with *D*=1.25 m	0	57.61	1.34
	231	43.81	2.04
	462	35.57	2.53
	693	21.76	4.98
Model with *D*=1.5 m	0	42.17	1.40
	162	34.91	1.43
	324	27.59	2.15
	486	25.68	2.58

acceleration chosen so as to reveal resonances. Recorded acceleration signals have been subjected to the Fast Fourier Transform analysis in order to determine the existence of resonances and magnification of vibrations in the frequency domain. Then, the half-power bandwidth method has been used to calculate damping ratios (see Chopra 1995). The representative examples of the results (accelerometer no. 2) for the first natural frequency for different levels of water filling are summarized in Table 2. The results confirm previous findings (see section 3.1) that filling the tank with water leads to substantial reduction in natural frequencies. It can be seen from Table 2, that the value of the first natural frequency for the tank model with diameter *D*=1.25 m has been reduced by 24.0%, 38.3% and 62.2% after filling the tank with 231 mm, 462 mm and 693 mm of water, respectively. On the other hand, the value of the first natural frequency for the tank model with diameter *D*=1.5 m has been reduced by 17.2%, 34.6% and 39.1% after filling the tank with 162 mm, 324 mm and 486 mm of water, respectively. It should be underlined comparing Table 2 with Table 1 that the results for both models obtained from the sweep-sine tests are somehow consistent with the results from the impact tests (the largest difference between determined frequencies is equal to 7.6%).

It is also important to underline the relation between the level of water filling and the value of structural damping ratio. It can be seen from Table 2 that the increase in the liquid level results in significant increase in the damping ratio, which is the effect of damping properties of water as the result of its sloshing (compare the studies on liquid dampers – see Banerji *et al.* 2000, for example). In the case of the tank model with diameter *D*=1.25 m, the value of damping ratio for the first natural vibration mode has been increased by as much as 52.2%, 88.8% and 271.6% after filling the tank with 231 mm, 462 mm and 693 mm of water, respectively. On the other hand, for the tank model with diameter *D*=1.5 m, the value of damping ratio for the first natural vibration mode has been increased by 2.1%, 53.6% and 84.3% after filling the tank with 162 mm, 324 mm and 486 mm of water, respectively.

4. Seismic and paraseismic tests

The next stage of the experimental investigation has been focused on seismic and paraseismic shaking table tests. The following three dynamic excitations have been used in the study:

a) Polkowice mining tremor, 02.02.2001 (EW component, PGA=0.503 m/s^2),
b) Polkowice mining tremor, 20.02.2002 (NS component, PGA=1.634 m/s^2),
c) El Centro earthquake, 18.05.1940 (NS component, PGA=3.402 m/s^2),

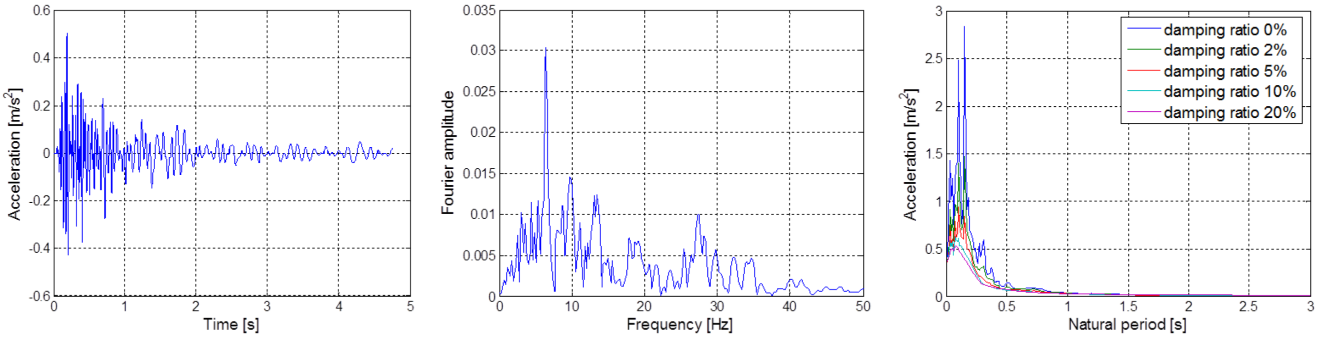
where PGA stands for the peak ground acceleration.

Excitation time history, Fourier spectrum and acceleration response spectra for each of the considered ground motion are presented in Figs. 5-7. The first two excitations are typical examples of mining-induced seismicity, whereas the last one can be somehow considered as the example of moderate earthquake.

According to the principles of modelled probability, the time-scaling factors equal to λ_T=0.2099 (for tank with diameter *D*=1.25 m) and λ_T=0.1732 (for tank with diameter *D*=1.5 m) have been applied to scale the dynamic excitations. The factors have been calculated based on the following relation (De Angelis *et al.* 2010):

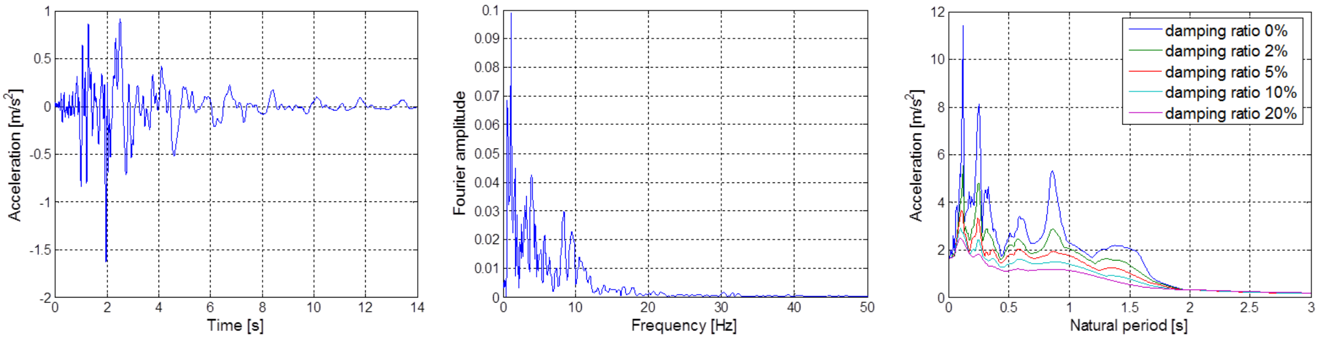
$$\lambda_T = \frac{1}{\sqrt{S}} \tag{1}$$

where *S* is a scale value for the experimental models (*S*=22.69 for tank with diameter *D*=1.25 m and *S*=33.33 for



