Experimental study on the behaviour of cylindrical steel tanks under moderate earthquakes and rockburst-induced ground motions

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SUMMARY:
Cylindrical steel tanks are very popular structures used for storage of products of chemical and petroleum industries. Their safety and reliability is really crucial because any failure may have serious consequences. Earthquakes are the most dangerous and also the most unpredictable dynamic loads acting on such structures. On the other hand, rockburst-induced ground motions are usually considered to be less severe due to lower acceleration levels observed. The aim of the present paper is to show the results of the shaking table experimental study focused on the behaviour of steel cylindrical tanks filled with liquid under moderate earthquakes as well as rockburst-induced ground motions. The results of the study confirm that the level of liquid filling is essential in the structural analysis. They indicate that filling the tank with water leads initially to reduction in values of structural accelerations; however beyond a certain level of water filling this regularity is inverted. It has also been noticed that the tank geometry and the nature of excitation are also parameters influencing the response of steel tank models.

Keywords: cylindrical steel tank, earthquake, rockburst-induced ground motion, shaking table

1. INTRODUCTION

Cylindrical steel tanks are very popular structures used for storage of products of chemical and petroleum industries around the world. Their safety and reliability is really crucial because any failure may have serious consequences. Earthquakes, as the natural phenomena, are the most dangerous and, at the same time, the most unpredictable dynamic loads acting on such structures (see De Angelis *et al.*, 2010). On the other hand, rockburst-induced ground motions, which are induced due to mining activity of human being, are usually considered to be less severe due to lower acceleration levels observed. A relatively large number of numerical analyses on the behaviour of different types of steel tanks under earthquakes has been conducted (see, for example, Chen *et al.*, 2007, Dong and Redekop, 2007, Virella *et al.*, 2003). However, the results of the experimental studies are quite limited (see De Angelis *et al.*, 2010), although the experimental investigations are usually very useful in earthquake engineering (see, for example, Jankowski, 2010). On the other hand, according to the authors' knowledge, no studies have been conducted so far concerning the behaviour of steel tanks under rockburst-induced ground motions related to mining tremors.

Structures in Poland do not have to be designed for dynamic loads associated with seismic excitations. On the other hand, in the case of mining tremors only general guidelines have been formulated. The majority of Polish territory is in the area of small or negligibly small seismicity. However, from time to time, earthquakes causing serious damages to building structures are recorded. The recent earthquakes in the north eastern as well as southern Poland (see Zembaty *et al.*, 2005a, 2005b) are the examples of such events. There are also a number of places in south of the country where rockburst-induced ground motions occur as the result of mining industry. Vibrations recorded in these regions have different characteristics than natural earthquakes (see Zembaty, 2004), although some of them can also have destructive consequences.

The aim of the present paper is to show the results of the shaking table experimental study focused on the behaviour of steel cylindrical tanks under moderate earthquakes (observed in such countries as Poland) as well as rockburst-induced ground motions. The models have been tested with different levels of liquid filling (empty tanks, tanks partly filled with liquid, tanks fully filled with liquid).

2. EXPERIMENTAL MODELS OF TANKS

Two experimental models of real tanks with self-supported roofs have been prepared (see Figures 1,2). The first model is a scaled model (scale 1:22.69) of the steel tank of the total capacity of 10000 m^3. Its diameter and the total height is equal to 1.25 m and 0.84 m, respectively (aspect ratio is equal to 0.67). The model has the total weight equal to 71.4 kg. The second model is a scaled model (scale 1:33.33) of the steel tank of the capacity of 32000 m^3. Its diameter and the total height is equal to 1.5 m and 0.7 m, respectively (aspect ratio is equal to 0.47). The model has the total weight equal to 86 kg. For both models, the thickness of the bottom plate, shell and roof is equal to 3 mm, 1.2 mm and 1.2 mm, respectively. The models have been made of stainless steel. The structure of the first and the second tank has been fixed by fourteen M10 bolts with seven plates and eighteen M10 bolts with nine plates to the platform of the shaking table, respectively.

