# Numerical Modelling of Cylindrical Fluid Filled Tank

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*Abstract:* - The demand for drinking and service water storage is rising with changing climate conditions and increasing life expectancy. The tanks are commonly used to store large volumes of liquids and materials in various fields of the economy. This paper presents the model of the numerical simulation for the steel tank filled with fluid, using the finite element method. The results of the tank filled with water are presented, by the results: the pressure of the fluid the effective stress, and the maximum deformation of the tank solid domain. The correctness of the pressure values was verified by the simple calculation of the fluid pressure. Finally, the paper documents the results for various fluid fillings with a considered range of fluid densities. The influence of the fluid filling height on the behavior of the solid domain of the fluid filling container loaded by the static loading as well as the effect of the width of the tank on the behavior of the solid domain of the fluid filling container.

*Key-Words:* - Fluid, tank, FEM, static, analysis, density.

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## 1 Introduction

As climate patterns shift and life expectancy increases, the need for storing drinking and service water is on the rise. Tanks serve as vital reservoirs for large quantities of liquids and materials across various sectors of the economy. However, categorizing them can pose challenges due to their diverse shapes, intended uses, and construction materials, [1].

The cylindrical tanks present advantages in terms of the pressure and tension stress management on their exteriors, as well as the material efficiency, [2], [3]. Yet, their construction demands intricate formwork, [4], [5].

The Solving of the problem of the reservoir filled with liquid also includes a wide range of problems, [6], [7], [8], [9], [10], [11], such as:

- the interaction of the fluid filling with the solid domain of the reservoir,
- the interaction of the solid domain of the reservoir with the foundation,
- the interaction of the fluid-filled reservoir and the foundation situated on the real subsoil.

From the point of view of the solutions, there are different levels of the solutions available, ranging from analytical problem-solving to the numerical simulations, [12], [13], [14], [15].

The finite element method (FEM) is used to solve a wide range of problems, [16], FEM is being developed and constantly improved thanks to the development of high-performance computing techniques, [17], [18], [19], [20].

Today, FEM is the most widely used calculation tool in many branches of engineering and science, also used for solving, [21], [22], [23].

## 2 Problem Formulation

The finite element method (FEM) is the powerful numerical approach used to solve the complex problems in the engineering and the applied sciences, [24].

FEM has gained wide application in practice due to its versatility in solving a large number of problems, from simple structures to complex systems, [25], [26]. Its applications include various fields including structural mechanics, fluid dynamics, heat transfer, and electromagnetic fields, [27].

The essence of FEM is that it divides complex systems, and structure domain, into smaller components known as finite elements, [28], [29], [30]. These elements are interconnected at designated points referred to as nodes, as shown in Figure 1. Each finite element is described by a system of equations. These equations are then combined into a set of descriptive equations that describe the behavior of the analyzed system, [31] as a whole.

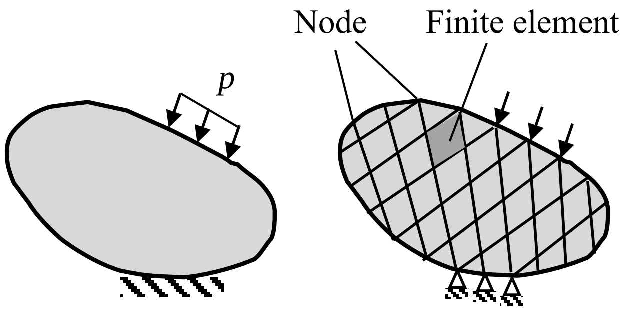



Fig. 1: Solution of structure using FEM, a) schematic representation of the structure domain, b) (a) the division of the structure domain into smaller parts - finite elements

When solving the fluid-structure interaction problems, the FEM offers two principal methodologies: the Eulerian and the Lagrangian approaches, [32].

Within the Eulerian framework, the fluid's behavior is delineated in terms of a pressure potential, as elucidated in literature, [33]. This approach allows for the expression of the fluid behavior through analytical functions tailored to the specific geometries or via finite element models where the nodal pressures serve as the primary unknowns. Throughout the solution process of the fluid-structure system, the interaction effects are enforced through iterative techniques, [34].

Conversely, the Lagrangian approach characterizes the fluid behavior acting on the structures, expressing it in terms of the displacements at the finite element nodes. Consequently, the equilibrium and the compatibility conditions are inherently satisfied along the fluid-structure interface, [35]. In this paradigm, the fluid element is typically conceptualized as the elastic solid element possessing the nominal shear modulus and the volumetric elasticity modulus equivalent to the fluid's bulk modulus, [36].

The advantage of the Lagrangian approach, compared to the Eulerian approach, is that the Lagrangian approach can be easily incorporated into the general-purpose structural analysis programs for the solution of the fluid-solid element considered since there obviates the necessity for the specialized interface equations in the Lagrangian approach.

The potential-based fluid elements, used for the meshing of the fluid domain, incorporate the following assumptions:

- inviscid, irrotational medium with no heat transfer,
- compressible or almost incompressible medium,
- relatively small displacements,
- actual fluid flow with velocities below the speed of sound (subsonic formulation) or no actual fluid flow (linear formulation).

The potential-based fluid elements can be coupled with the structural elements by the fluid-structure interface elements. The fluid-structure interface elements apply the structural motions to the potential-based fluid elements and apply the potential-based fluid element pressures to the structure. The 3-D fluid element can either be the displacement-based fluid elements or the potential-based fluid elements. However, in practice, the use of displacement-based elements is rather restricted to special applications in static and dynamic analyses. The potential-based element is much more general and is usually the recommended element to use.

# 3 FEM Model of the Cylindrical Fluid Filled Tank

The cylindrical water tank is considered and subjected to the gravity loading (Figure 2). The dimensions are

- the inner radius $R = 15$ m,
- the wall height $H = 25$ m,
- the wall thickness is 50 mm,
- the thickness of the bottom is 500 mm.

The steel tank material has properties

- Young's modulus $E = 2.07 \cdot 10^{11}$ N/m$^2$,
- Poisson number $\nu = 0.3$,
- the density $\rho_s = 7800$ kg/m$^3$.

