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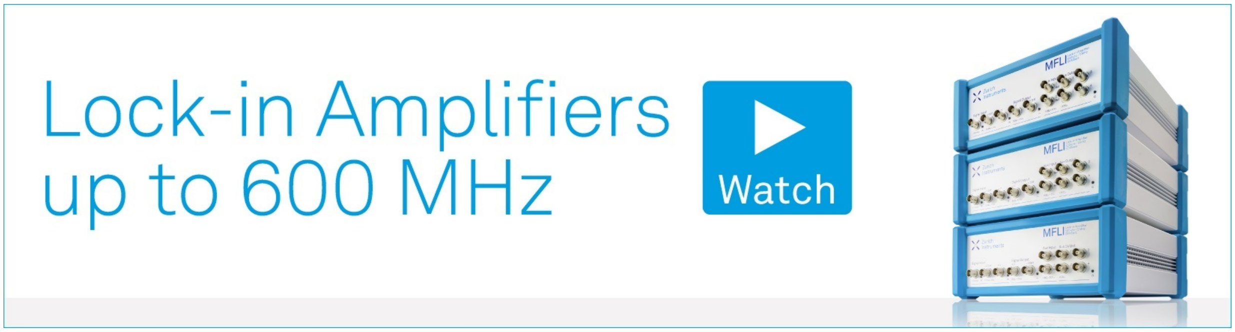
Daniel Burkacki, and Robert Jankowski



Response of Cylindrical Steel Tank under Stochastically Generated Non-Uniform Earthquake Excitation

Daniel Burkacki[1, a)] and Robert Jankowski[1, b)]

[1]*Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland*

[a)]danburka@pg.edu.pl
[b)]Corresponding author: jankowr@pg.edu.pl

Abstract. Cylindrical steel tanks are very important structures in industrial facilities since their application is related to storing different types of products. Their safety and reliability have become a crucial issue because any damage may cause significant consequences, including ecological disaster. The most dangerous dynamic load acting on cylindrical steel tanks is related to earthquakes, especially that the seismic excitation may differ from place to place due to spatial seismic effects related to the propagation of seismic wave. Previous studies have confirmed that such non-uniform earthquake excitation may influence the response of large structures significantly. Stochastic methods of analysis have become an advantageous approach to simulate a spatiotemporal variation of ground motion field for the earthquake engineering problems. The aim of the present paper is to show the results of FEM numerical investigation focused on the response of a cylindrical steel tank under stochastically generated non-uniform earthquake excitation. The analysis has been conducted for the tank fully filled with petroleum. A method of conditional stochastic simulation of ground motions, using the spatiotemporal correlation function, has been applied to generate unknown acceleration time histories for different support locations, based on the earthquake record specified for one location. The results of the analysis clearly indicate that the consideration of spatial effects related to seismic wave propagation leads to the considerable changes in the response of cylindrical steel tank under earthquake excitation. It has also been shown that the application of the stochastic simulation with the spatiotemporal correlation function is an effective method which can be successfully used to generate earthquake records in different locations so as to consider the non-uniform ground motion excitation.

INTRODUCTION

The liquid products of many industry branches, such as petroleum or chemical industries, are stored in special containers, mainly in cylindrical steel tanks. Therefore, the safety and reliability of these structures are very important issues. Any damage or leakage of the structure can lead to serious consequences, including an ecological disaster. One of the most unpredictable excitation, that can affect steel tanks, is related to earthquakes (see, for example, [1-4]). Previous studies have shown that shell tanks are extremely susceptible to earthquake damage [3,4]. It should be underlined that seismic excitation effects can be different if spatial seismic effects related to the propagation of seismic wave are taken into account (see [5,6]). The dynamic response of large structures subjected to non-uniform seismic excitation may be substantially different comparing to the case with uniform excitation (see [7]). In earthquake engineering, the simulation of spatiotemporal variation of ground motion field is successfully conducted using the stochastic approach (see [8-10]).

Historically, Housner was the first one to propose mechanical models of tanks with rigid walls (see [11-13]). The mechanical model of Housner, with minor modifications, is still widely used. An example of Housner's model adaptation for short and slender tanks was investigated by Wozniak and Mitchell [14]. The first analytical approach to analyse flexible liquid-filled containers was performed by Veletsos [15]. The first complex numerical analysis of steel tanks under earthquake excitation was carried out by Edwards [16]. He used the Finite Element Method (FEM) and a refined shell theory to predict seismic stresses and displacements in a vertical cylindrical tank, including the

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interaction between the structure and liquid. Moreover, Haroun and Housner [17] proposed a mechanical model with deformability of the tank wall which was widely applied in design because of its simplicity. Veletsos [18] investigated another model of a flexible tank. Based on his study, Malhotra et al. [19] proposed the simplified procedure for analysis of liquid-storage tanks which was adopted in Eurocode 8. Recently, many researchers have focused their analyses on a better description of fluid-structure interaction during earthquakes (see, for example, [20-22]). Another issue is the influence of different base-isolation systems on the dynamic and seismic behaviour of cylindrical liquid storage tanks (see, for example, [23-26]). Besides the numerical analyses, the experimental investigations on seismic response of steel tanks have also been conducted (see , for example, [27]).

The aim of the present paper is to show the results of the FEM numerical investigation focused on the dynamic response of a cylindrical steel tank under stochastically generated non-uniform earthquake excitation. The analysis has been conducted based on the method of conditional stochastic simulation of ground motions for large shell tanks using the spatiotemporal correlation function.