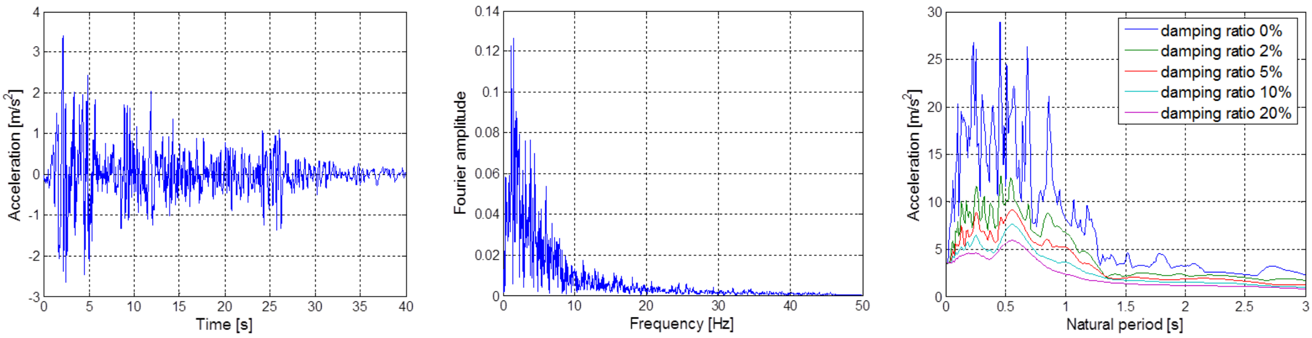
(a) Excitation time history (b) Fourier spectrum (c) Acceleration response spectra

Fig. 5 Polkowice 2001 mining tremor (EW component)



(a) Excitation time history (b) Fourier spectrum (c) Acceleration response spectra

Fig. 6 Polkowice 2002 mining tremor (NS component)



(a) Excitation time history (b) Fourier spectrum (c) Acceleration response spectra

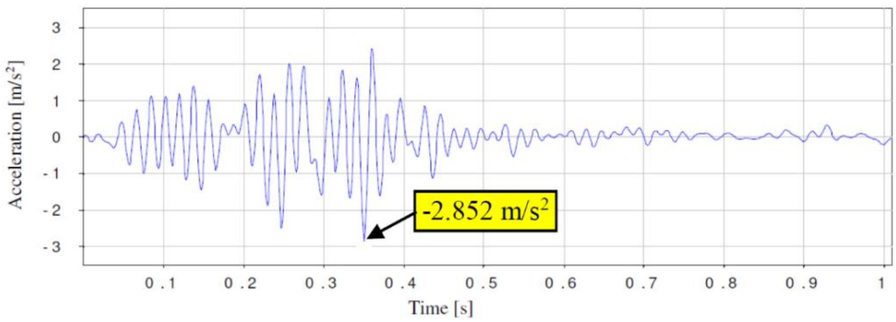
Fig. 7 El Centro 1940 earthquake (NS component)

tank with diameter D=1.5 m – see section 2.1).

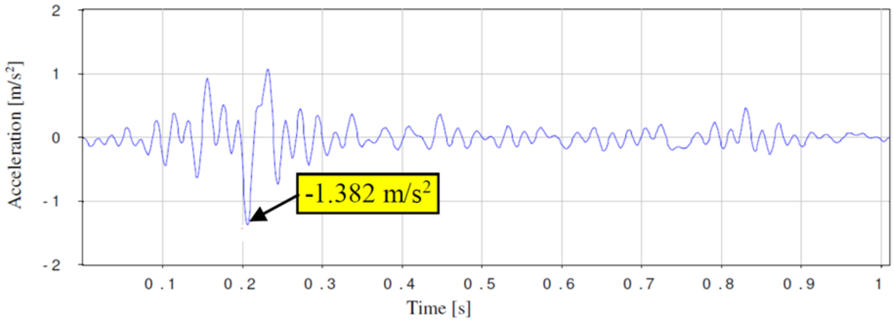
The acceleration and strain measurements have been conducted for the time length of 20 s with a sampling frequency of 1000 Hz and 400 Hz, respectively. During the data analysis, the dynamic characteristics with extreme values (in time domain) for each measuring point have been obtained. Stresses have been calculated after multiplication of strain values by the Young modulus of steel equal to 200 GPa.

A large number of results for different levels of water filling have been obtained for the dynamic excitations considered in the study. The representative examples of the results of structural responses (accelerometer no. 2), in the form of acceleration time histories for the model with D=1.25 m under the Polkowice 2001 and 2002 mining tremors as well as under the El Centro 1940 earthquake, are presented in Figs. 8-10. On the other hand, Figs. 11-13 show the representative examples of the stress time histories (gauge no. TA6) for the model with D=1.5 m under all three dynamic excitations. Additionally, peak values of accelerations and stresses for all measuring points of two tank models for different levels of water filling under considered seismic and paraseismic excitations are also summarized in Tables 3-4.

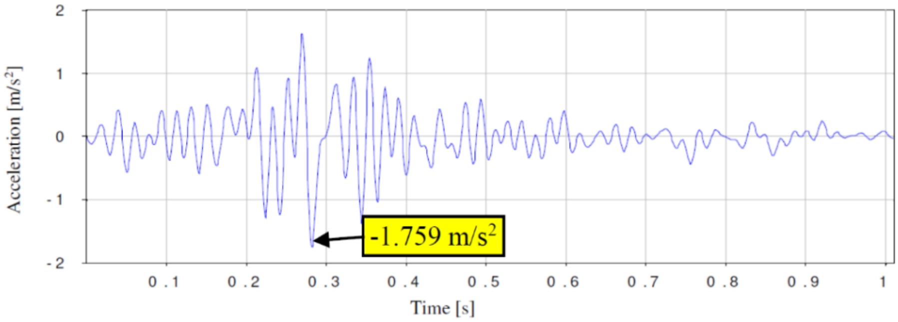
The results of the study presented in Figs. 8-10, as well as in Tables 3-4, indicate that filling the tank with water leads initially to considerable reduction in values of acceleration; however, beyond a certain level of water filling, this regularity is inverted and acceleration values increase. It can be seen from Fig. 8 that, in the case of the Polkowice 2001 mining tremor, the value of peak acceleration has been reduced by 51.5% and then has grown