The fluid filling is

- water,
- the height filling $H_f$ is 20 m,
- the water density $\rho_w$ = 1000 kg/m$^3$,
- the water bulk modulus κ = 2.1 N/m$^2$.

The presented model encapsulates one common comprehensive model that includes both domains, i.e. the solid domain and the fluid domain. At the beginning of the numerical simulation, the solid domain of the fluid-filled tank was created, in which the cylindrical contours of the tank were defined, the mesh for the tank solid domain was created, and the physical and material characteristics of the solid domain were defined. Once the solid model was created, the focus turned to modelling the liquid fill, its shape, and its physical and material characteristics.

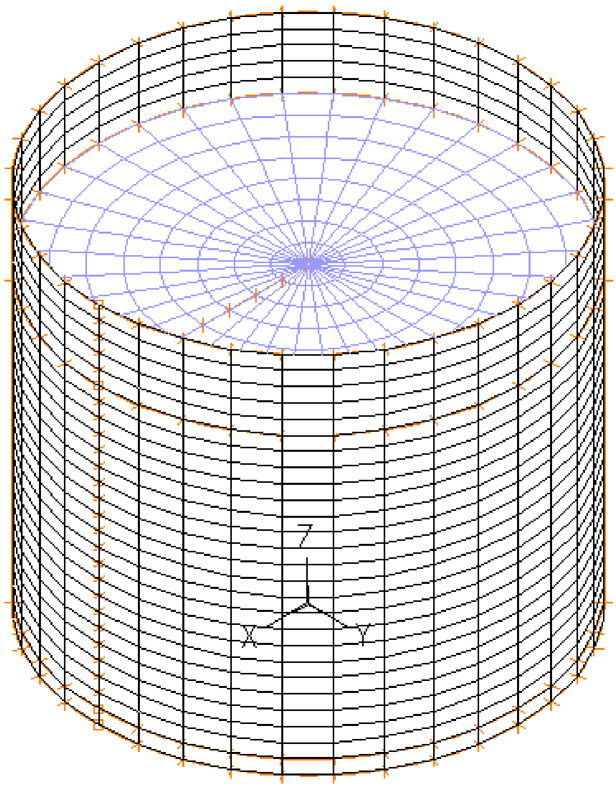



Fig. 2: Computational model of the cylindrical filled fluid-filled tank

Due to the coexistence of these domains within the model, the differentiated approach was necessary. Specifically, the fluid modeling methodology required avoiding overlapping nodes between domains. As a result, the fluid domain was created slightly smaller than its solid counterpart, ensuring an accurate 1 mm distance between their respective nodes. The dimensions of the fluid domain were therefore carefully calibrated to reflect this deliberate reduction.

The 4-node shell element was used for meshing the solid domain of the tank. Integration through Shell thickness was used Gauss approach.

The 8-node brick Linear Potential-Based fluid element was used for meshing of the fluid domain.

Whereas the cylindrical tank boasts a radius of 15 meters, the fluid fill radius was intricately adjusted to 14.999 m, maintaining the requisite gap. Similarly, meticulous consideration was given to the vertical dimension, necessitating the modeling of a 1 mm clearance between the solid tank domain and the fluid fill domain. Hence, the height of the fluid domain was precisely given at 19.999 m.

Following the delineation of the fluid fill's shape, the meshing of its domain was executed, complemented by the comprehensive specification of the fluid's physical and material attributes. Through this rigorous approach, the model achieves a holistic representation, meticulously capturing the dynamic interplay between the solid structure and the fluid contents it houses.

A numerical simulation, considered the static solution, was executed on the specified tank model, with its cavity filled with fluid, under the assumption of the tank resting upon the rigid solid foundation.

The pressure exerted by the water filling upon the tank's solid domain has been documented and graphically depicted in Figure 3. Notably, the highest pressure manifests at the base of the fluid domain, peaking at 195,823 Pa.

In an effort to validate these findings, a thorough verification of the calculations was undertaken. Utilizing the formula $p = \rho g H_f$, where $\rho$ represents the density of the fluid, $g$ denotes the gravitational acceleration, and $H_f$ signifies the height of the fluid column, the pressure was recalculated. Employing a fluid density of 1000 kg/m$^3$ and the gravitational acceleration of 9.81 m/s$^2$, the analytical given pressure yields 196,190 Pa. This recalculated pressure aligns closely with the originally documented value, reaffirming the robustness and accuracy of the numerical simulation results. Consequently, these findings serve to verification of the model and its utility in analyzing the structural behavior of the tank under varying conditions.