NUMERICAL MODEL

For the purpose of the analysis, numerical model of the real cylindrical steel tank has been generated. The tank has the total volume capacity of V=32,000 m^3. 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 equipped with the self-supported roof consisting of steel profiles: IPE360 (radial elements), C100, C120, C140 (circumferential elements), L65x6, L80x8, L100x8 (wind bracings) and the roof sheathing with the thickness of 5 mm. Steel with Young's modulus E=210 GPa, Poisson's ratio v=0.3 and mass density ρ=7850 kg/m^3 is the material of the tank. The material of liquid is petroleum with the bulk modulus K=1.30 GPa, Poisson's ratio v=0.4999 and mass density ρ=720 kg/m^3.

The numerical model of the tank has been created 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 the structure have been considered to be constrained. In the study, a model of sloshing of liquid considered by Virella *et al.* [28] has been applied and the fluid-structure interaction has been modelled by the contact surfaces ('hard' contact - see [29]). 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 numerical model of the analysed tank is shown in Fig. 1. Four marked nodes (X_d, X_s, X_g, X_t) represent reference nodes considered in the analysis.

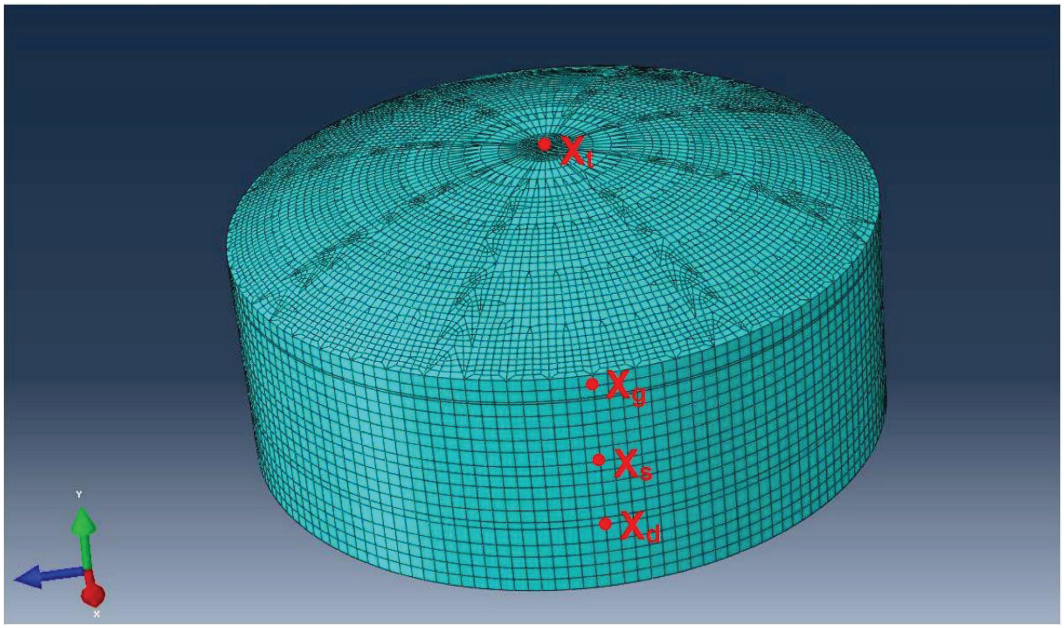

FIGURE 1. FE model of steel tank

SEISMIC ANALYSIS

The numerical analysis has been conducted for tank filled to allowable height limit (equal to 16.2 m, according to the design project). The El Centro earthquake (18.05.1940) has been considered in the study as the seismic excitation. The following three components of the earthquake have been used:

- NS component with PGA=3.402 m/s^2 (applied in UX horizontal direction),
- EW component with PGA=2.107 m/s^2 (applied in UZ horizontal direction),
- UD component with PGA=2.013 m/s^2 (applied in UY vertical direction),

where PGA stands for the peak ground acceleration. The fact that the ground motion differs from place to place due to spatial seismic effects has been taken into account in the numerical investigation. These seismic effects include the following issues (see [5]):

- the difference in the arrival times of seismic wave at various locations (wave passage effect),
- the loss of coherency of the 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)
- the change in the seismic wave propagation paths due to spatially varying local soil conditions (site response effect).

For the purposes of simulation, a method of conditional stochastic simulation of ground motions for structures with extended foundations has been used. It should be mentioned, that the method based on the spatial correlation function has been originally proposed for multisupport structures, such as long bridges [9]. Then, it has been modified so as to deal with large structures with continuous foundations, such as buildings or dams, by introducing the spatiotemporal correlation function [30]. The ground motion upcoming from the sub-soil is averaged on the contact plane between structure-foundation-subsoil allowing us to generate unknown acceleration time histories for different support locations of the structure. It has been confirmed that the method is useful and effective for large structures with extended continuous foundations (see [30] for details). The spatiotemporal correlation function, applied in the method, is defined as [30]:

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

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 β - time scale parameter ($\beta > 0$) describing the degree of time correlation.

Following the principles of conditional stochastic modelling, the ground motion records for different locations have been generated based on specified acceleration time history (see [30,31] for details). The base plate of steel tank has been divided into eight segments (see Fig. 2). The ground motion for the structural location no. 1 has been assumed as a specified one and acceleration time histories for other 7 locations have been determined. Simulations have been conducted for the apparent seismic wave velocity of v=1000 m/s and for five variants of the space and time scale parameters:

- case “A”: d=1, β=100,
- case “B”: d=0.5, β=100,
- case “C”: d=2, β=100,
- case “D”: d=1, β=50,
- case “E”: d=1, β=200.