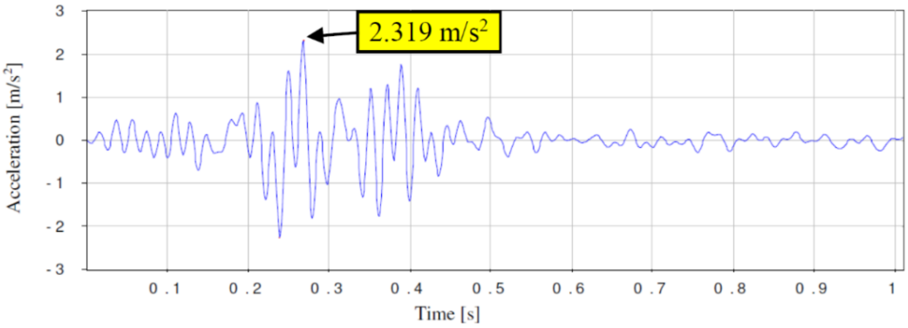
(a) Empty tank



(b) Tank filled to 1/3 of allowable limit



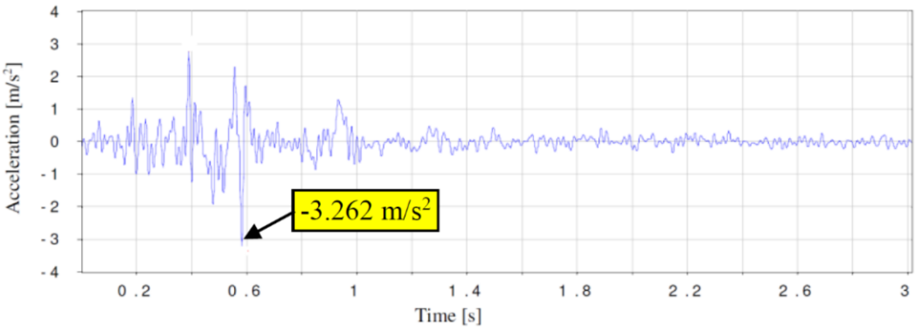
(c) Tank filled to 2/3 of allowable limit



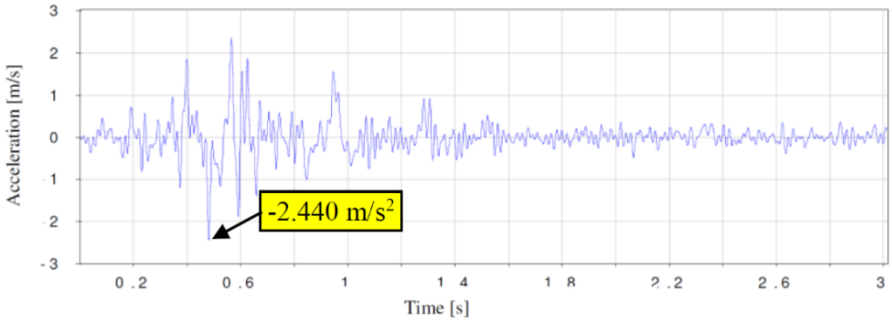
(d) Tank filled to allowable limit

Fig. 8 Acceleration time histories for the Polkowice 2001 mining tremor (model with *D*=1.25 m)

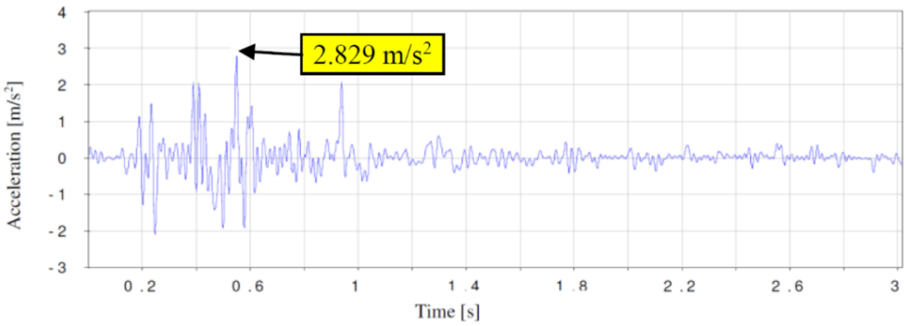
by 27.3% and 31.8% when the model filled with the consecutive levels of water are compared one to another. For the Polkowice 2002 mining tremor, the peak acceleration has decreased by 25.2% and then has increased by 15.9% and 1.7% (see Fig. 9). Finally, it can be seen from Fig. 10 that, in the case of the El Centro 1940 earthquake, the peak acceleration has been reduced by 13.6% and then has grown by 2.5% and 17.2% for the model filled with the consecutive levels of water. It is believed that the initial reduction in the acceleration values is related to damping properties of water as the result of its sloshing (see section 3.2), whereas further increase in the accelerations results from the fact that the total mass of the structure becomes substantially larger and this effect is more predominant. It is also important to underline, that the power amplification factor of the mining tremors may be larger than the seismic power amplification factor. In the case of the Polkowice 2001 mining tremor, for example, the peak response acceleration is larger than the peak ground acceleration by as much as 467%. On the other hand, the same calculations