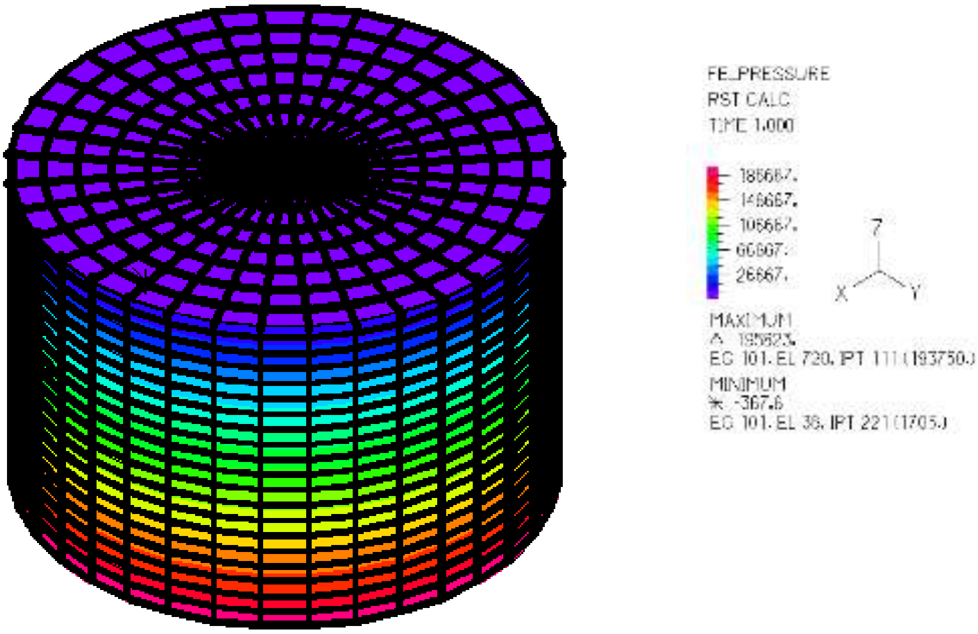



Fig. 3: The pressure of the fluid domain

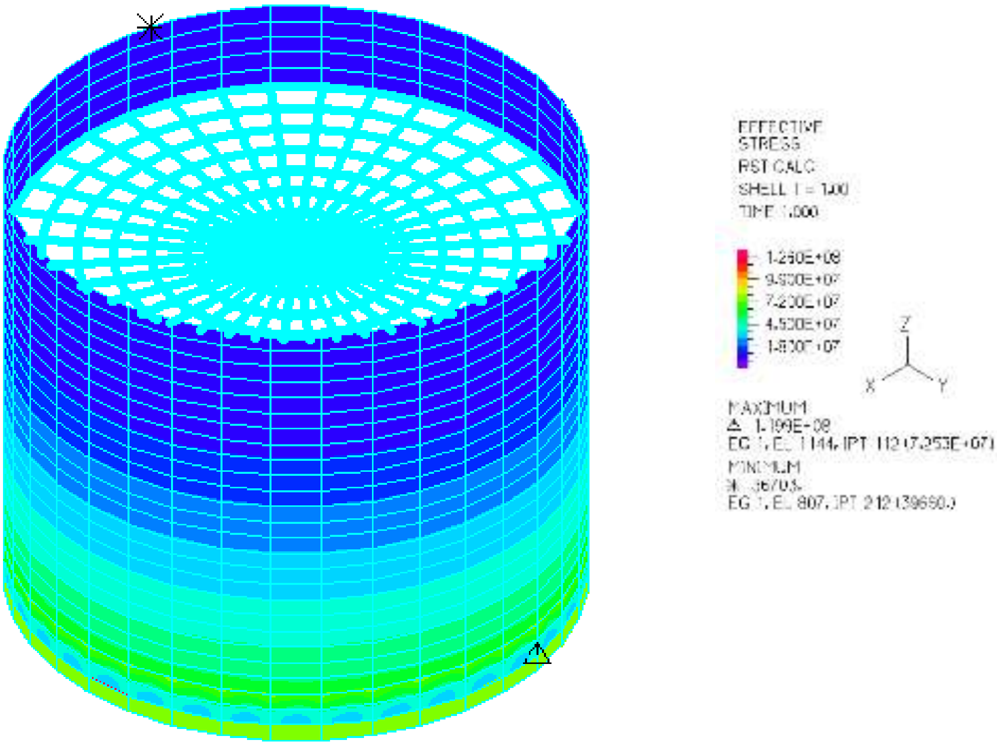
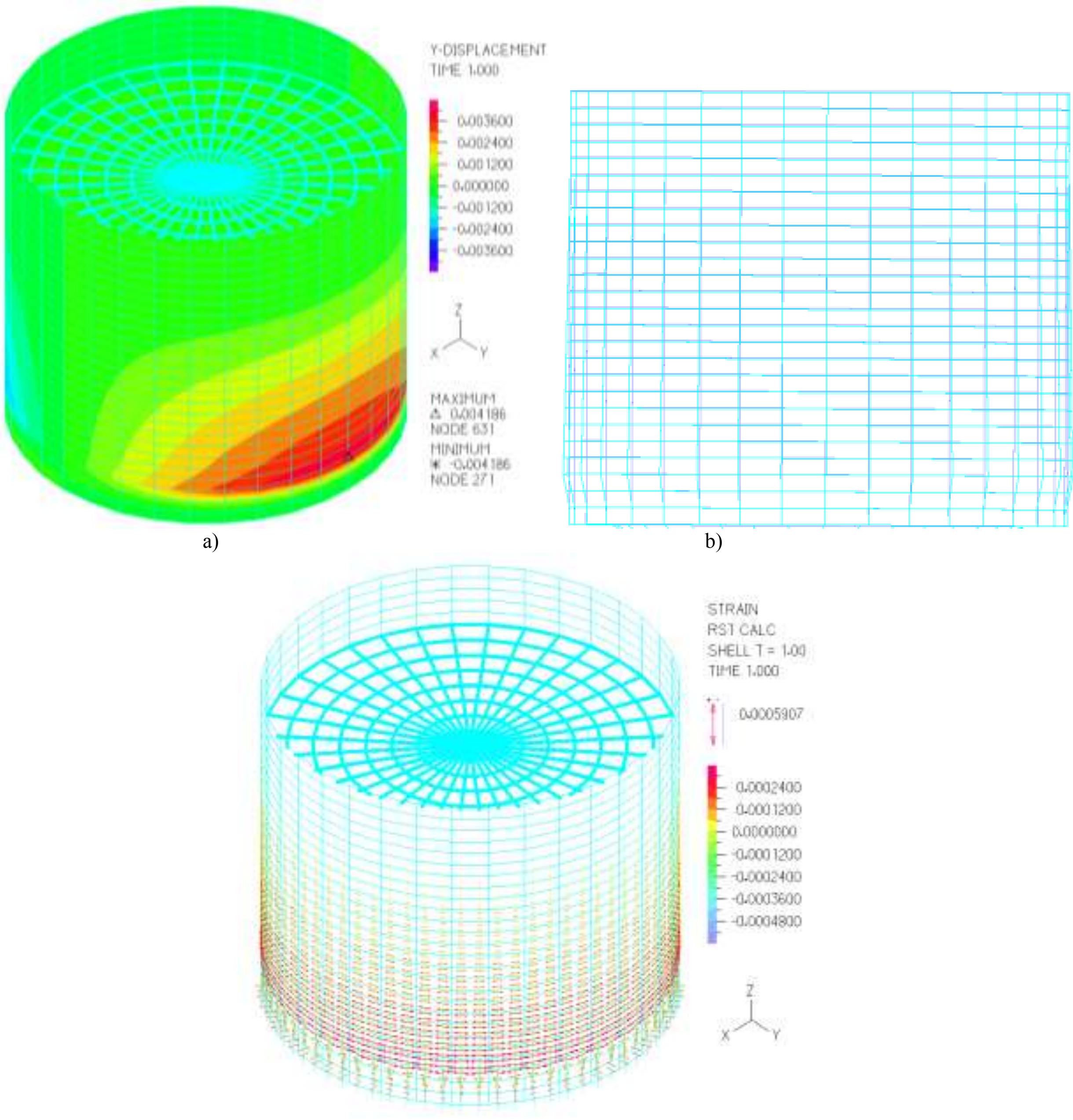



