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Research Article

Stress-Strain State of a Metro Vestibule Under Impact Loading, Considering the Depth of the Structural Arrangement

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Abstract: The paper analyses the structure of a metro vestibule and considers the possibility of impact loading affecting it. Three-dimensional finite element models were developed to research changes in the stress-strain state of the metro vestibule. The models reflect the complex structure of the vestibule, including the excavation support as a "slurry wall" and the depth of the structural arrangement. The developed models simulate three depths of the structural arrangement (1.8 m; 3.6 m; 7.2 m). A numerical analysis of the models was performed to estimate the impact loading applied as a quasi-static effect. The patterns of changes in the stress-strain state of the metro vestibule, considering the depth of the structural arrangement, were obtained. A reinforced-concrete slab is proposed as the reinforcement structure for the vestibule. A numerical analysis of the reinforcement structure for impact loading was performed.

Keywords: metro vestibule, numerical analysis, stress-strain state, impact loading, reinforcement structure

I. INTRODUCTION

The vestibule is an underground structure that connects the metro station to the surface [1]. The primary purpose of the metro vestibule is to gather passengers, including those with limited mobility, as they descend into the station and to form controlled flows from them [2-3]. For shallow metro lines (10 to 15 meters), there are two options for tunnel placement. If the metro station is situated at a depth of 1.5 to 2.5 meters, it makes sense to build an above-ground or semi-underground vestibule. This type of structure collects potential passengers from the day surface and brings them to the platform via escalator and/or stairs. Alternatively, the vestibule can be built underground, which is typical when the metro line depth exceeds 2.5 meters, often reaching 7.0 meters or more [4-5]. This option typically involves using several flights of stairs or, more commonly, escalators to allow passengers to descend to the platform.

The vestibule structure is a three-span two-storey frame with two rows of columns (**Fig. 1**) [5]. The columns are supported by a double-cantilever span, on which the ribbed slabs of the upper floor of the middle and extreme spans are supported. The slabs of the extreme spans are supported on the other side by wall blocks. The distance between the axes of the columns in the cross-section of the vestibule is 5.0 m (4.5 m between the faces of the columns with a cross-section of 0.5×0.5 m).

The minimum height of the stair flight from the station platform, considering the floor thickness, is 3.1 m. A machine room is located beneath the vestibule floor, with its dimensions determined based on the size of the escalator setups.

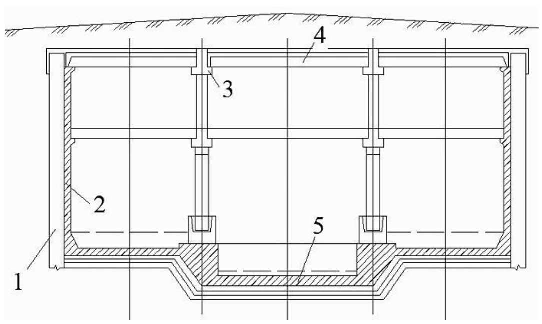


Figure 1. *Design of an underground vestibule of a shallow-depth station: 1 – "a slurry wall"; 2 – a load-bearing wall with a crossbar for fastening the floor; 3 – span for fastening the floor; 4 – floor; 5 – trough part made of monolithic concrete*

The load complex acting on the metro vestibule structure includes: 1) the effect of backfilling, which depends on the embedment depth; 2) the self-weight of the structure; 3) hydrostatic pressure from groundwater; 4) a distributed load from passengers. Therefore, the load complex consists of both permanent (loads 1)-3)) and temporary (load 4)) impacts [5-6]. However, as an emergency load scenario, one extreme load is added to the existing impacts, representing an emergency situation, such as an earthquake (seismic activity) [7-8], impulsive loading (short-term effect of the explosion) [9-11], or impact one from falling objects [12]. Based on the probabilities of extreme influence, only one loading is selected for the load complex.