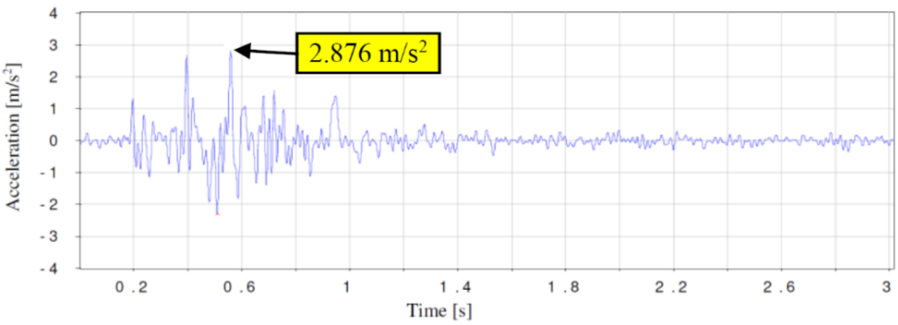
(a) Empty tank



(b) Tank filled to 1/3 of allowable limit



(c) Tank filled to 2/3 of allowable limit

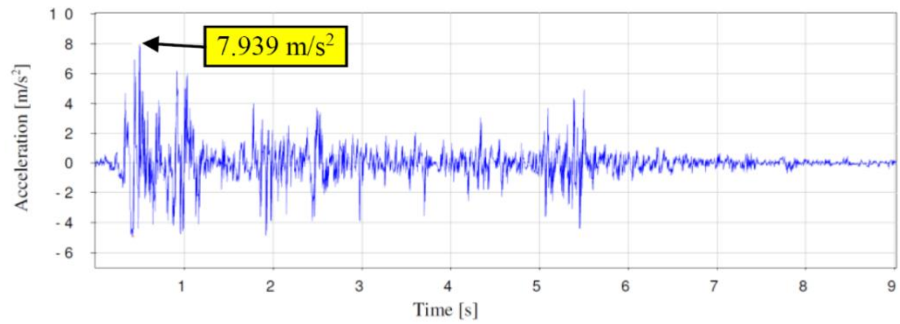


(d) Tank filled to allowable limit

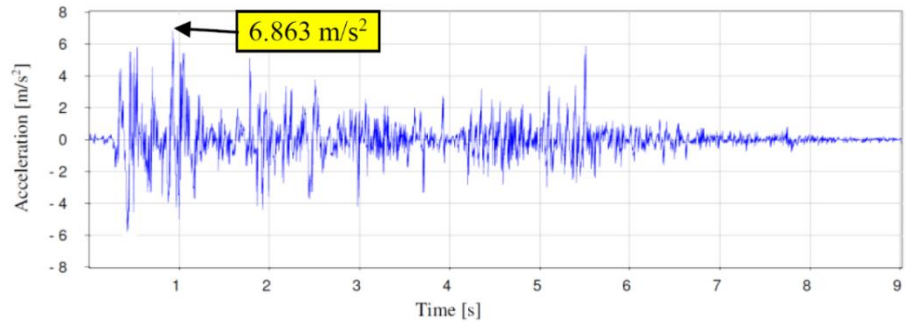
Fig. 9 Acceleration time histories for the Polkowice 2002 mining tremor (model with D=1.25 m)

for the El Centro 1940 earthquake give the value of only 142%. Such a situation results mainly from the fact that higher values of frequencies are usually induced during mining tremors, as compared to earthquakes (see Figs. 5-7 and Zembaty 2004, Maciag *et al.* 2016), and they are closer to the range of the predominant frequencies of steel tanks.

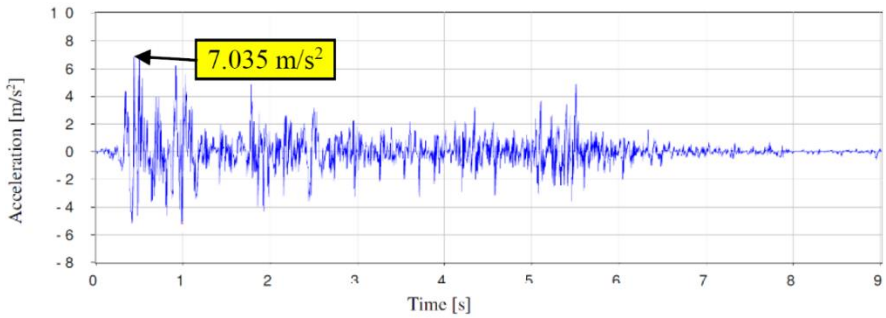
The results of the study presented in Figs. 11-13 and Tables 3-4 show that filling the tank with water leads to the considerable increase in stress values. It can be seen from Fig. 11 that, in the case of the Polkowice 2001 mining tremor, the value of peak stress has increased by 14.9%, 157.5% and 30.8%, respectively, when the model filled with the consecutive levels of water are compared one to another. For the Polkowice 2002 mining tremor, the peak stress has increased by 63.2%, 58.6% and 102.5%, respectively (see Fig. 12). Finally, it can be seen from Fig. 13 that, in the case of the El Centro 1940 earthquake, the peak stress has increased by 56.8%, 102.4% and 93.6%, respectively, for the model filled with the consecutive levels of water. The above results indicate that the range of increase in the stress



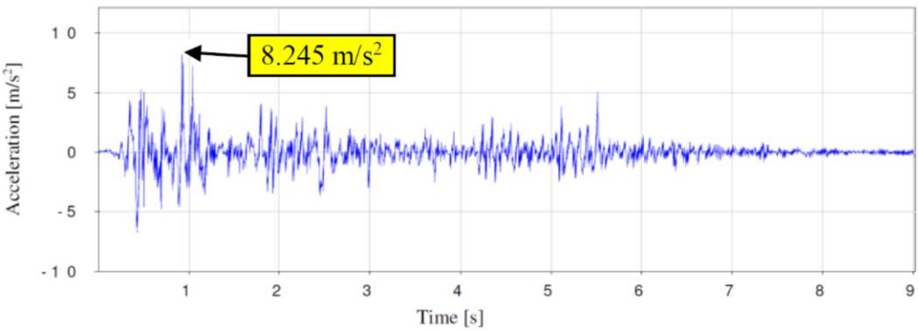
(a) Empty tank



(b) Tank filled to 1/3 of allowable limit



(c) Tank filled to 2/3 of allowable limit



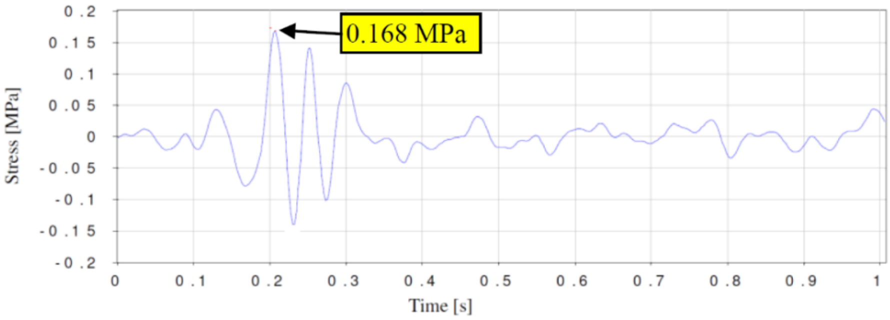
(d) Tank filled to allowable limit

Fig. 10 Acceleration time histories for the El Centro 1940 earthquake (model with D=1.25 m)

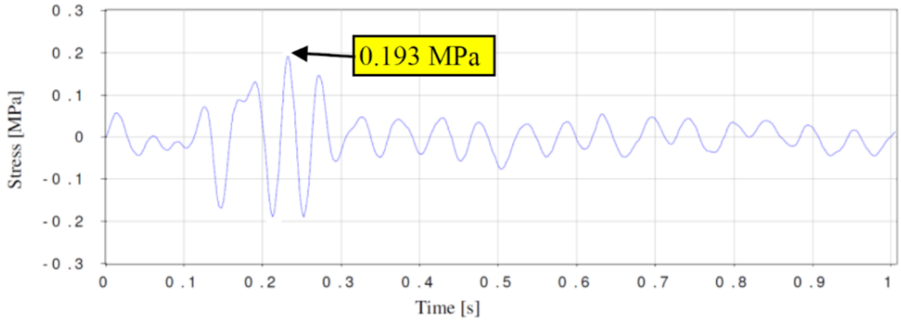
vales is not uniform and it is different for different dynamic excitations. It is however important to underline that the measured values of stresses are relatively low and the allowable level of stresses has not been exceeded in any case for none of the models of steel tanks.