For all cases, numerical tests of steel tank under non-uniform earthquake excitation have been carried out. The results, in the form of the displacement UX (horizontal direction) time histories for reference node X_g, as well as the extreme distribution of von Mises stresses, have been compared with results obtained for the uniform El Centro excitation. Figs. 3-8 present the displacement time histories and Figs. 9-14 show the maps of stresses. The obtained results clearly indicate that the consideration of spatial effects related to seismic wave propagation leads to the considerable decrease in the structural response during the earthquake. For example, it can be seen comparing Fig. 3 with Figs. 4-8 that the peak value of UX displacement has decreased by 78.1%, 85.7%, 68.8%, 88.4% and 83.1% for cases from “A” to “E”, respectively, when the uniform El Centro excitation is replaced by the non-uniform one. Similarly, comparison between Fig. 9 and Figs. 10-14 indicates that the decrease in value of the maximum von Mises stress is equal to 15.5%, 17.1%, 13.8%, 15.0%, 15.5% for the same structure and seismic excitation.

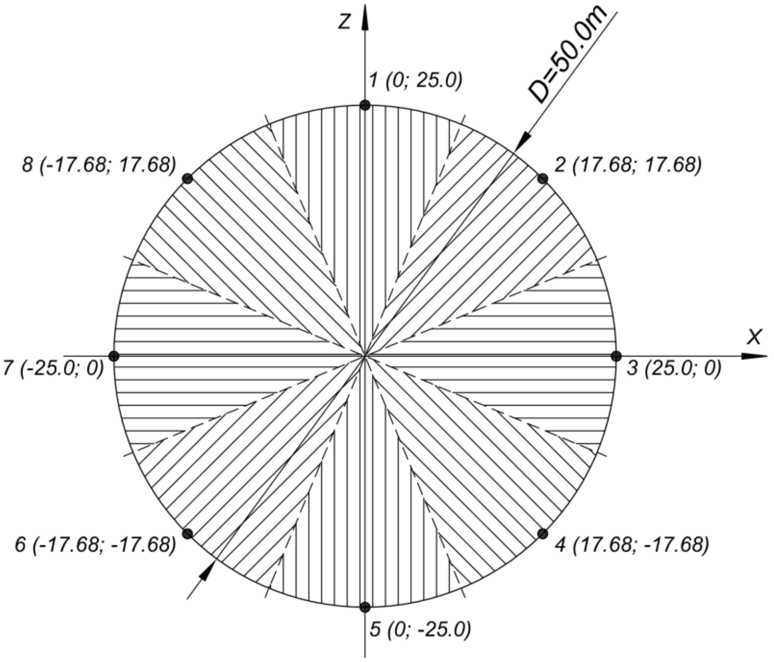

FIGURE 2. Segments of base plate of tank

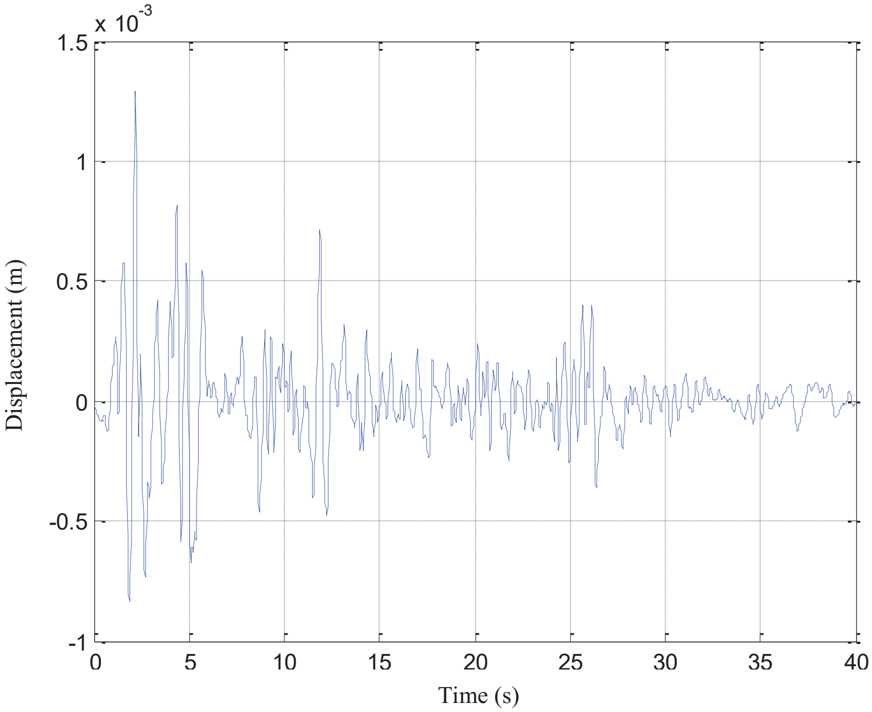

FIGURE 3. Displacement UX time history for the tank under uniform El Centro earthquake – reference node X_g (peak value: $1.25 \cdot 10^{-3}$ m)