Fig. 4: The effective stress of the tank solid domain




c)

Fig. 5: The results of behavior tank solid domain, a) the maximum deformation in the direction of axis y, b) the meshing of the deformed and undeformed solid domain of the tank, c) the strain of the tank solid domain

The effective stress of the tank solid domain by the numerical simulation in the software Adina, is documented in Figure 4. The maximum value of the effective stress of the tank solid domain pressure is in the bottom of the tank domain and its value is $1.199 \cdot 10^8$ Pa.

The behavior of the solid domain of analyzed solid domain of the fluid-filled container, loaded by gravity loading, the maximum deformation, the shape of the container, and the strain shown in Figure 5, Figure 5a) the maximum deformation in the direction of axis y, Figure 5b) the state of meshing of the original nonloaded solid domain of container and the deformed solid domain of the cylindrical water-filled tank subjected to the gravity loading, and the Figure 5c) the strain of the tank solid domain.

### 3.1 The Effect of the Fluid Filling Density

The density of fluid is given by values in the range of 600 - 1600 kg/m$^3$. The numerical simulation was performed for the consideration of the fluid filling with the densities 600 kg/m$^3$, 800 kg/m$^3$, 1000 kg/m$^3$, 1200 kg/m$^3$, and 1400 kg/m$^3$.

The cylindrical filled fluid-filled tank is considered, and subjected to gravity loading with the dimensions:

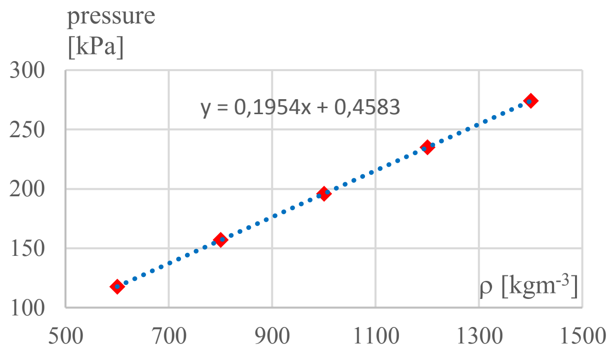
- the inner radius $R = 15$ m,
- the wall height $H = 25$ m,
- the wall thickness is 50 mm,
- the thickness of the bottom is 500 mm.

The steel tank material has properties:

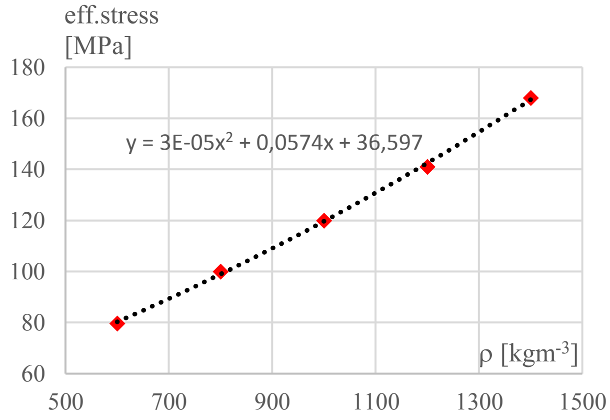
- Young's modulus $E = 2.07{\cdot}10^{11}$ N/m$^2$,
- Poisson number $\nu = 0.3$,
- The density $\rho_s = 7800$ kg/m$^3$.

Figure 6 documented the results of the behavior of the numerical simulation of the fluid-filled container for the considered range of the fluid densities. Figure 6a) documents the maximum pressure of the fluid domain for the considered densities of the fluid filling, and the trend line is linear. The resulting maximum effective stress of the tank solid domain for the considered densities of the fluid filling is presented in Figure 6b). The trend line of the resulting maximum effective stress of the tank solid domain is given by the polynomial function of the second degree. Figure 6c) shows the maximum deformation of the tank solid domain depending on the fluid filling density.

Figure 7 and Figure 8 are documented of the selected results processed in graphs in Figure 6. The effective stress of the tank solid domain for the stored fluid filling of the density 600 kg/m$^3$ is documented in Figure 7a) and for the stored fluid filling of the density 1400 kg/m$^3$ in Figure 7b). The maximum deformation of the tank solid domain for the stored fluid filling of the density 600 kg/m$^3$ in the direction of the axis y is documented in Figure 8a) and for the stored fluid filling of the density 1200 kg/m$^3$ in the direction of the axis y in Figure 8b). The maximum deformation of the tank solid domain for the stored fluid filling of the selected density in the direction of axis x gives the same value of the maximum deformation as in the direction of the axis y. Along the circumference at the same height, the horizontal deformations are the same at the same height.




a)

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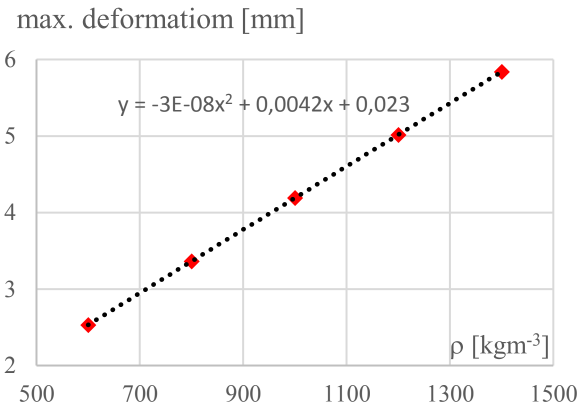



c)

Fig. 6: The results of numerical solution depending on fluid filling density, a) The resulting maximum pressure of the fluid domain, b) the effective stress of the tank solid domain, c) the maximum deformation of the tank solid domain