3. TEST PROGRAMME AND MEASURING EQUIPMENT

A shaking table located at the Gdansk University of Technology (Poland) was used in the experimental study. It is a unidirectional device with the platform dimensions of 2.0×2.0 m which allows for testing the specimens with a maximum mass of 1000 kg. The models are symmetrical and, for this reason, the vibration excitation has been implemented for only one direction, consistent with the movement of the shaking table platform. The shaking table tests have been carried out for four variants of the water level:

1) empty tank,
2) tank filled with water up to 1/3 of allowable limit (231 mm of water for tank with diameter D=1.25 m, 162 mm of water for tank with diameter D=1.5 m),
3) tank filled with water up to 2/3 of allowable limit (462 mm of water for tank with diameter D=1.25 m, 324 mm of water for tank with diameter D=1.5 m),
4) tank filled with water up to allowable limit (693 mm of water for tank with diameter D=1.25 m, 486 mm of water for tank with diameter D=1.5 m).

Two types of excitations have been considered:

1) El Centro earthquake (18.05.1940, NS component),
2) Polkowice rockburst-induced ground motion (20.02.2002, NS component).

According to the similitude laws (see De Angelis *et al.*, 2010), the time-scale 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 used.

To implement the measurements of accelerations, special laboratory equipment has been used, which includes:

1) five single-axis accelerometers,
2) twelve-channel amplifier (five channels were active),
3) digital-analog measuring card,
4) PC for recording the measurements.

Acceleration measurements have been conducted simultaneously in five points. They include four points located at the tank model and one point located at the shaking table platform. Locations of accelerometers are presented in Figure 1.

Figure 1. Tank model with diameter D=1.25 m – locations of accelerometers

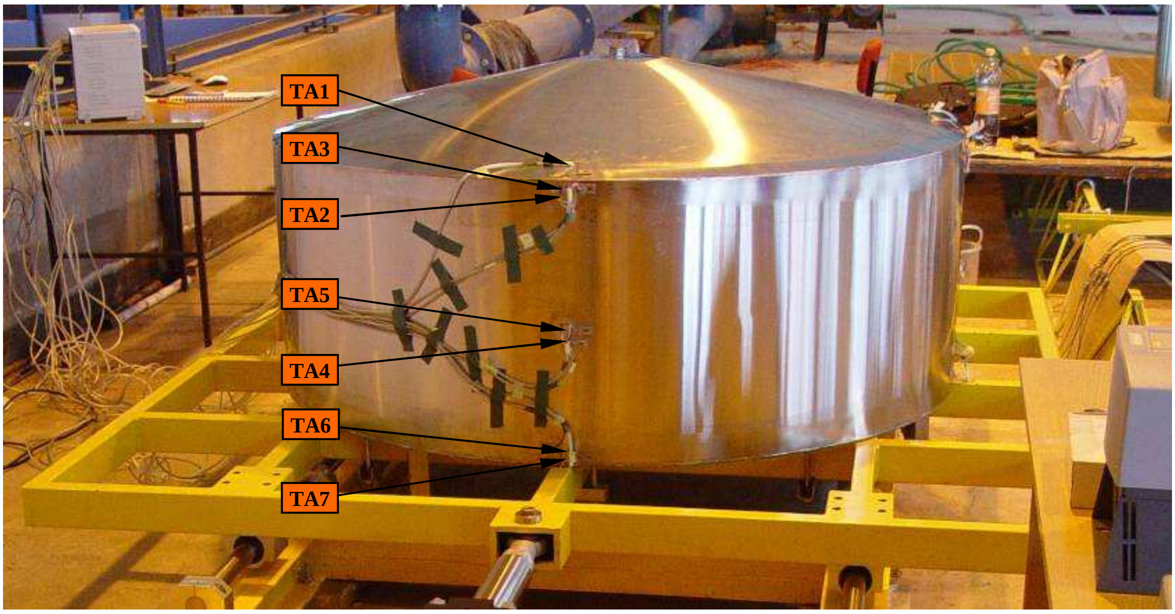

Figure 2. Tank model with diameter D=1.5 m – locations of strain gauges

To implement the measurements of strains, special laboratory equipment has been used, which includes:

1) seven active unidirectional strain gauges,
2) seven compensatory unidirectional strain gauges,
3) sixty four-channel strain measuring system (seven channels were active)

Strain measurements have been conducted simultaneously in seven points. They include one point located at the model roof (for radial strains), three points located at the model shell (for longitudinal strains) and another three points located at the model shell (for circumferential strains). Locations of strain gauges are presented in Figure 2.