It should be noted that in different countries the formation of a load complex taking into account extreme influence is not the same. If in Ukraine, as has already been analyzed, this complex of loads is recommended, then in other countries specific extreme influences are highlighted, which are defined as the most important. For example, in France, the seismic effect is recognized as not as important as the effect of free vibrations on the tunnel [13]. At the same time, impact or explosion loads are currently considered as additional and not very likely, but this situation may change for objective reasons. In India and, in particular, in Delhi, the mandatory extreme influence is the seismic impact [14], while, given the geological conditions of most megacities, the dynamic effect of the metro train is considered to a lesser extent. In China, on the contrary, the influence of geological conditions and the presence of complex underground infrastructure (twin tunnels, tunnel intersections at different levels, the influence of metro lines under construction on already built tunnels, etc.) dictates the addition of extreme influences of dynamic loads with a small impulse [15]. In this case, an analytical approach and numerical analysis are used.

The calculation of underground metro facilities is effectively performed during numerical analysis using the finite element method [9-12, 15]. Numerical analysis, implemented based on calculation complexes, allows for obtaining and analyzing any stress and displacement components [16-18]. Simultaneously, creating finite element models of underground objects, which are quite complex structurally, considering their features. For example, during the construction of vestibules or shallow stations, “slurry wall” support is most often used in excavation pits. The use of such excavation support technology entails a change in the design of the underground object, which includes not only fastening elements but also powerful reinforced concrete “slurry walls”. Consequently, the structure of the metro vestibule is located inside the reinforced concrete enclosure and deforms quite differently than without a “slurry wall”. Considering such design features allows for the creation of a more accurate finite element model reflecting the real structure [12].

Numerical analysis based on the finite element method also allows for the consideration of additional structural features that are not related to the underground structure itself but are elements of its protection against impact loading. The metro system, in general, is considered a very vulnerable transportation system, although it is identified as an important part of passive protection. Accordingly, the more protected the metro facilities (vestibules, underpasses and corridors, shallow stations, etc.), the greater the protection of the overall metro system. The protection system of the metro vestibule is its embedment depth and additional fastening, which reduce the influence of impact loading.

Therefore, the scientific research aims to determine the stress-strain state of the metro vestibule under impact loading conditions. Additionally, the task will be addressed by varying two parameters: the impact loading magnitude and the embedment depth of the metro vestibule. This approach will enable us to assess the stress-strain state by changing the initial conditions and to develop dependencies of stresses and displacements on these parameters.

The scientific novelty of the research is brought to the specific new regularities of the stress-strain state from the embedment depth. Such dependencies do not allow to assess the impact of the loading at a fixed embedment depth. Also, such dependencies prevent damage to the inverse task, namely the application at a fixed value of the impulse of the embedment depth of the metro vestibule. At what value of the stress-strain state does this design begin for the first time.

II. METHODS

The defined problem is difficult to fully solve in a planar formulation because the structure of the metro vestibule consists of repeating elements (columns). If we use a planar formulation for the calculation, the spatial factor that results from the vestibule's connectivity in the longitudinal direction (columns connected by spans) will be lost [8, 12, 16-18]. Even calculating two-dimensional models (at the column location and the span location) does not solve the problem, as the deformation of the span connecting the sections modeled by these models is lost.

Accordingly, the problem of determining the stress-strain state of the metro vestibule under impact loading is solved using a spatial formulation (**Fig. 2**).

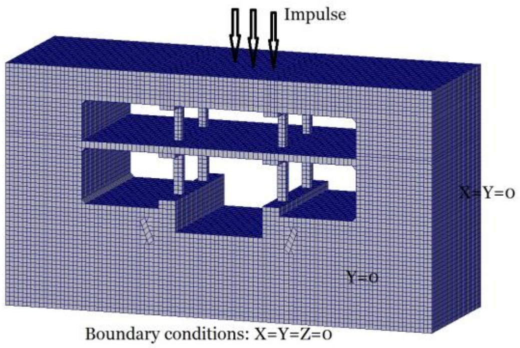


Figure 2. *The finite element model of the metro vestibule with the embedment depth of 1.8 m*

A finite element model has been developed that allows for sufficiently quick changes in loading parameters and embedment depth.