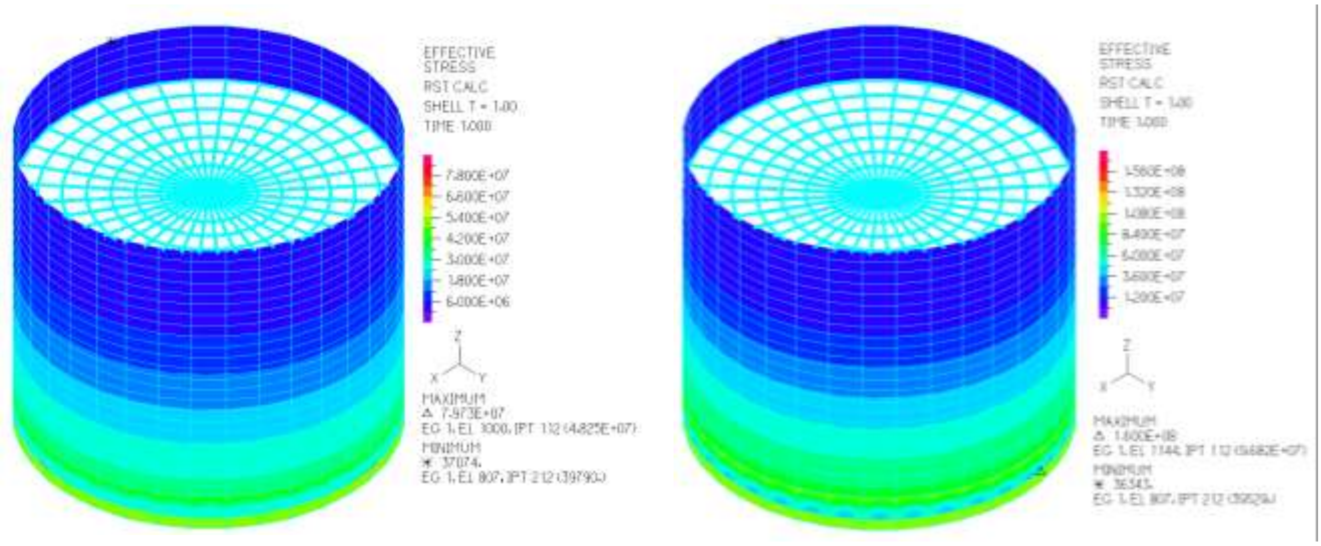



Fig. 7: The effective stress of the tank solid domain for the fluid filling density, a) 600 kg/m$^3$, b) 1400 kg/m$^3$

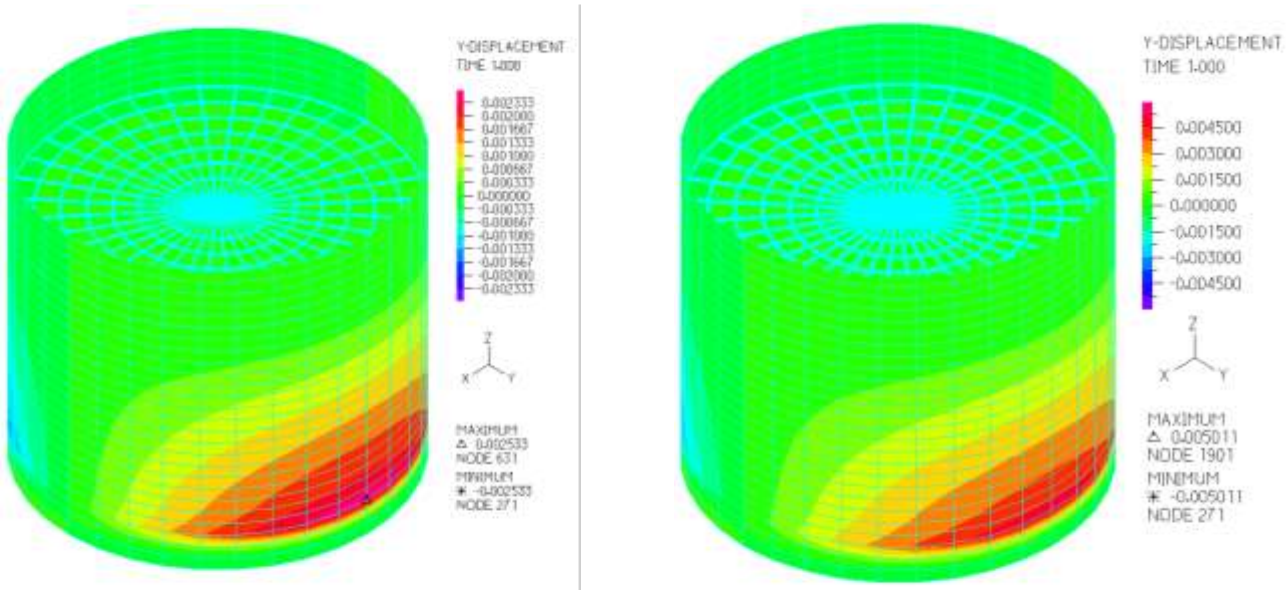



Fig. 8: The maximum deformation of the tank solid domain, a) for the fluid filling density 600 kg/m$^3$, b) for the fluid filling density 1200 kg/m$^3$

## 3.2 The Effect of the Fluid Filling Height

In the next part of the numerical experiments, the influence of the height of the liquid filling on the behavior of the solid domain of the fluid filling container loaded by the static loading was monitored. The fluid filling with the height $H_f$ of 5 m, 10 m, 15 m, and 20 m was analyzed.