4. RESULT OF EXPERIMENTAL TESTS

A number of tests for two steel tank models filled with different level of water has been conducted. The examples of the results in the form of acceleration and stress response time histories under the El Centro earthquake and the Polkowice rockburst-induced ground motion are shown in Figures 3-10.

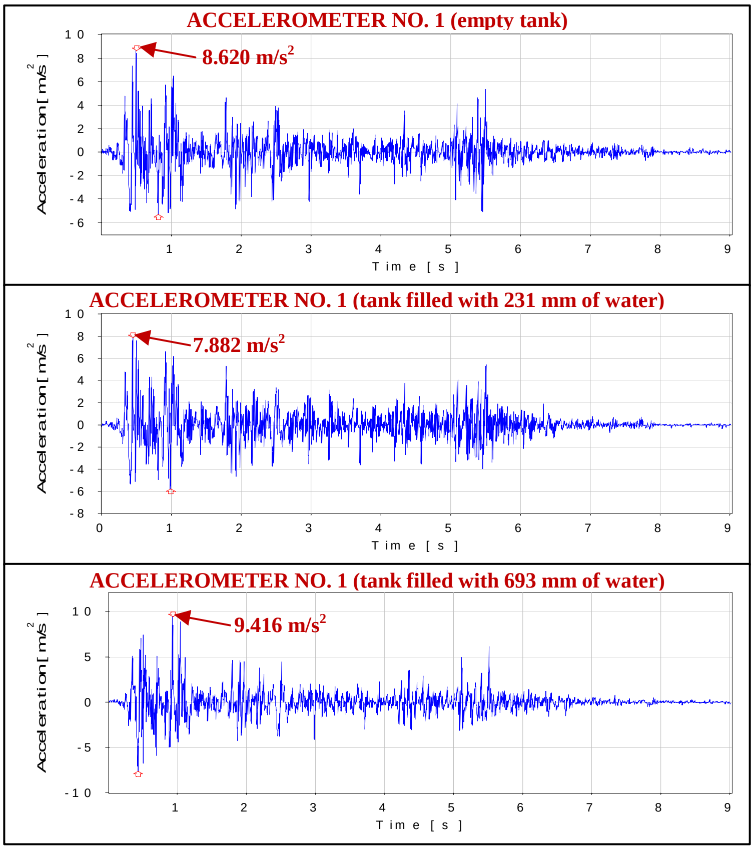

Figure 3. Acceleration time histories under the El Centro earthquake (D=1.25 m)