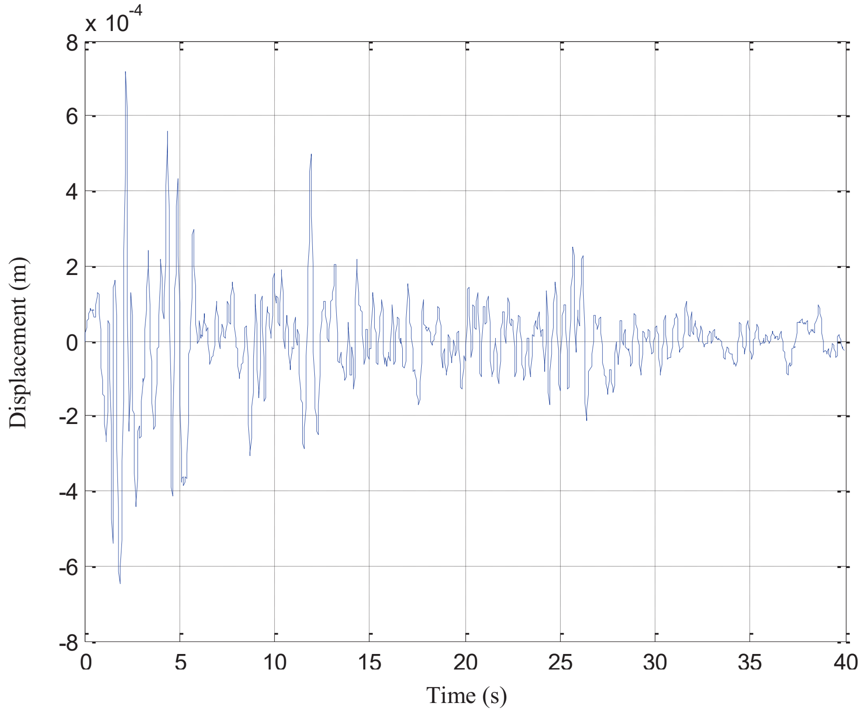

FIGURE 4. Displacement UX time history for the tank under non-uniform El Centro earthquake (case "A") – reference node X_g (peak value: $7.30 \cdot 10^{-4}$ m)

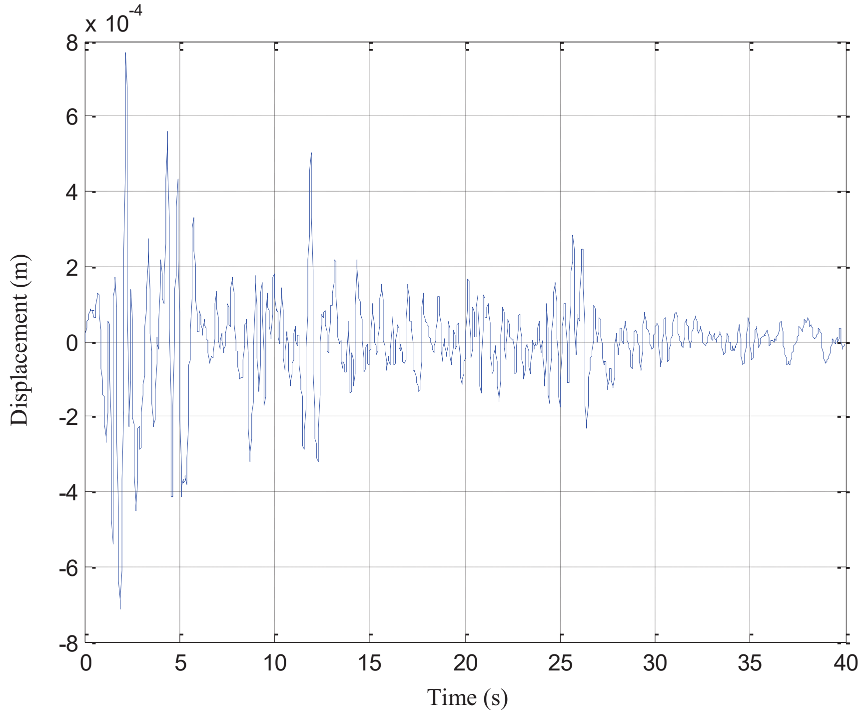

FIGURE 5. Displacement UX time history for the tank under non-uniform El Centro earthquake (case "B") – reference node X_g (peak value: $7.00 \cdot 10^{-4}$ m)