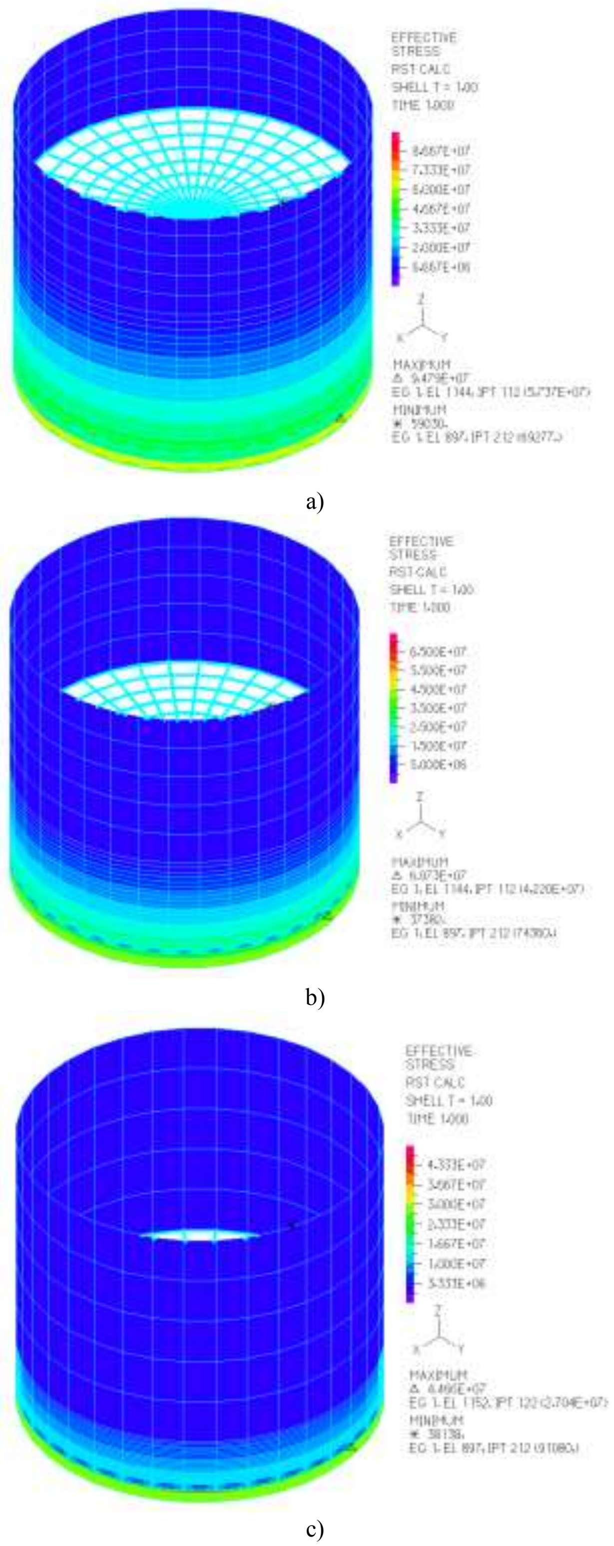



Fig. 9: The results of the effective stress of the tank solid domain, a) for the height of the fluid filling 15 m, b) for the height of the fluid filling 10 m, c) for the height of the fluid filling 5 m

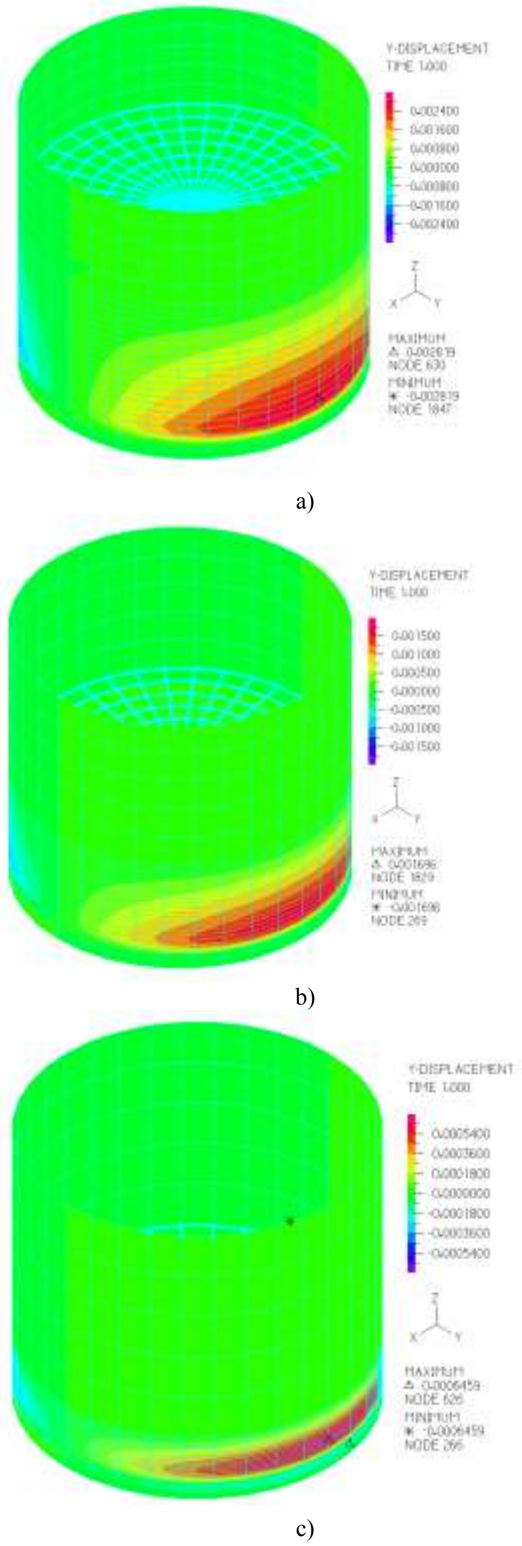



Fig. 10: The results of the maximum deformation of the tank solid domain, a) for the height of the fluid filling 15 m, b) for the height of the fluid filling 10 m, c) for the height of the fluid filling 5 m

The cylindrical water tank is considered, and subjected to gravity loading with the dimensions

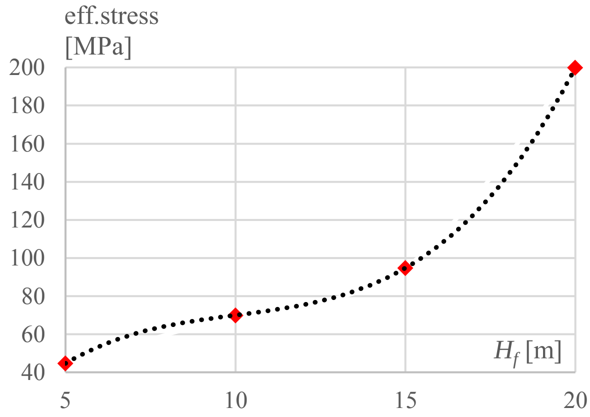
- the inner radius $R$ = 15 m,
- the wall height $H$ = 25 m,
- the wall thickness is 50 mm,
- the thickness of the bottom is 500 mm.