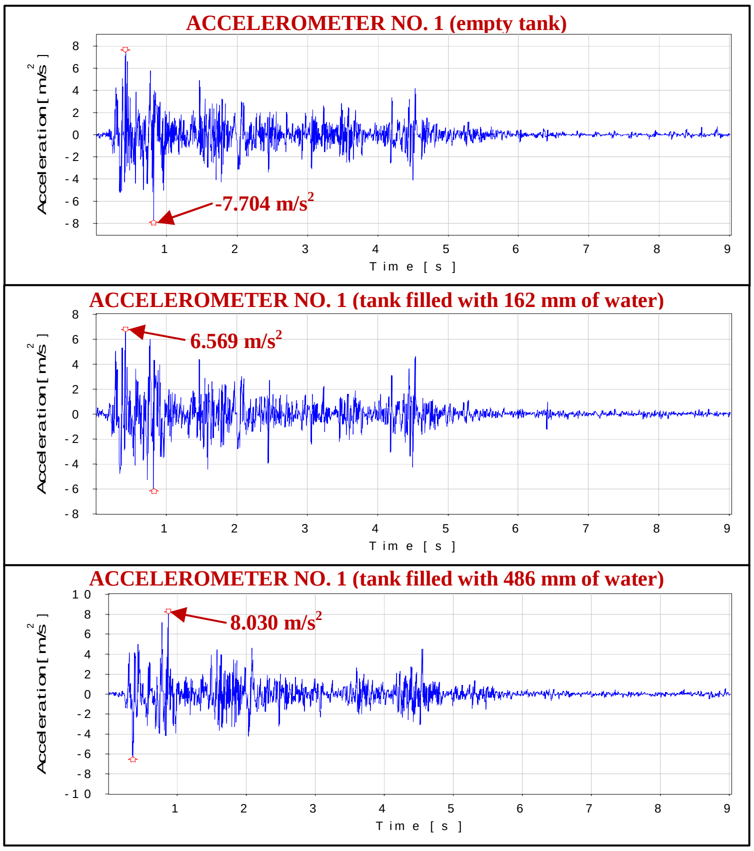

Figure 4. Acceleration time histories under the El Centro earthquake (D=1.5 m)

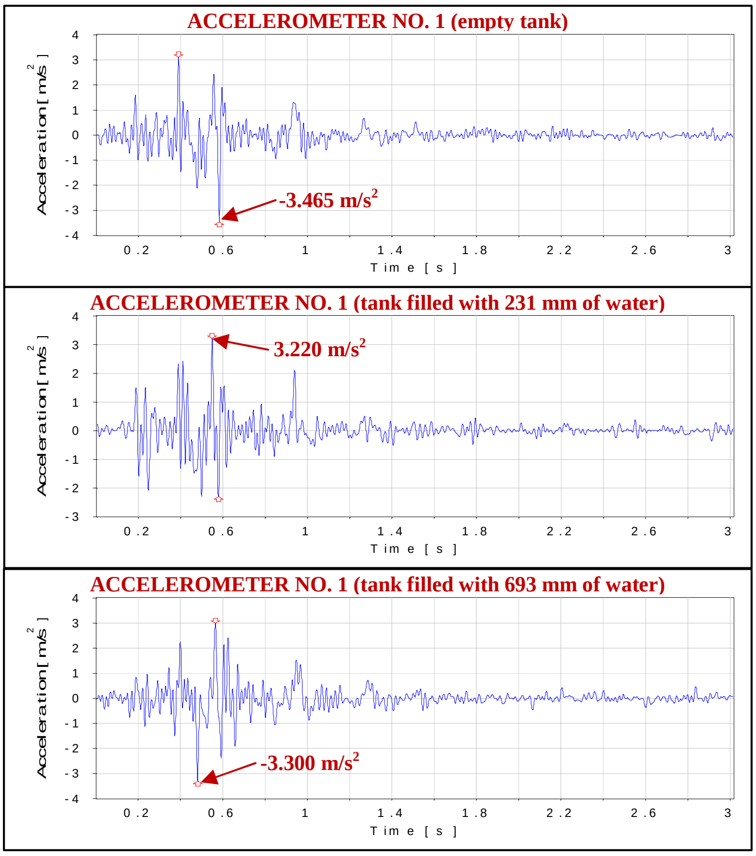

Figure 5. Acceleration time histories under the Polkowice rockburst-induced ground motion (D=1.25 m)