5. Diagnosis of damage

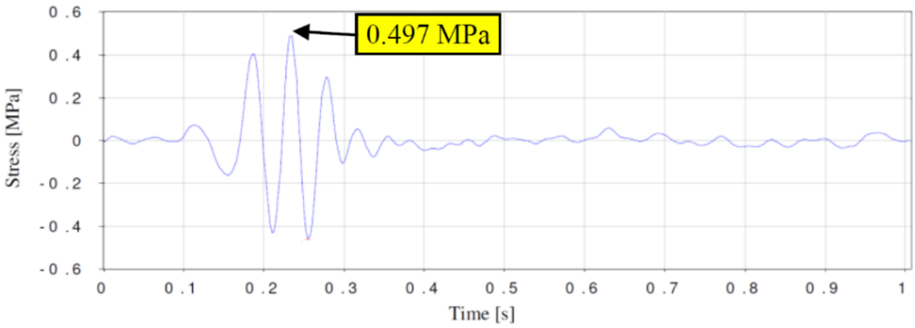
One of the most important issues of construction industry is the safety of civil engineering structures. For this reason, the assessment of damage has recently become of major problem to civil engineers (see, for example, Falborski *et al.* 2012, Jankowski 2015, Jankowski and Mahmoud 2010, 2015, 2016, Elwardany *et al.* 2017, Miari *et al.* 2019, Naderpour *et al.* 2019). Researchers apply different methods of diagnosis of damage (see Salawu 1997); however a method of measuring the changes in natural frequencies is still considered to be one of the most effective. It has been widely used in the case of relatively



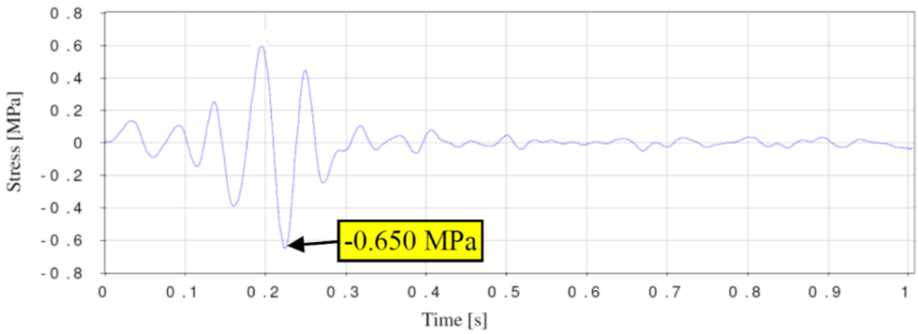
(a) Empty tank



(b) Tank filled to 1/3 of allowable limit



(c) Tank filled to 2/3 of allowable limit



(d) Tank filled to allowable limit

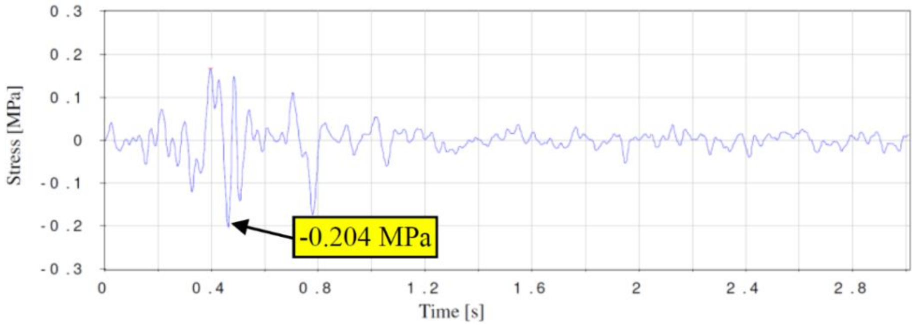
Fig. 11 Stress time histories for the Polkowice 2001 mining tremor (model with D=1.5 m)

small and middle-size structures, while the studies on large structures, i.e., large steel tanks, are very difficult and the application of the method needs to be fully confirmed (see Sohn *et al.* 2003). It is recommended that the method should be first verified through experimental investigations on scaled models conducted on shaking tables, since the tests on real structures are very difficult.

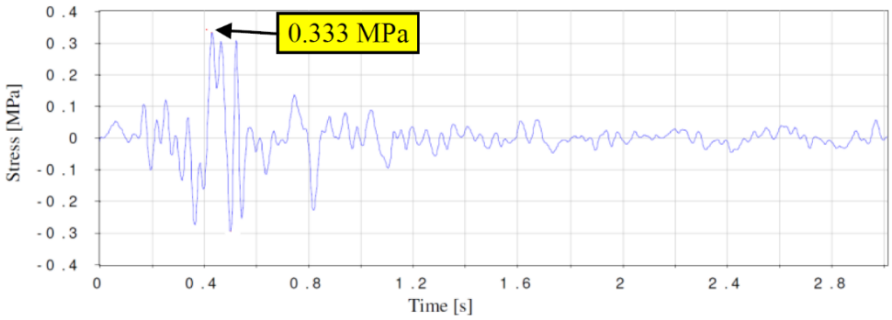
Because of the above aspects, the last part of the experimental study has been focused on diagnosis of damage introduced in one of the models (the model with diameter D=1.5 m has been chosen for this purpose). The tests have been carried out for the tank model fully filled with water (water height of 486 mm). Five accelerometers have been used in order to measure the response of the structure (see Fig. 2 for their locations).

The following cases of structural damage, which may somehow represent various types of damages typical for steel tanks, have been considered in the study:

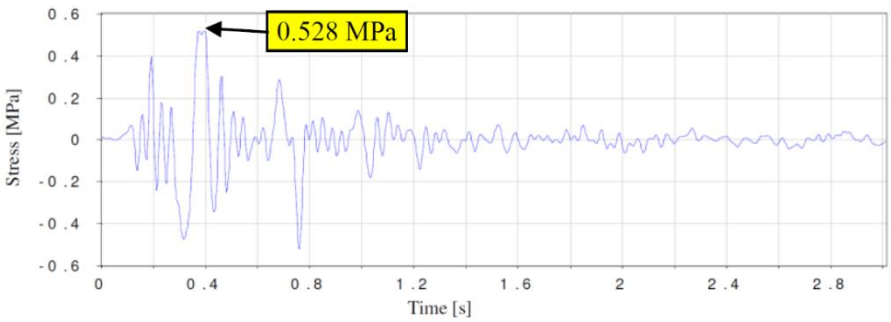
a) undamaged model,
b) model with unscrewed support bolts (see Fig. 14(a)),