Important in creating the model is that it reflects the repeating section of the vestibule, namely two halves of the span part, two rows of columns that have a distance equal to the length of the span (4.5 m) (**Fig. 3**).

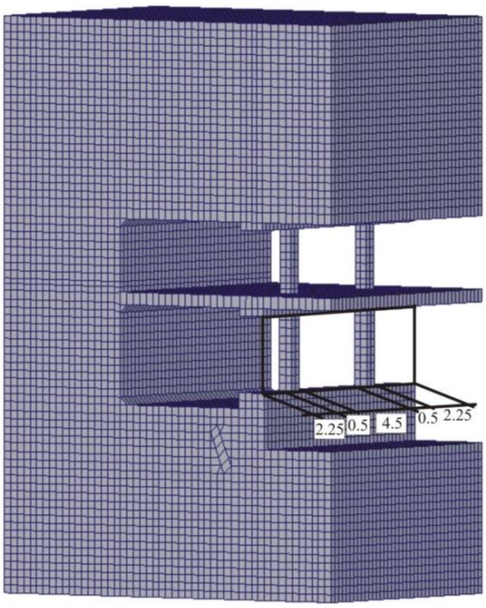


Figure 3. *The fragment of the model with the embedment depth of 7.2 m (a fragmented half of the model)*

After creating the geometry of the model, the following complex of boundary conditions was applied to it (**Fig. 2**): 1) the daylight surface is free from restrictions on deformation; 2) the side faces of the model are restricted along the horizontal (axe X) and longitudinal (axe Y) axes (movement along the vertical axis (axe Z) is allowed); 3) the end faces of the model are restricted exclusively along the longitudinal axis (plane strain condition, which takes into account the repeatability of the geometry of the metro vestibule reflected in the model); 4) the lower surface is restricted along all three axes (the further analysis of the vertical component of the deformed state indicates that the restriction along the vertical axis does not constrain the corresponding displacements, allowing them to deform freely).

Choosing this specific part of the metro vestibule with the complex boundary conditions imposed on it, which will be described below, allows us to account for the spatial factor and correctly apply the impact loading to the free surface of the finite element model. It should also be noted that the model simulates the enclosure ("slurry wall") of the excavation pit in which the vestibule was constructed. This required implementing somewhat increased dimensions of the entire model, which allowed the stress-strain state to develop without constraints. For the variation of the embedment depth, a model with a backfill thickness of 7.2 m was initially created (**Fig. 4**), which was reduced to 3.6 m in the second model by removing finite elements, and to 1.8 m in the third.

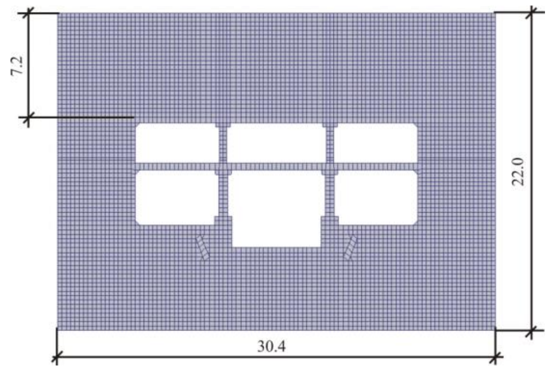


Figure 4. *Front view of the finite element model with the embedment depth of 7.2 m*

The StructureCAD for Windows (SCAD) computational complex allows you to create finite-element models of large dimensionality (more than 200 thousand finite elements).That is why the three created models of the metro vestibule with different embedment depth reflected the real structure on a scale of 1:1. This methodological step made it possible not to introduce additional hypotheses during the numerical analysis and analysis of the results obtained.

The main dimensions of the metro vestibule structure and concrete preparation are shown in **Fig. 5**.