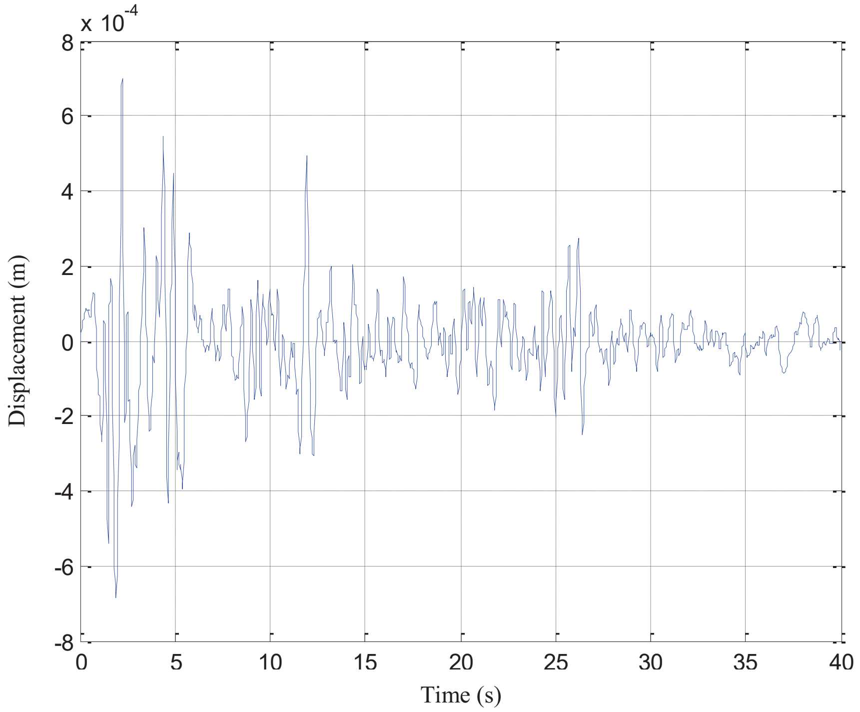

FIGURE 6. Displacement UX time history for the tank under non-uniform El Centro earthquake (case "C") – reference node X_g (peak value: $7.70 \cdot 10^{-4}$ m)

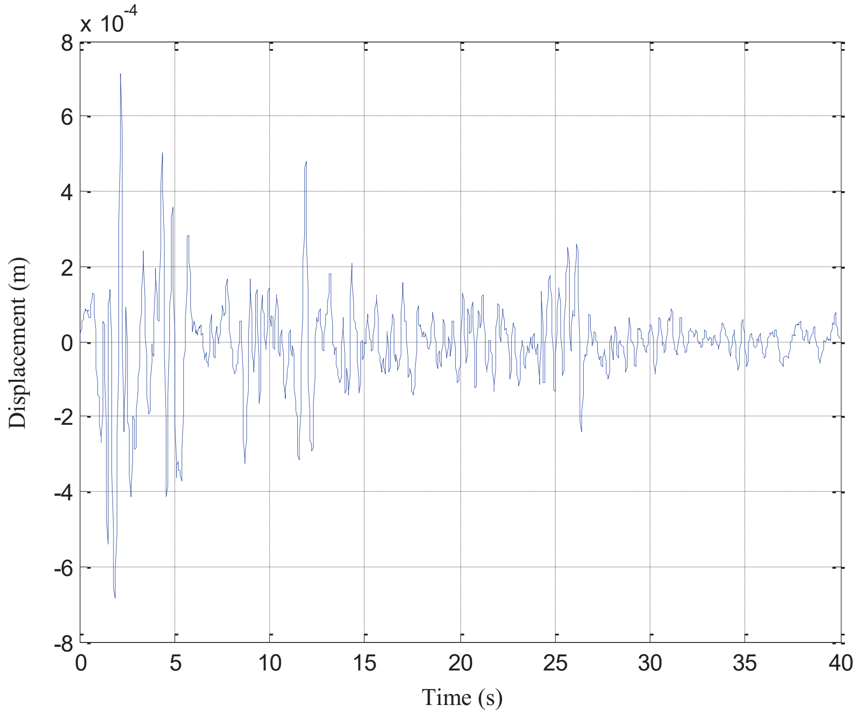

FIGURE 7. Displacement UX time history for the tank under non-uniform El Centro earthquake (case "D") – reference node X_g (peak value: $6.90 \cdot 10^{-4}$ m)

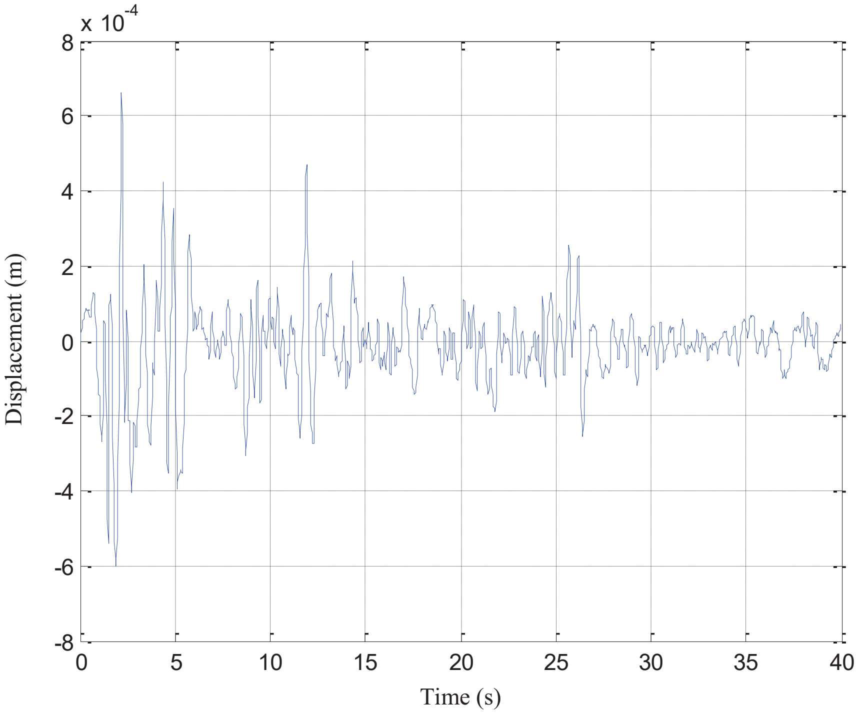

FIGURE 8. Displacement UX time history for the tank under non-uniform El Centro earthquake (case "E") – reference node X_g (peak value: $7.10 \cdot 10^{-4}$ m)