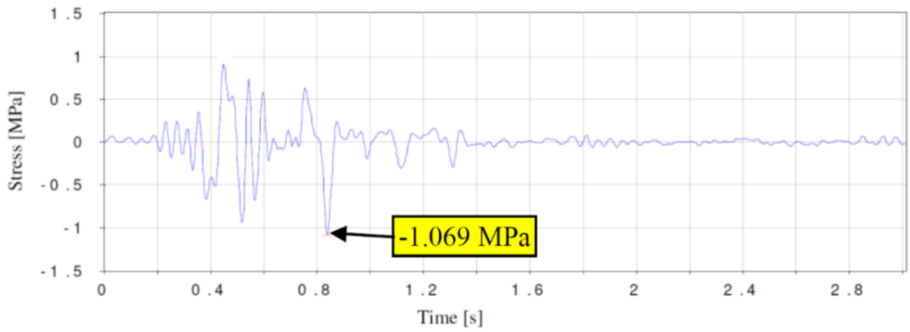
(a) Empty tank



(b) Tank filled to 1/3 of allowable limit



(c) Tank filled to 2/3 of allowable limit



(d) Tank filled to allowable limit

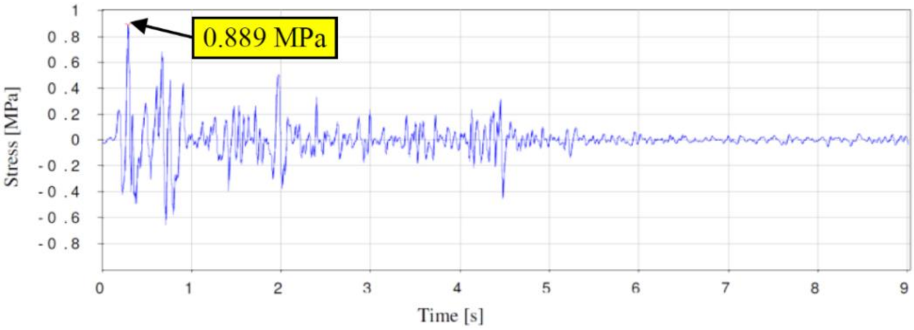
Fig. 12 Stress time histories for the Polkowice 2002 mining tremor (model with D=1.5 m)

c) model with circumferential cut of weld between the roof and shell (see Fig. 14(b)),

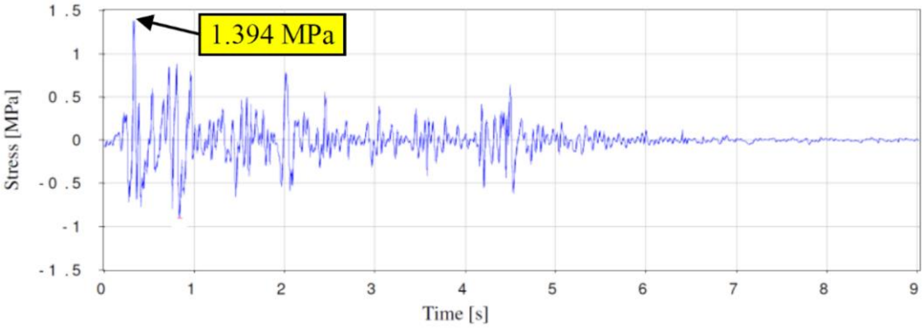
d) model with circumferential cut of weld between the roof and shell together with radial cut of weld in the roof itself (see Fig. 14(b)).

Similarly as during the analysis of dynamic properties (see section 3.2), the sweep-sine tests have been conducted for different types of damages. The excitation frequency of the shaking table platform varied from 1.0 Hz to 60 Hz with the amplitude of acceleration chosen so as to reveal resonances. Recorded acceleration signals have been subjected to the Fast Fourier Transform analysis in order to determine the existence of resonances and magnification of vibrations in the frequency domain. The representative examples of the results of the tests (accelerometer no. 2) are presented in Fig. 15. The results shown in the figure clearly indicate that the forms of the Fourier spectra, together with the frequency and power spectral density values, can be directly related to the specific case of structural damage.

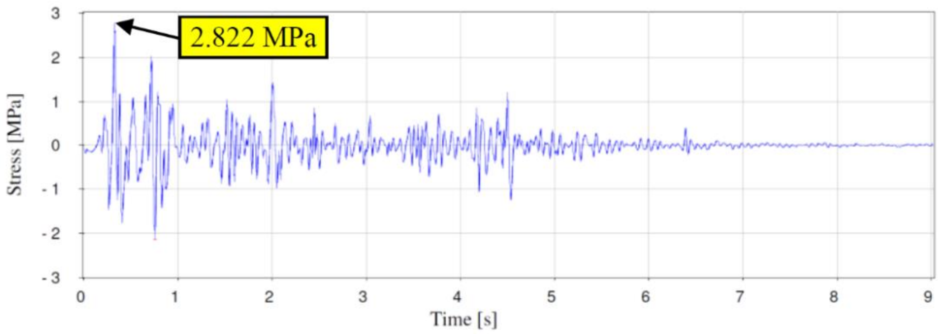
Fig. 15(b) shows the decrease in the natural frequencies



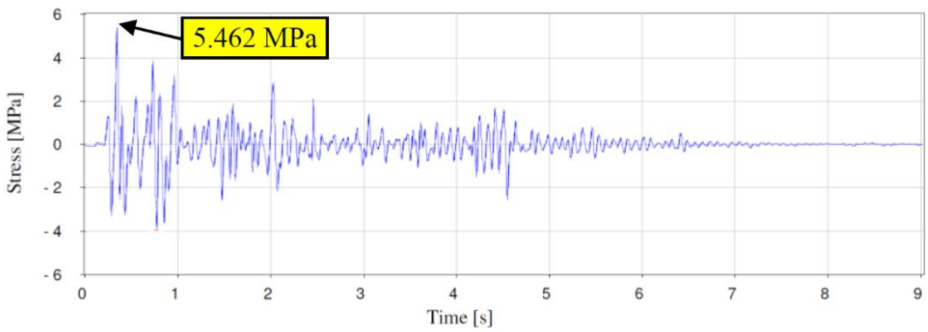
(a) Empty tank



(b) Tank filled to 1/3 of allowable limit



(c) Tank filled to 2/3 of allowable limit



(d) Tank filled to allowable limit

Fig. 13 Stress time histories for the El Centro 1940 earthquake (model with D=1.5 m)

for the model with unscrewed support bolts, which is characteristic for the global type of damage related to the structural supports with reduced stiffness. In the case of the first natural vibration mode, the decrease in the natural frequency (comparing it to the undamaged model) is as large as 81.8%. On the other hand, the results of the tests for circumferential and radial cuts of weld (see Fig. 15(c) and Fig. 15(d)), which can be considered as local types of structural damage, are much different. This time, the natural frequency values are nearly the same as for the undamaged model (the largest difference is as low as 2.2%). Instead, significant increase in the power spectral density values can be observed in the case of higher vibration modes (the largest increase is as large as 690%). This increase is due to the fact that higher values of accelerations have been recorded by accelerometers mounted in the vicinity of the introduced local damage (accelerometers no. 2 and 3 – see Fig. 14(b)).