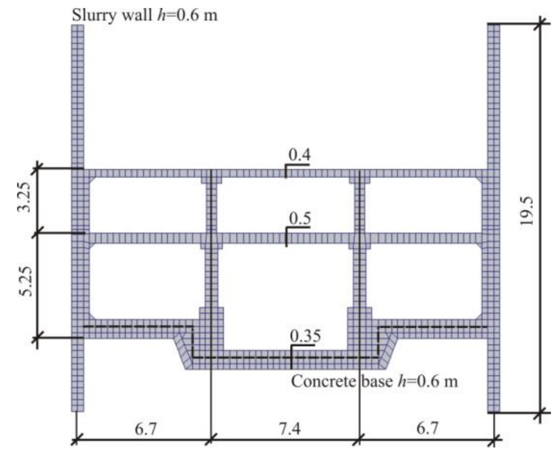


Figure 5. *Fragment of a finite-element model (vestibule structure)*

The modeled structure of the metro vestibule does not change in all three researched models. But, since the embedment depth of this structure is different, the number of nodes and finite elements in the models changes accordingly: with the embedment depth of 7.2 m – 250 384 nodes, 231 024 finite elements; with the embedment depth of 3.6 m – 200 692 nodes, 183 024 finite elements; with the embedment depth of 1.8 m – 175 846 nodes, 159 024 finite elements. The dimensions of the finite elements vary from 0.25×0.25×0.25 m to 0.25×0.3×0.3 m.

Most of the finite elements are rectangular prisms (the number of tetrahedral finite elements is no more than 3 … 7 % of the total number of elements). The number of finite elements characterizes the task as a large-scale task, and their size indicates that it provides sufficient accuracy for calculating the finite element model with overall dimensions (for the embedment depth of 7.2 m) of 30.4 m (width)×22.0 m (height)×10.0 m (longitudinal dimension).

The finite element model is given the deformation characteristics presented in **Table 1**.

In order to take into account the parameters of the impact loading, an integral characteristic should be applied, which is the impulse $I=mV$. The falling object is taken as a material point m, that is, from a certain height H (m), a point with mass m falls on the surface and bounces off it to a height h. The velocity of the point when hitting the surface is denoted V_1, when bouncing off the surface by V_2, with $V_1 > V_2$ (**Fig. 6**).

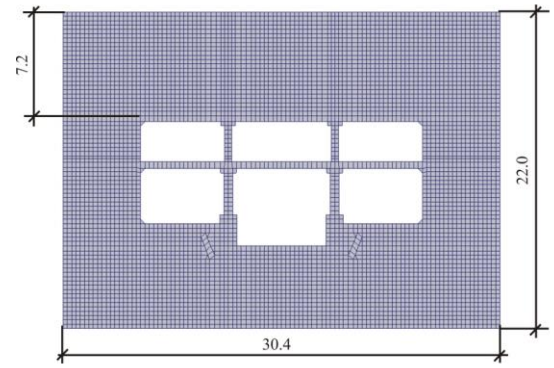


Figure 6. *Scheme for determining the coefficient of renewal in a direct impact*

The ratio of velocities $k=V_1/V_2$ is called the coefficient of renewal upon impact. To solve the problem in this research, we adopt an impact without renewal (k=0). Three values of impulse are adopted: 1) I_1=2000 kg·m/s; 2) I_2=500 kg·m/s and 3) I_3=125 kg·m/s. The impulse is applied quasi-statically in the form of a system of forces to the upper face of the finite element models to 30 nodes located on an area of 1.5 m^2 and located on the vertical projection between two rows of columns. After the final creation of the three finite element models, they were calculated using the finite element method.

III. RESULTS AND ITS ANALYSIS

After the calculation, the components of the stress-strain state were analyzed. Within the framework of this article, the components that are maximal and allow us to conclude the strength and stability of the structure of the vestibule under impact loading are subjected to more detailed analysis. Such components in the case of the deformed state are vertical displacements (mm), and for the stress state, they are vertical normal stresses (MPa). The following are characteristic patterns of the distribution of these displacements and stresses for the third model with the embedment depth of 1.8 m, and for clarity and understanding of their formation, a fragment of the model is presented, namely the vestibule structure without the surrounding soil and the enclosing “slurry wall” structure (**Fig. 7**).