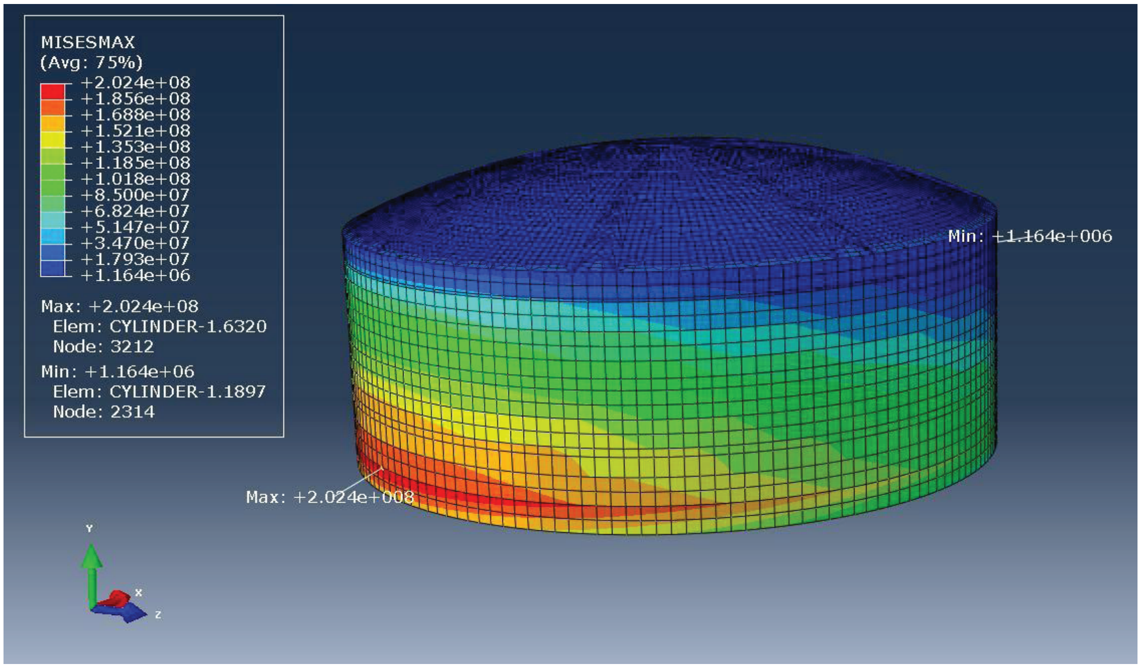

FIGURE 9. Extreme distribution of von Mises stress for the tank under uniform El Centro earthquake – t=2.16 s (max value: 202.40 MPa)

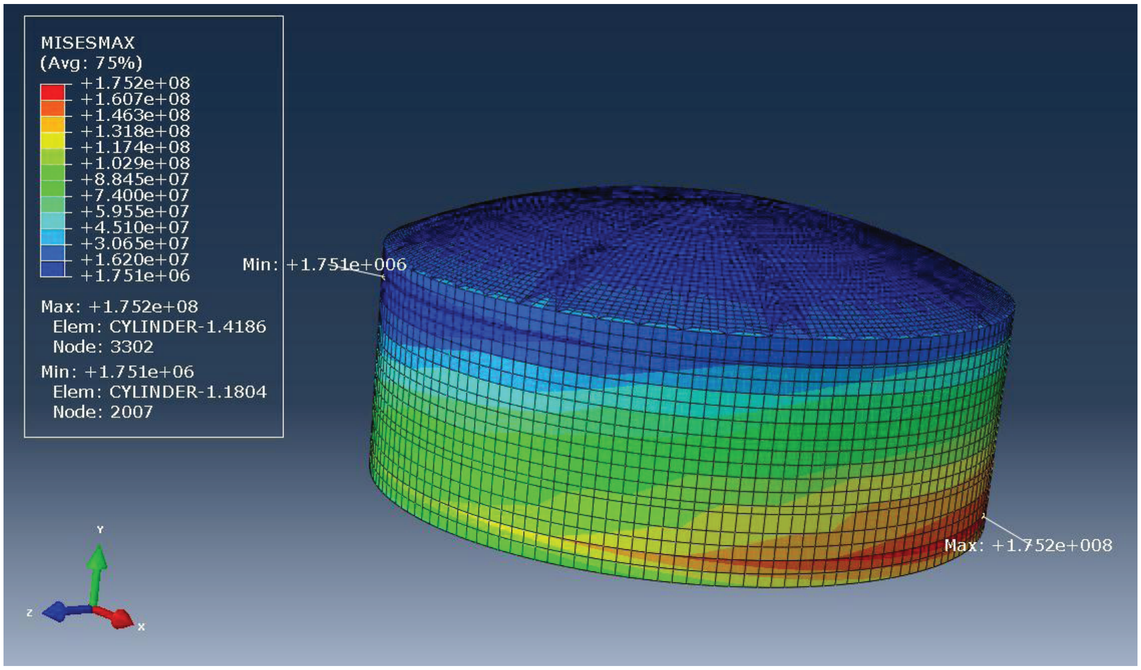

FIGURE 10. Extreme distribution of von Mises stress for the tank under non-uniform El Centro earthquake (case "A") – t=2.19 s (max value: 175.20 MPa)