The steel tank material has properties:

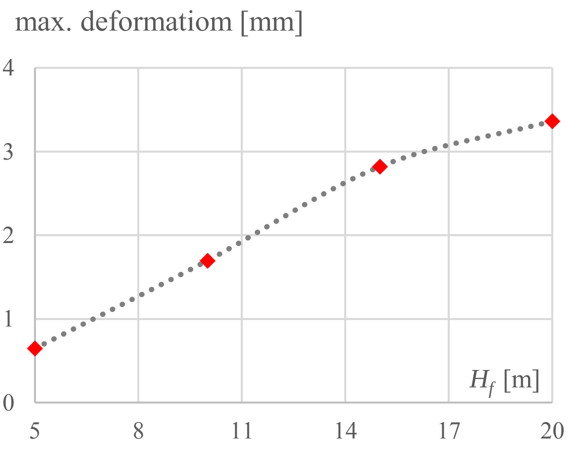
- Young's modulus $E = 2.07{\cdot}10^{11}$ N/m$^2$,
- Poisson number $\nu = 0.3$,
- The density $\rho_s$ = 7800 kg/m$^3$.

The fluid filling is:

- water,
- the water density is $\rho_w$ = 1000 kg/m$^3$,
- the water bulk modulus $\kappa$ = 2.1 N/m$^2$.




a)




b)

Fig. 11: The behavior of the solid domain of the fluid filling container loaded by the static loading depending on the fluid filling height, a) the effective stress of the tank solid domain, b) the maximum deformation of the tank solid domain

The results of the effective stress of the tank solid domain for the height of fluid filling 15 m, 10 m, and for the height of fluid filling 5 m are presented in Figure 9, Figure 9a) for the height of the fluid filling 15 m, Figure 9b) for the height of the fluid filling 10 m, Figure 9c) for the height of the fluid filling 5 m, Figure 4 for the fluid filling with the height of 20 m.

Figure 10 shows the results of the maximum deformation of the tank solid domain for the height of fluid filling 15 m, 10 m, and 5 m, Figure 10a) for the height of the fluid filling 15 m, Figure 10b) for the height of the fluid filling 10 m, Figure 10c) for the height of the fluid filling 5 m. The maximum deformation of the tank solid domain for the fluid filling with a height of 20 m is presented in Figure 5a.

The behavior of the solid domain of the fluid filling container loaded by the static loading depending on the fluid filling height is summarized in Figure 11. The results of the effective stress of the tank solid domain depending on the height of the fluid filling is presented in Figure 11a), and the results of the maximum deformation of the tank solid domain in depending on the height of the fluid filling is in Figure 11b).

### 3.3 The Effect of the Fluid Filling Width

In the last part of the numerical experiments, the influence of the width on the behavior of the solid domain of the fluid filling container loaded by the static loading was monitored. The width of the reservoir with the diameter $D$ is 10 m, 20 m, and 30 m for 20 m fluid filling were analysed.

The cylindrical water tank is considered, and subjected to gravity loading with the dimensions

- the wall height $H$ = 25 m,
- the wall thickness is 50 mm,
- the thickness of the bottom is 500 mm.

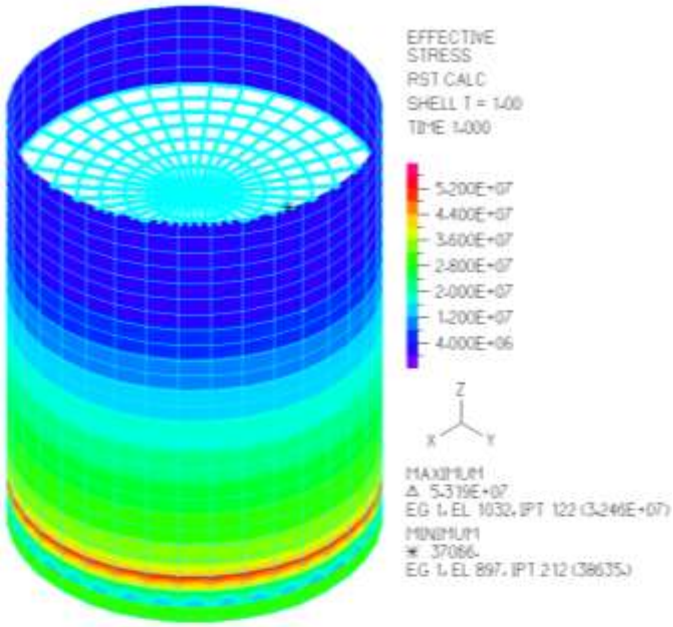
The steel tank material has properties

- Young's modulus $E = 2.07{\cdot}10^{11}$ N/m$^2$,
- Poisson number $\nu = 0.3$,
- The density $\rho_s$ = 7800 kg/m$^3$.

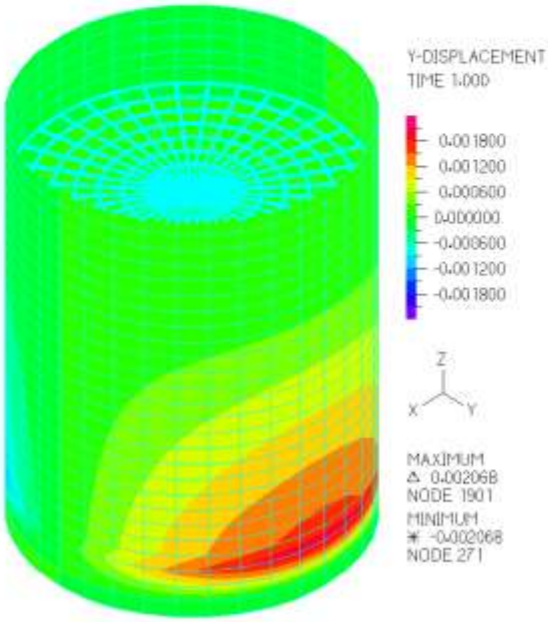
The fluid filling is

- water,
- the height filling $H_f$ is 20 m,
- the water density is $\rho_w$ = 1000 kg/m$^3$,
- the water bulk modulus $\kappa$ = 2.1 N/m$^2$.