Table 1. *Deformation and weight characteristics of a model*

Material name	***Modulus of elasticity E, MPa***	***Poisson's ratio μ***	***Specific weight γ, kN/m³***
Loam	30	0.3	18.5
Foundation concrete and “slurry wall”	$3.0 \cdot 10^3$	0.2	24.0
Reinforced concrete structures	$3.6 \cdot 10^3$	0.2	24.5

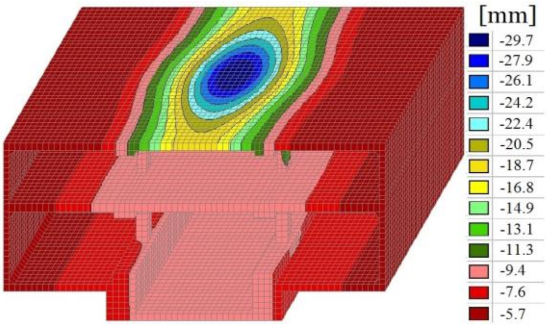


Figure 7. *Distribution of vertical displacements (mm) in a model fragment (the vestibule structure) at an impulse value of I_1=2000 kg·m/s*

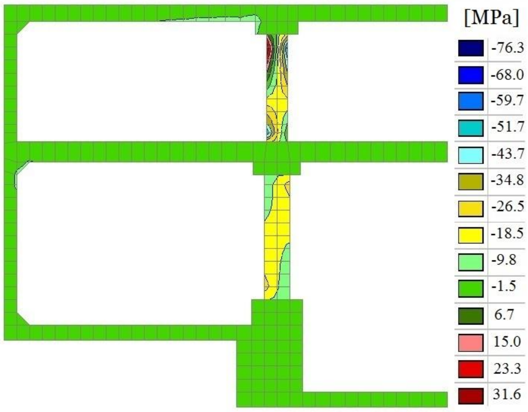


Figure 8. *Distribution of vertical normal stresses (MPa) in a model fragment (half of the vestibule structure) at an impulse value of I_1=2000 kg·m/s*

A qualitative analysis of the distribution of displacements and normal stresses of the vertical component indicates that for all three models, the formation of the stress-strain state is similar, but the values of the components change. Characteristic is the elliptical field of maximum vertical displacements (**Fig. 7**) on the floor of the vestibule's middle hall, as well as significant stress concentrations in the columns (**Fig. 8**) of the upper hall. This distribution indicates a rather local nature of the impact loading action during the formation of the stress-strain state in the case of impact effect. Figures 6 and 7 show data on the most dangerous case of impact loading (maximum impulse value is I_1=2000 kg·m/s and the minimum embedding depth of 1.8 m). The maximum vertical slab displacement of the vestibule in the center of the impact loading is 29.8 mm, which allows us to conclude a significant deflection, which will lead to crack formation and possible local failure. The analysis of the maximum vertical normal stresses in the columns of the upper hall indicates that their values are in the range of 26.5 to 76.3 MPa. Such values are greater than the design strength of concrete C25/30, which is 21.0 MPa by 1.26 to 3.63 times, indicating the destruction of the columns of the upper hall and, accordingly, local damage in this part of the vestibule. We accept this model with this loading as a reference in a negative sense, that is, as a model that collapses under the action of maximum impact loading.

In order not to present all the distributions of displacements and normal stresses of the vertical component, their values are analyzed and presented in the form of diagrams (**Fig. 9**).