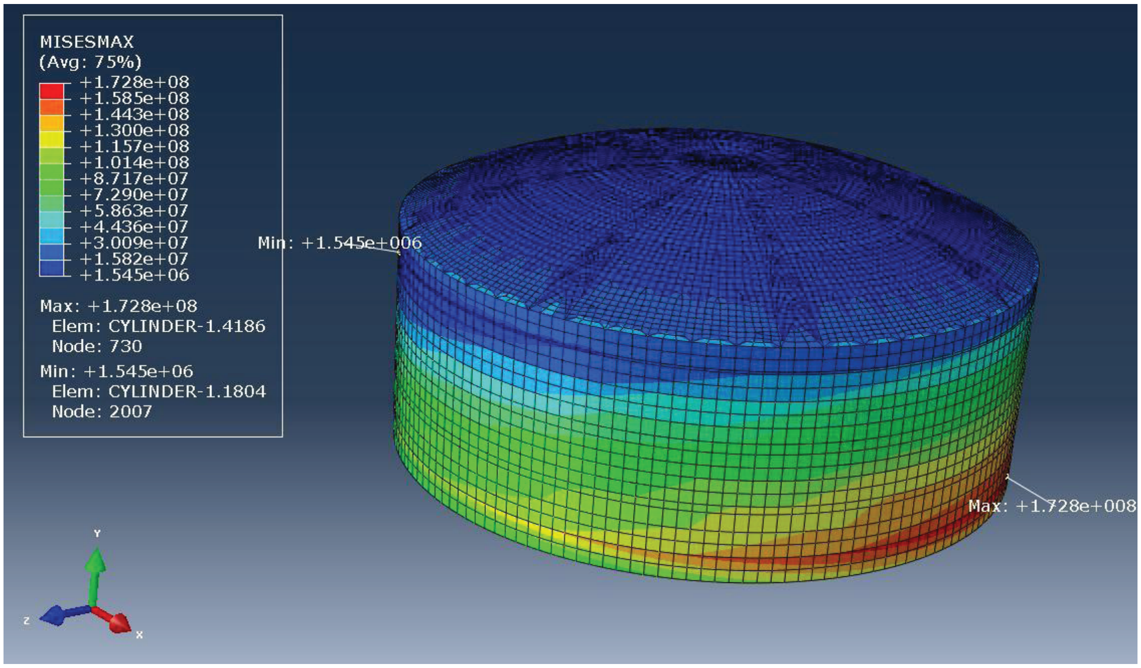

FIGURE 11. Extreme distribution of von Mises stress for the tank under non-uniform El Centro earthquake (case "B") – t=2.19 s (max value: 172.80 MPa)

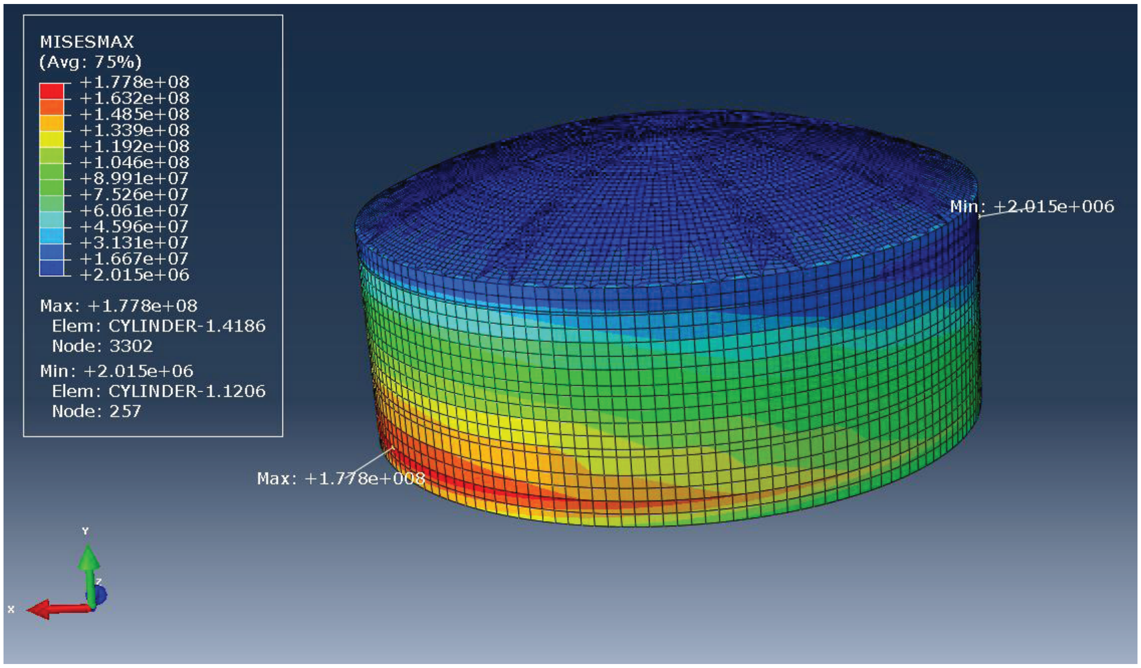

FIGURE 12. Extreme distribution of von Mises stress for the tank under non-uniform El Centro earthquake (case "C") – t=2.19 s (max value: 177.80 MPa)