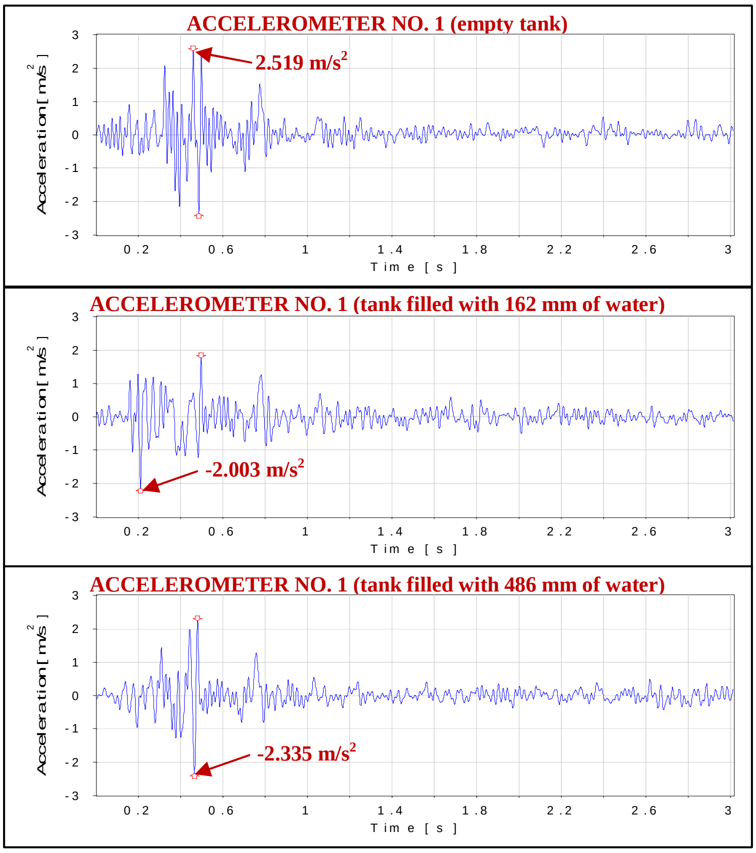

Figure 6. Acceleration time histories under the Polkowice rockburst-induced ground motion (D=1.5 m)

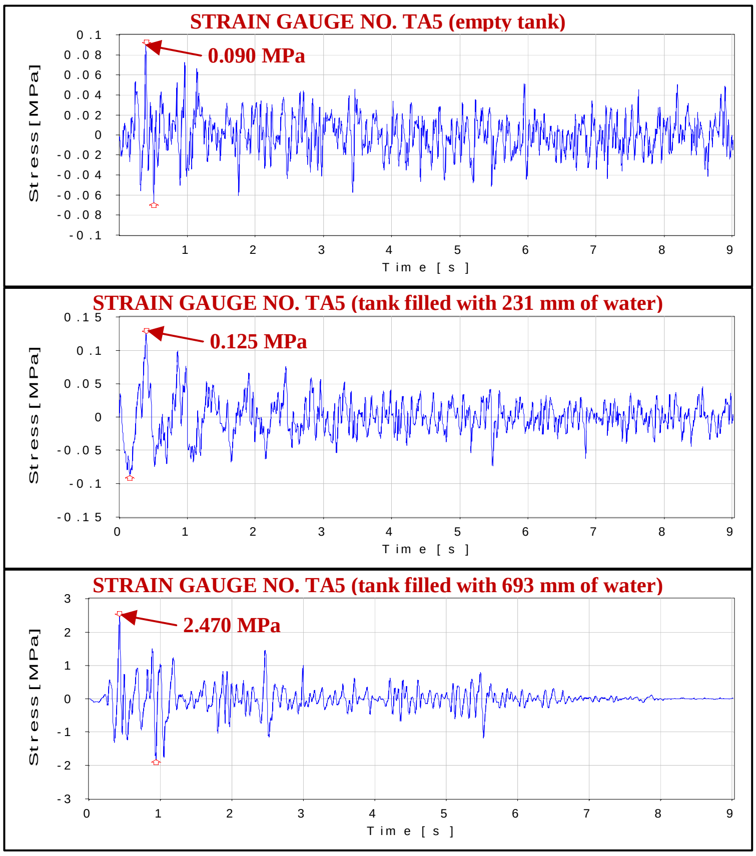

Figure 7. Stress time histories under the El Centro earthquake (D=1.25 m)