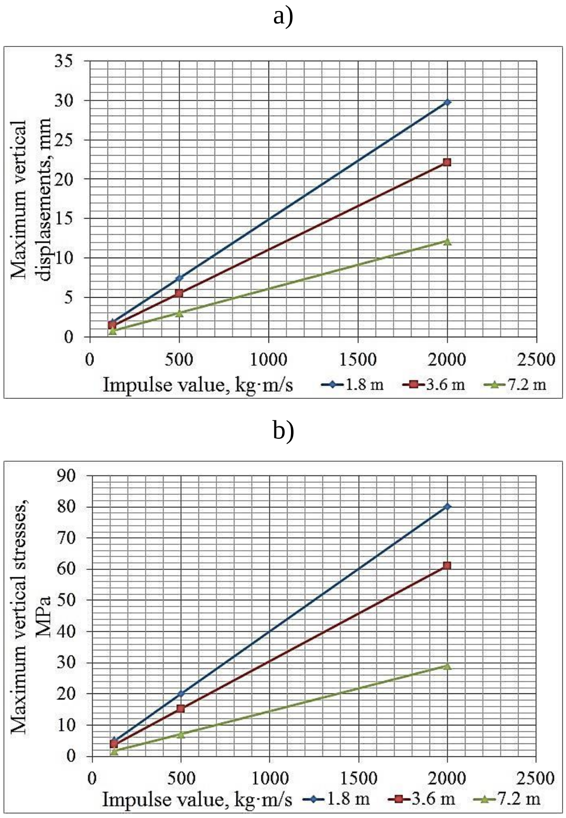


Figure 9. *Graphs of the dependencies of maximum vertical displacements (a) and maximum vertical normal stresses (b) on the impulse value*

The analysis of the obtained dependencies proves that they are linear with a high degree of approximation for each embedment depth. An unambiguous conclusion after analyzing the dependence of the maximum vertical normal stresses on the impulse value (**Fig. 9, b**) is that for the researched embedment depths, the strength of the columns is not satisfactory, that is, an impulse with a value of I_1=2000 kg·m/s is critical for the strength of the vestibule structure with any embedment depth.

For the model with the embedment depth of 7.2 m, the maximum impulse at which the maximum vertical stress occurs in the columns with a value of 21.0 MPa (design strength of concrete C25/30) is I=1400 … 1500 kg·m/s. At such an impulse value, floor displacement of 8 … 9 mm occurs in this model, which is a normal value of the deformed state. For the model with the embedment depth of 3.6 m, the maximum impulse at which the maximum vertical stress occurs in the columns with a value of 21.0 MPa (design strength of concrete C25/30) is *I*=700 … 720 kg·m/s. At such an impulse value, floor displacement of 7 … 8 mm occurs in this model, which is also a normal value of the deformed state. For the model with the embedment depth of 1.8 m, the maximum impulse at which the maximum vertical stress occurs in the columns with a value of 21.0 MPa (design strength of concrete C25/30) is *I*=500 … 510 kg·m/s. At such an impulse value, floor displacement of 6 … 7.5 mm occurs in this model, which is also a normal value of the deformed state. Accordingly, with vertical floor displacement of 6 … 9 mm, increasing the embedment depth allows to withstand an impulse increased by 1.5 to 2.0 times.

To protect the structure of the metro vestibule in the case of impact loading, a reinforcement structure is used, which is called a reinforced concrete or concrete mattress. Such a reinforcement structure is a slab that is located at a certain depth and is made of concrete or reinforced concrete. For the research in this article, a reinforced concrete mattress with a thickness of 0.3 m, located at a depth of 0.3 m, is adopted (no rigid connection between “slurry walls” and concrete mattress is introduced in the model) (**Fig. 10**).