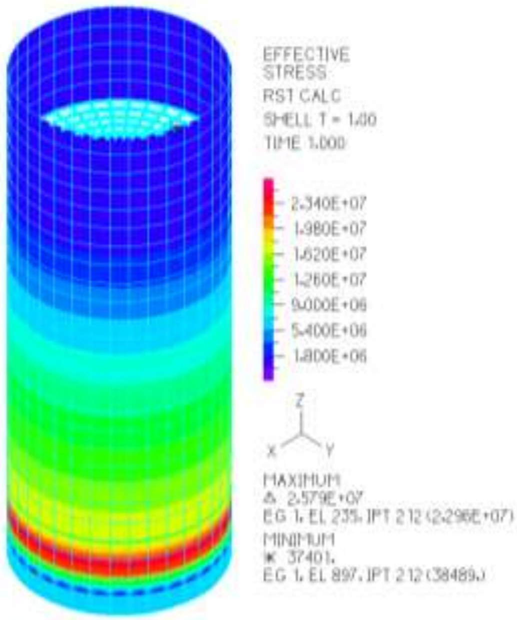
The results of the effective stress of the tank solid domain for the tank diameters 10 m, and 20 m are presented in Figure 12, and for the tank diameter 30 m in Figure 4. The results of the maximum deformation of the tank solid domain for the tank diameter 10 m, 20 m are presented in Figure 13 and for the tank diameter 30 m in Figure 5a).




a)




a)

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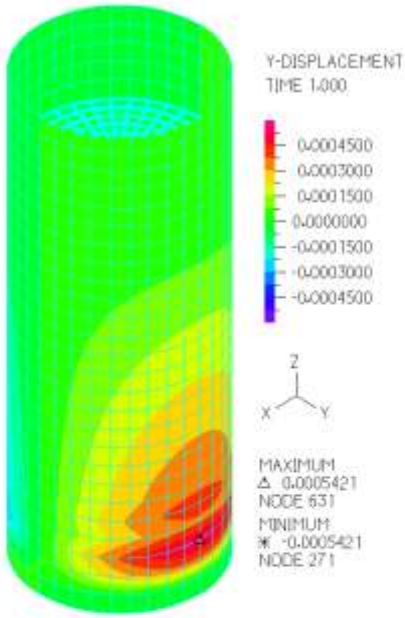
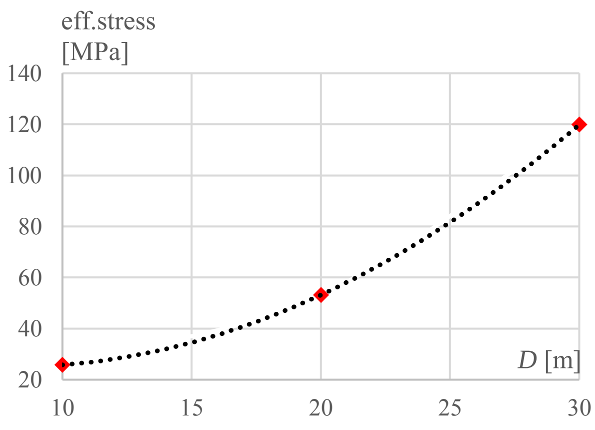


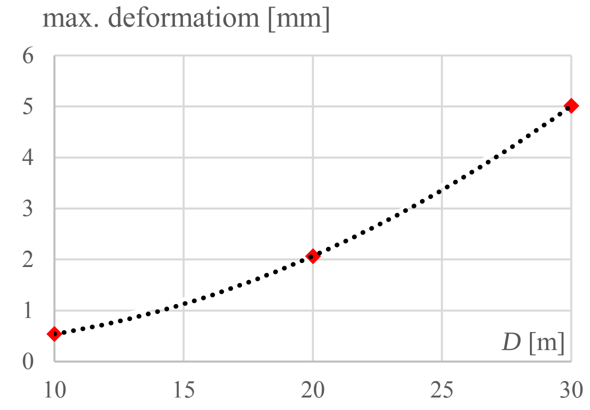

b)

Fig. 12: The results of the effective stress of the tank solid domain, a) for the tank diameter of 20 m, b) for the tank diameter of 10 m

Fig. 13: The results of the maximum deformation of the tank solid domain, a) for the tank diameter of 20 m, b) for the tank diameter of 10 m




a)




b)

Fig. 14: The behavior of the solid domain of the fluid filling container loaded by the static loading depending on the width of the tank, a) the effective stress of the tank solid domain, b) the maximum deformation of the tank solid domain

The behavior of the solid domain of the fluid filling container loaded by the static loading depending on the fluid filling width is summarized in Figure 14. The results of the effective stress of the tank solid domain depending on the diameter of the tank is documented in Figure 14a), and the results of the maximum deformation of the tank solid domain in depending on the diameter of the tank is documented in Figure 14b).

## 4 Conclusion

This paper presents the possibilities of modeling of the steel tank filled with fluid, using numerical simulation by the finite element method. The results of the tank filled with the liquid are presented by the pressure of the fluid filling domain the effective stress and the maximum deformation of the tank solid domain. The correctness of the pressure value was verified by the simple analytical calculation of the fluid pressure. Finally, the paper documents the results for various fluid fillings with different values of the density, considering range of the fluid densities. The influence of the fluid filling height on the behavior of the solid domain of the fluid filling container loaded by the static loading as well as the effect of the width of the tank on the behavior of the solid domain of the fluid filling container.

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- Kamila Kotrasova carried out the supervision, simulation, organization, and writing – review & editing.
- Petr Frantik has participated in conceptualization, writing – original draft, visualization, and validation.
- Eva Kormanikova has executed for methodology, investigation, formal analysis, and funding.

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**Conflict of Interest**

The authors have no conflict of interest to declare.