Table 3 Summary of results of seismic and paraseismic tests (model with D=1.25 m)

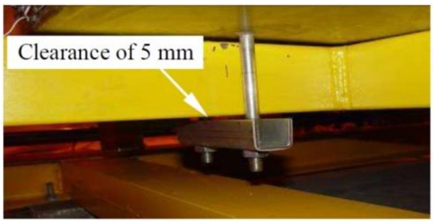
Measuring point	Polkowice 2001 mining tremor				Polkowice 2002 mining tremor				El Centro 1940 earthquake			
	Level of water filling (mm)											
	0	231	462	693	0	231	462	693	0	231	462	693
	Peak values of acceleration (m/s^2)											
1	3.617	1.891	2.263	3.388	3.617	1.891	2.263	3.395	3.617	1.891	2.263	9.416
2	2.852	1.382	1.759	2.319	2.852	1.382	1.759	2.876	2.852	1.382	1.759	8.245
3	2.270	1.159	1.494	1.597	2.270	1.159	1.494	2.576	2.270	1.159	1.494	7.769
4	2.891	1.497	1.519	1.935	2.891	1.497	1.519	2.816	2.891	1.497	1.519	6.185
5	1.469	0.985	1.439	2.166	1.469	0.985	1.439	1.958	1.469	0.985	1.439	5.452
	Peak values of stress (MPa)											
TA1	0.034	0.056	0.060	0.062	0.034	0.056	0.060	0.144	0.034	0.056	0.060	0.521
TA2	0.040	0.044	0.051	0.058	0.040	0.044	0.051	0.070	0.040	0.044	0.051	0.171
TA3	0.045	0.054	0.057	0.059	0.045	0.054	0.057	0.115	0.045	0.054	0.057	0.354
TA4	0.039	0.050	0.054	0.058	0.039	0.050	0.054	0.086	0.039	0.050	0.054	0.283
TA5	0.050	0.062	0.139	0.224	0.050	0.062	0.139	0.603	0.050	0.062	0.139	2.470
TA6	0.044	0.057	0.061	0.078	0.044	0.057	0.061	0.170	0.044	0.057	0.061	0.753
TA7	0.073	0.113	0.127	0.314	0.073	0.113	0.127	0.369	0.073	0.113	0.127	1.311
TB1	0.030	0.036	0.038	0.083	0.030	0.036	0.038	0.137	0.030	0.036	0.038	0.351
TB2	0.022	0.024	0.032	0.050	0.022	0.024	0.032	0.046	0.022	0.024	0.032	0.125
TB3	0.032	0.038	0.044	0.091	0.032	0.038	0.044	0.133	0.032	0.038	0.044	0.263
TB4	0.041	0.047	0.064	0.051	0.041	0.047	0.064	0.064	0.041	0.047	0.064	0.084
TB5	0.039	0.048	0.058	0.078	0.039	0.048	0.058	0.070	0.039	0.048	0.058	0.148
TB6	0.045	0.053	0.112	0.165	0.045	0.053	0.112	0.207	0.045	0.053	0.112	0.900
TB7	0.050	0.063	0.145	0.237	0.050	0.063	0.145	0.295	0.050	0.063	0.145	0.853

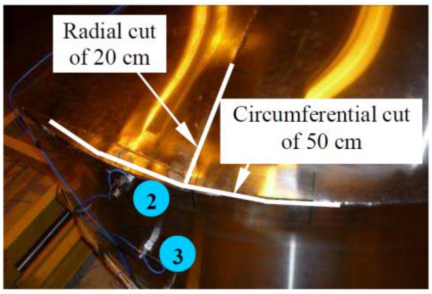
Table 4 Summary of results of seismic and paraseismic tests (model with D=1.5 m)

Measuring point	Polkowice 2001 mining tremor				Polkowice 2002 mining tremor				El Centro 1940 earthquake			
	Level of water filling (mm)											
	0	231	462	693	0	231	462	693	0	231	462	693
	Peak values of acceleration (m/s^2)											
1	2.271	1.776	2.126	2.498	2.519	2.003	2.138	2.335	7.704	6.569	6.995	8.030
2	1.934	1.413	1.782	1.860	2.078	1.613	1.641	2.144	6.719	5.509	6.072	6.450
3	1.984	0.971	1.636	1.693	1.891	1.190	1.344	1.767	6.202	5.331	5.429	5.717
4	1.612	1.086	1.390	1.469	1.931	1.531	1.601	1.967	5.303	4.613	4.394	4.849
5	1.568	0.824	1.236	1.402	1.686	1.362	1.482	1.515	4.707	4.582	4.802	5.410
	Peak values of stress (MPa)											
TA1	0.039	0.051	0.061	0.072	0.039	0.040	0.044	0.063	0.061	0.065	0.140	0.314
TA2	0.037	0.038	0.043	0.045	0.034	0.035	0.046	0.047	0.043	0.047	0.048	0.091
TA3	0.054	0.055	0.057	0.082	0.056	0.060	0.062	0.066	0.106	0.114	0.139	0.224
TA4	0.035	0.037	0.040	0.056	0.050	0.052	0.053	0.062	0.054	0.055	0.056	0.127
TA5	0.039	0.064	0.120	0.214	0.044	0.062	0.173	0.379	0.092	0.132	0.690	1.708
TA6	0.168	0.193	0.497	0.650	0.204	0.333	0.528	1.069	0.889	1.394	2.822	5.462
TA7	0.069	0.128	0.279	0.433	0.095	0.165	0.327	0.662	0.244	0.610	1.754	3.710
TB1	0.030	0.035	0.041	0.048	0.041	0.044	0.053	0.085	0.046	0.060	0.117	0.247
TB2	0.031	0.035	0.039	0.041	0.040	0.041	0.043	0.046	0.048	0.049	0.053	0.066
TB3	0.045	0.048	0.055	0.064	0.048	0.050	0.051	0.078	0.055	0.099	0.218	0.610
TB4	0.041	0.044	0.049	0.048	0.048	0.049	0.054	0.060	0.057	0.062	0.079	0.150
TB5	0.042	0.045	0.046	0.071	0.045	0.046	0.054	0.058	0.058	0.061	0.066	0.091
TB6	0.041	0.043	0.052	0.069	0.056	0.060	0.063	0.102	0.049	0.072	0.184	0.358
TB7	0.043	0.048	0.101	0.114	0.056	0.058	0.130	0.236	0.092	0.147	0.583	1.146