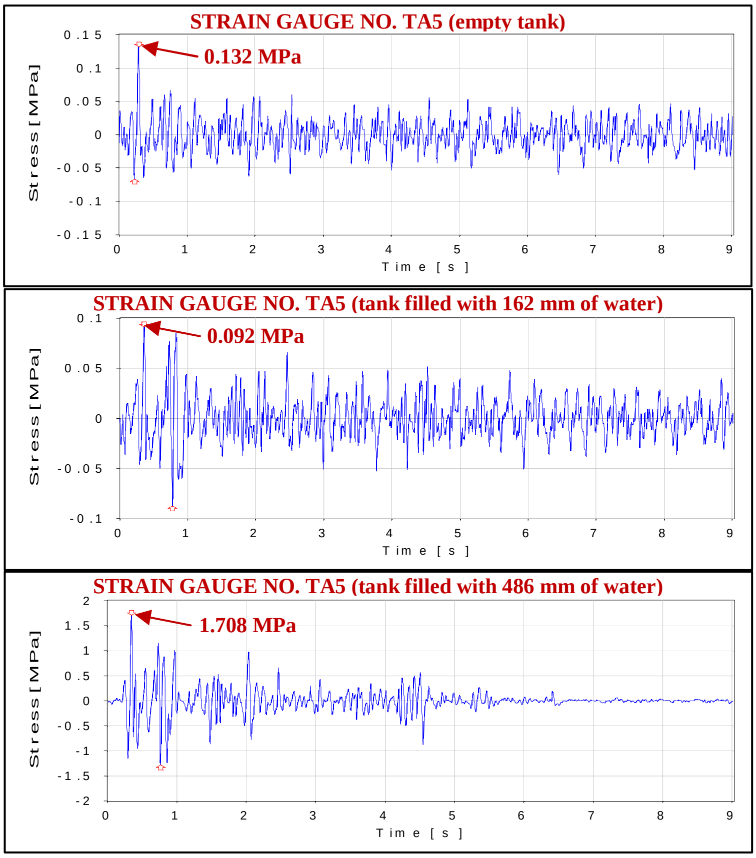

Figure 8. Stress time histories under the El Centro earthquake (D=1.5 m)

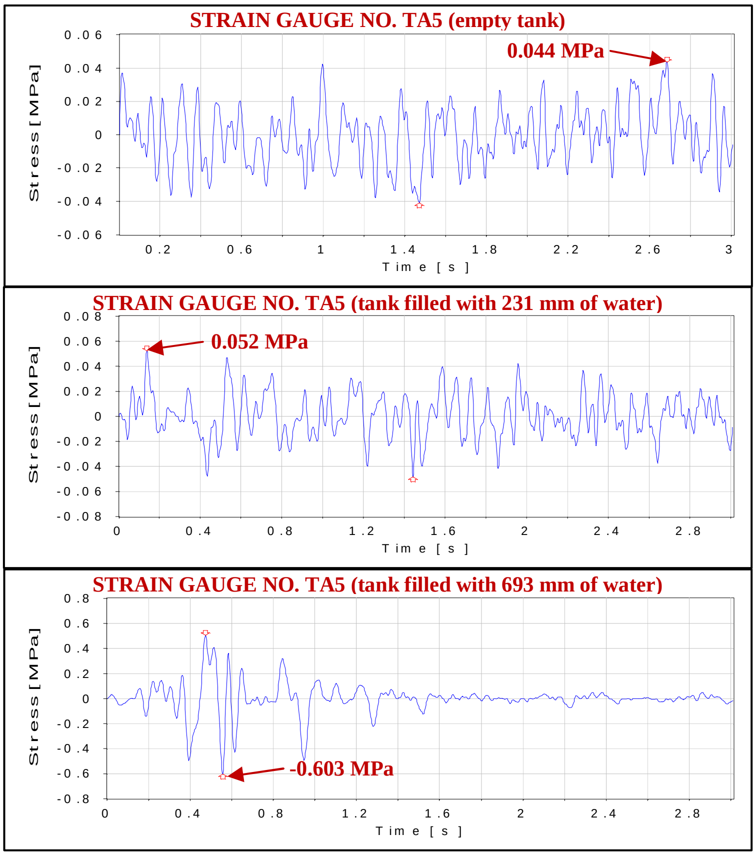

Figure 9. Stress time histories under the Polkowice rockburst-induced ground motion (D=1.25 m)