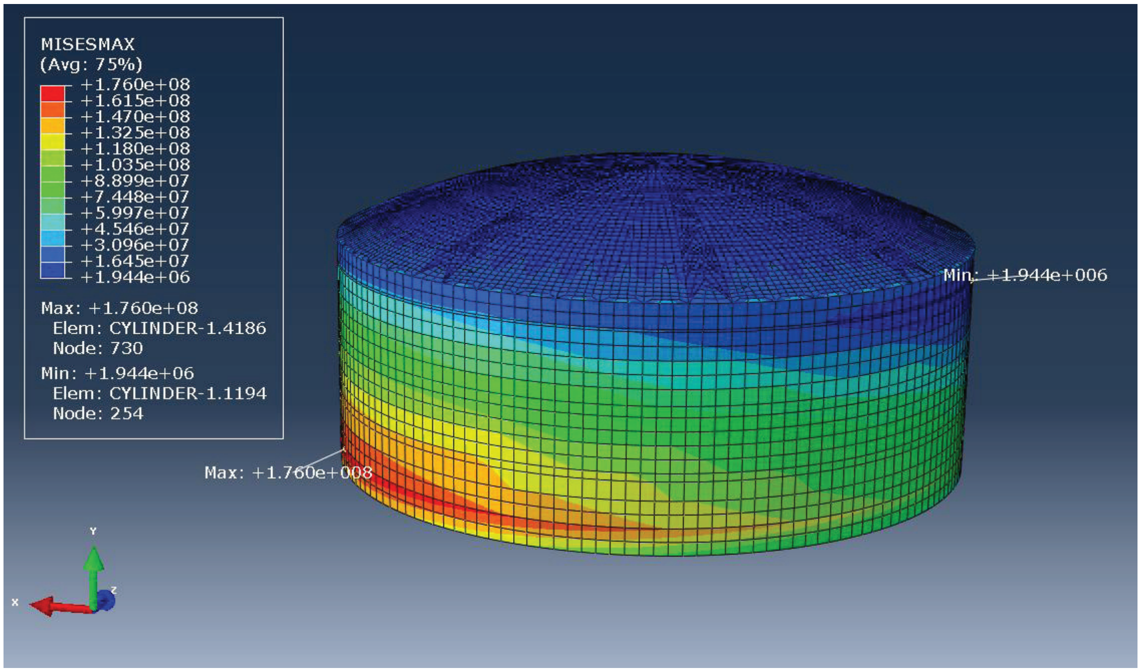

FIGURE 13. Extreme distribution of von Mises stress for the tank under non-uniform El Centro earthquake (case "D") – t=2.19 s (max value: 176.00 MPa)

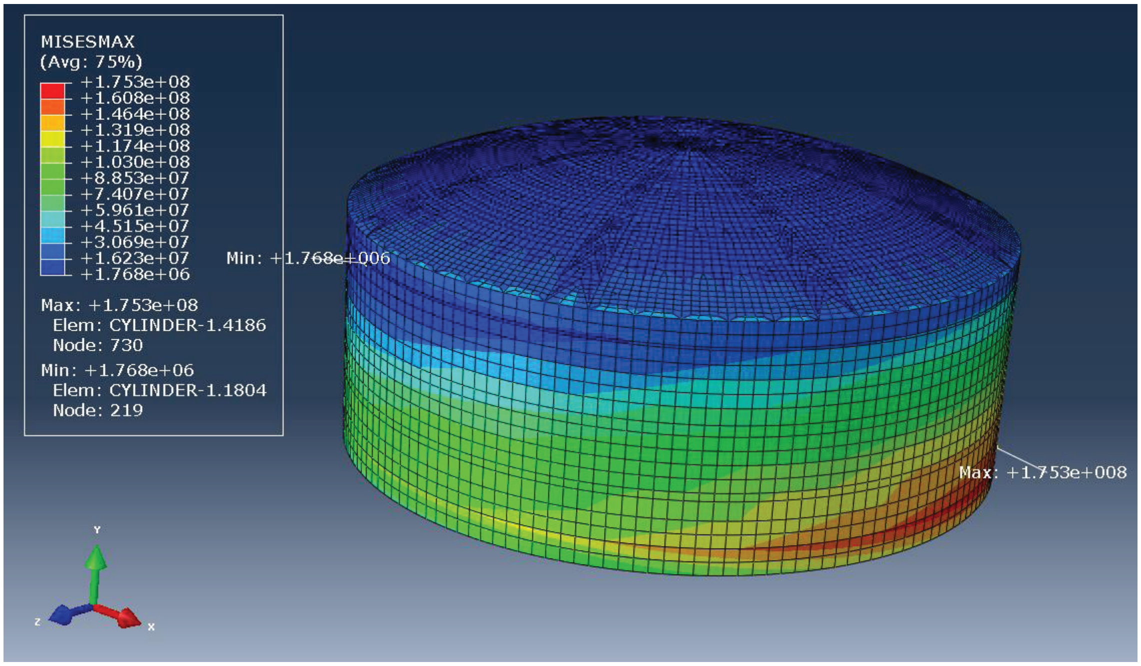

FIGURE 14. Extreme distribution of von Mises stress for the tank under non-uniform El Centro earthquake (case "E") – t=2.19 s (max value: 175.30 MPa)

CONCLUDING REMARKS

A numerical investigation concerning the dynamic behaviour of cylindrical steel tank under seismic excitation has been conducted and described in this paper. The effects of fluid-structure interaction for fully filled structure, as well as the influence of the non-uniform ground motion excitation have been taken into account in the study. The created numerical model of real structure has been analysed using the FEM.

The results of the numerical analyses show that that dynamic seismic behaviour of the analysed tank is considerably different for uniform and non-uniform excitations. They indicate that consideration of spatial seismic effects, due to the seismic wave propagation, leads to the significant decrease in the structural response. Moreover, the analysis has shown that the application of the stochastic simulation with the spatiotemporal correlation function is an effective method of generation unknown earthquake records in different locations so as to consider the non-uniform ground motion excitation.

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