6. Conclusions

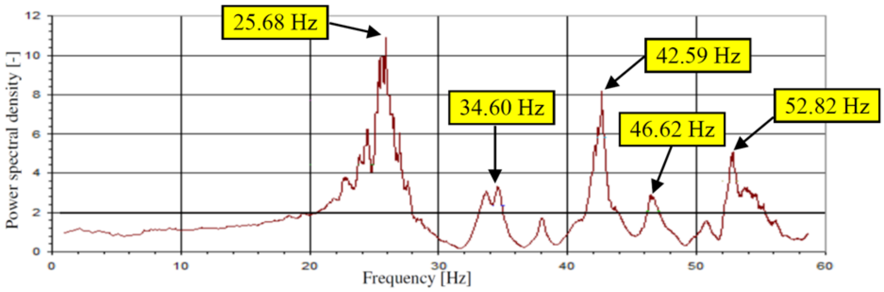
The comprehensive shaking table experimental study focused on dynamic behaviour of two models of cylindrical steel tanks under mining tremors and moderate earthquakes has been conducted and described in this paper. Firstly, the impact and the sweep-sine tests have been carried out, so as to determine the dynamic properties of models filled with different levels of water. Then, the models have been subjected to dynamic excitations by seismic and



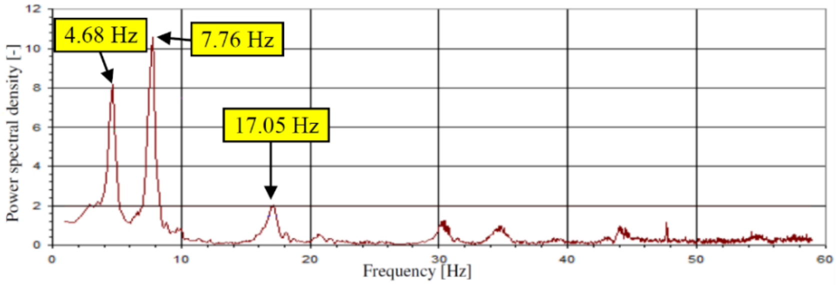


(a) Unscrewed bolts (b) Weld cuts

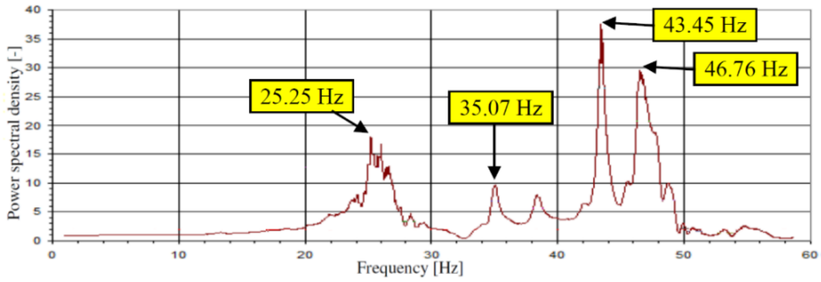
Fig. 14 Experimental setup for the damage diagnosis tests (model with D=1.5 m)



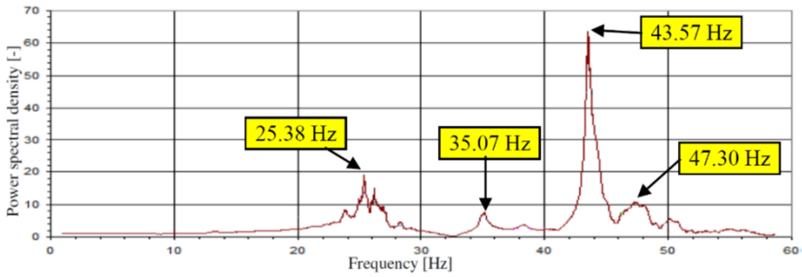
(a) Undamaged model



(b) Model with unscrewed support bolts



(c) Model with circumferential cut of weld



(d) Model with circumferential and radial cuts of weld

Fig. 15 Fourier spectra for different types of structural damage (model with D=1.5 m)

paraseismic ground motions. Finally, one fully filled experimental model has been tested after introducing two different types of damages, so as to verify the method of damage diagnosis.

The results of the impact and the sweep-sine tests show that filling the models up to different levels of water leads to substantial reduction in natural frequencies, due to gradually increasing overall mass. Moreover, the results of sweep-sine tests clearly indicate that the increase in the liquid level results in significant increase in the damping structural ratio, which is the effect of damping properties of water due to its sloshing.

Also, the results of seismic and paraseismic tests show that the level of liquid is really essential in the structural analysis. They indicate that filling the tank with water leads initially to considerable reduction in values of acceleration (damping effect of water due to its sloshing); however, beyond a certain level of water filling, this regularity is inverted and acceleration values increase (effect of increasing total mass of the structure). Moreover, comparison of the responses under mining tremors and moderate earthquakes indicate that the power amplification factor of the mining tremors may be larger than the seismic power amplification factor. This is mainly due to higher frequency contents of mining tremors which are closer to the natural frequencies of steel tanks. Moreover, the results of seismic and paraseismic tests show that filling the tank with water leads to the considerable non-uniform increase in stress values which depends on type of dynamic excitation. It is however important to underline that the allowable level of stresses has not been exceeded in any case for none of the models of steel tanks.

The results of damage diagnosis of fully filled steel tank model indicate that the forms of the Fourier spectra, together with the frequency and power spectral density values, can be directly related to the specific type of structural damage. They show the decrease in the natural frequencies for the model with unscrewed support bolts, which is characteristic for the global type of damage. On the other hand, cutting the welds, which can be considered as the local type of damage, has resulted in significant increase in values of the power spectral density for higher vibration modes. For the above reasons, we can conclude that the shaking table tests can be considered to be quite effective in diagnosing structural damage in models of large civil engineering structures.

The study described in the present paper has been conducted using scaled models of large steel tanks, since tests on real structures are very difficult. Moreover, due to technical restrictions and safety reasons, water has been used as filling liquid. Therefore, the results obtained for analysed structures for different levels of liquid filling should be treated as the qualitative rather than the quantitative ones. Further, detailed numerical study is planned to be conducted, so as to verify the structural response of real steel tanks under different dynamic excitations. Due to large plan dimensions of the structures, the analysis will include stochastically generated (see Jankowski and Walukiewicz 1997) non-uniform ground motion excitations caused by the spatial seismic effects related to the propagation of seismic wave.

Acknowledgments

The research described in this paper has been financially supported by the Polish National Centre of Science through a research project no. N N506 121240. This support is greatly acknowledged.

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