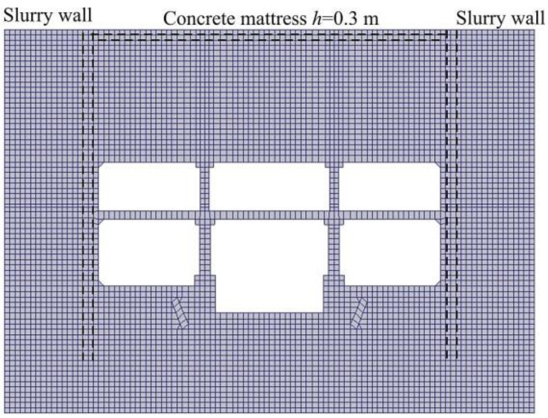


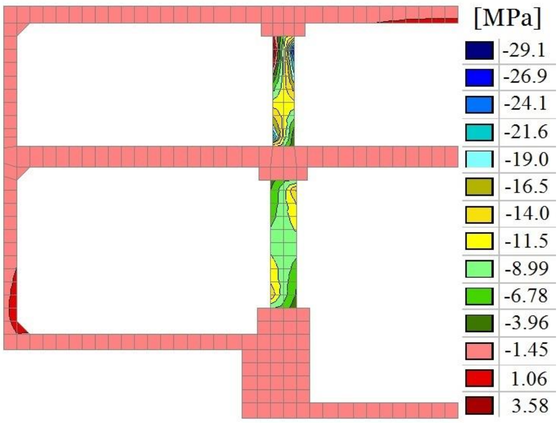
Figure 10. *Front view of the finite element model with the embedment depth of 7.2 m and the “slurry walls” and reinforced concrete mattress marked with a dashed line*

The obtained results of the stress state indicate that even in the model with a reinforced concrete mattress, the impulse with a value of I_1=2000 kg·m/s is critical for the strength of the vestibule structure (**Fig. 11**).

The reduction of maximum vertical displacements in the model with a such reinforcement structure is not significant (approximately 1 … 2 mm).

Maximum vertical normal stresses have decreased by 4 to 5 MPa (from 29.1 MPa to 24.4 MPa), but still exceed 21.0 MPa (design strength of concrete C25/30).

a)



b)

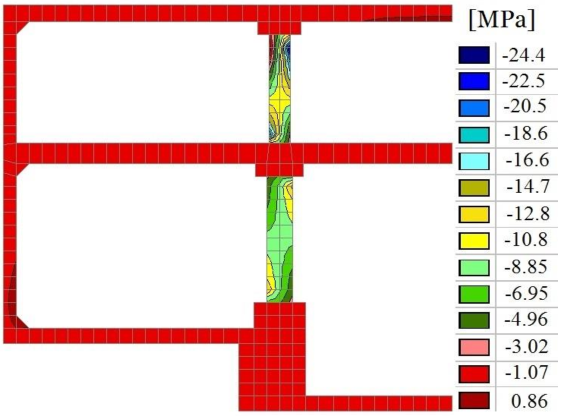


Figure 11. *Distribution of vertical normal stresses (MPa) in a model fragment (half of the vestibule structure) without a reinforced concrete mattress (a) and with it (b) at an impulse value of* I_1*=2000 kg·m/s*

IV. Conclusions

Three three-dimensional finite element models of the metro vestibule were created to research the change in the stress-strain state, taking into account the depth of the structure (1.8 m; 3.6 m; 7.2 m). The models take into account the excavation pit support in the form of a “slurry wall”, the location of the structure in depth, and the impact loading, which is applied quasi-statically in the form of an impulse with a value of 2000; 500; 125 kg·m/s.

The patterns of changes in the stress-strain state of the metro vestibule, taking into account the depth of the structure, were obtained, which, with a high degree of approximation, are linear for each depth of embedment. Analysis of the dependence of maximum vertical normal stresses on the value of the impulse proves that the impulse with a value of I=2000 kg·m/s is critical for the strength of the vestibule structure with any depth of embedment.

It was found that for a model with an embedment depth of 7.2 m, the maximum impulse at which the maximum vertical stress with a value of 21.0 MPa (design strength of concrete C25/30) occurs in the columns is I=1400 … 1500 kg·m/s, and increasing the embedment depth allows to perceive an impulse increased by 1.5 to 2.0 times.

The reinforcement structure of the vestibule in the form of a reinforced concrete mattress with a thickness of 0.3 m was proposed. A numerical analysis for the reinforcement structure under impact loading shows that the use of the reinforcement structure in the form of a reinforced concrete mattress is effective within the impulse value of I=1600 … 1800 kg·m/s. It can also be argued that increasing the embedment depth is a more effective parameter for reducing maximum vertical displacements and stresses than the use of the reinforcement structure.

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Author Contributions

O. Tiutkin: Conceptualization, Supervision, Writing, Review and editing.

O. Dubinchyk: Writing, Theoretical analysis, Review and editing.

S. Bielikova: Finite element modelling, Writing.

Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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