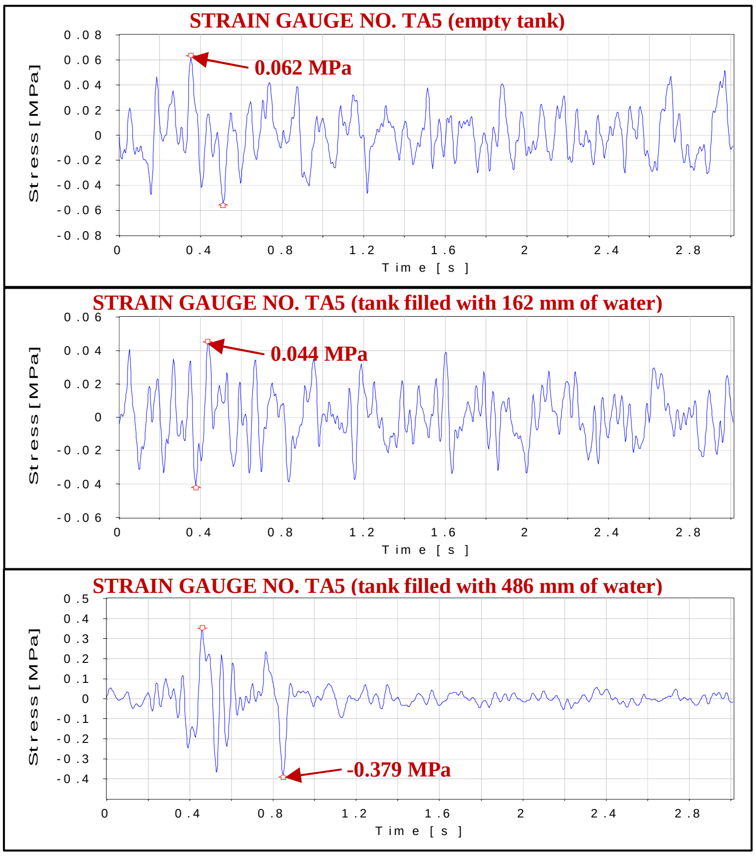

Figure 10. Stress time histories under the Polkowice rockburst-induced ground motion (D=1.5 m)

The results from Figures 3-6 indicate that filling the tank with water leads initially to reduction in values of structural accelerations; however, beyond a certain level of water filling this regularity is inverted. For example, it can be seen from Figure 4 that the value of the peak acceleration has been reduced (as compared to empty tank) by 14.7% and has grown by 4.2% by filling the tank with 162 mm and 486 mm of water, respectively. It is believed that this behaviour results form the fact that filling the tank with water increases it's damping properties due to sloshing of liquid. On the other hand, however, adding water substantially increases also the total mass of the tested structure and that is why the increased trend is observed for higher levels of water filling. Moreover, it can be seen from Figures 7-10 that the higher level of water leads generally to the increase in stress values. For example, it can be seen from Figure 7 that the value of the stress has grown (as compared to empty tank) by 38.9% and 2644% by filling the tank with 231 mm and 693 mm of water, respectively. In the case of the tank geometry, model with higher value of aspect ratio is characterized by larger magnitude of acceleration and stress values at the analogical level of water filling.

5. FINAL REMARKS

In the present work, the shaking table experimental study focused on the behaviour of steel tanks models under seismic excitation and rockburst-induced ground motion has been presented. The results of the study confirm that the level of liquid filling is essential in the structural analysis. The dynamic behaviour of structures has been found to be different for the fully filled, partly filled and empty tanks. It has also been noticed that the tank geometry and the nature of excitation are also parameters influencing the response of steel tank models.

Further detailed numerical study is planned to be conducted so as to determine the structural response of steel tanks at different level of water filling under dynamic excitations, such as moderate earthquakes and rockburst-induced ground motions, in order to verify the results obtained.

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