Theoretical and experimental studies of seismic resistance of underground passages

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Abstract. In this article theoretical calculations of the construction of the underground passages under the influence of seismic forces are conducted and refined by a series of experiments. As a result of experimental studies, the authors have clarified the value of the active pressure of the ground on the construction and the active seismic inertial forces, taking into account the design. As a result of theoretical and experimental studies of seismic resistance of underground pedestrian crossings at different ground, areas of stress concentration in these constructions have been determined, which allows these sections to provide anti-seismic beams, which ensures the safety of the constructions to an earthquake or significantly reduce the degree of damage.

1. Introduction

The construction of the underground passage is made of assembled reinforced concrete elements and works on compression (figure 1). It allows to reduce reinforcement and wall thickness, because expansion forces in the arch are compensated by mutual ties and active ground pressure. The ground around the structure is further compacted, that increases the dynamic rigidity of the structure, and this increases its stability to seismic forces.

For the determination the more dangerous sections of underground pedestrian crossings we use the dynamic theory of seismic resistance [1-3].

2. Calculation and discussion

During of an earthquake the vibrations of an underground passage system, consisting of a vault, side walls and a floor, connected with each other, described by a system of partial differential equations [4,5]:

\[
B \frac{\partial^2 u}{\partial x^2} - m \frac{\partial^2 u}{\partial t^2} - L_p \tau_x = 0,
\]

where B is longitudinal rigidity of the construction, \(u\) is longitudinal displacement, \(m\) is unite mass of the structure length, \(\tau_x\) is specific force of interaction between structure and ground on its unit length, \(L_p\) is perimeter of the structure.

The force on the section \(n\) can be determined through relative deformations:
\[ P_n = E \left( f_n + u_n / L_c \right) \] (2)

where \( E \) is modulus of elasticity of the material of the construction, \( F \) is the cross-sectional square of the construction, \( L_c \) is the width of the underground passage.

\[ u_n = k_x \left( u - u_0 \right) \left[ 1 - w(u - u_0) \right], \] (3)

where \( k_x \) is compliance factor, \( w \) is plasticity function.

\[ \tau_n = L_p k_L u_0 (x, t) - u_n (x, t), \] (4)

\[ \tau_{n-1} = L_p k_L u_0 (x_n, t) - u_{n-1} (x_n, t) \] (5)

From (4) and (5) one can obtain the following equation systems:

\[ \int_{0}^{0.5} dx_n = \left( L_p k_L L_c / 8 \right) \left[ 3 \left( u_{on} - u_n \right) + \left( u_{on+1} - u_{n+1} \right) \right] \] (6)

\[ \int_{0}^{0.5} dx_n = \left( L_p k_L L_c / 8 \right) \left[ 3 \left( u_{on} - u_n \right) + \left( u_{on-1} + u_{n+1} \right) \right] \]

\[ mL_n / 2u_n + \left( 2EI / L_c + 3L_p k_L L_c / 4 \right) u_n = \left( L_p k_L L_c / 8 - EI / L_c \right) (u_n - u_{n-1}) = L_p k_L u_{on+1} \] (7)

where \( u_{on} = u_n (x_n, t) \) at \( x_n = 0 \), \( u_{on}^k \) is the second derivative of absolute displacements \( n \) of the construction site, \( u_{on}^k \) is the second derivative of the ground movement of the section construction under seismic action.

The solution of the system (6) in relative coordinates gives an estimate of the influence of the length of the site of the structure on the stress-strain state of the structure [6-8].

let's accept ground model around the construction as elastic-visco-plastic, so that

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Let’s accept ground model around the construction as elastic-visco-plastic, so that

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\[ \int_{0}^{0.5} dx_n = \left( L_p k_L L_c / 8 \right) \left[ 3 \left( u_{on} - u_n \right) + \left( u_{on-1} + u_{n+1} \right) \right] \]

\[ mL_n / 2u_n + \left( 2EI / L_c + 3L_p k_L L_c / 4 \right) u_n = \left( L_p k_L L_c / 8 - EI / L_c \right) (u_n - u_{n-1}) = L_p k_L u_{on+1} \]

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where \( u_{on} = u_n (x_n, t) \) at \( x_n = 0 \), \( u_{on}^k \) is the second derivative of absolute displacements \( n \) of the construction site, \( u_{on}^k \) is the second derivative of the ground movement of the section construction under seismic action.

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Figure 1. The construction of an underground passage: \( f_a = 0.04L \), \( f_k = 0.003L \), \( f_p = 0.002L \).
The graphs of displacement and change of stresses in various sections of the construction, obtained for clay and sandy loamy soils, are shown in Figure 2, 4 with the velocity of the seismic wave propagation for the clay with \( u_p = 350\ \text{m/c} \) and sandy loam with \( u_p = 1500\ \text{m/c} \).

The relative displacement of the structure is as follows -

\[
u_n' = \frac{u_n}{A}
\]

where \( A \) is amplitude of ground vibration during an earthquake.

From the graphs in Figure 2, 3 it can be determined, that the greatest strains from seismic action arise both from theoretical and experimental calculations at \( n = (5 \div 7) \). The average value of \( n = 6\ \text{m} \), i.e. every 6 meters, there is a maximum strain in the construction turn up and in these sections it is necessary to build anti-seismic joints, recommended in [9-12].

**Figure 2.** Changing in the construction’s stress versus the compliance factor \( k_x \). 1 is for ground - clay a solid line is after theoretical calculations, 2 is for ground - sandy loam, intermittent line is after the experimental results.

**Figure 3.** Change in strain in the construction on number is after \( n \) from the initial point. 1 is for ground - clay, 2 is for ground - sandy loam, solid line is after theoretical calculations, intermittent line is after the experimental results.
In the construction of an underground pedestrian passage proposed, all spacer forces are partially damped by mutual impact, because they represent a single structure that works on compression forces, which avoid bending deformations and allows to reduce the thickness of the construction and the reinforcement percentage. In this case the logarithmic decrement of oscillations $\delta$ increases by 22%, i.e. the resistance of the construction to seismic forces increases [13-17].

In our experimental researches the value of the active ground pressure on the structure $E_{ak}$ and the active seismic inertial forces $S_{ak}$ are adjusted and the following expressions have been obtained:

$$E_{ak} = E_a \cdot a \cdot k, \quad S_{ak} = S_a \cdot a \cdot k$$

(8)

where $E_a$ is the active pressure of the ground on the retaining wall, $a$ is factor taking into account the arch curvature of the structure with $a = 0.7$, $k$ is coefficient that takes into account the construction of the floor with $\kappa = 0.85$, $S_a$ is seismic loads on the structure determined by known SNiP KR 2002 – 2009 formulas [18,19,20].

3. Conclusion
In the result of our theoretical and experimental studies of earthquake resistance of underground pedestrian passages with various grounds strain concentration sections in these constructions have been determined, that allows to foresee setting up the anti-seismic joints in these sections, which ensures the preservation of the constructions safety during an earthquake or significantly diminish the degree of their damage.

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Acknowledgments
The work was supported by Act 211 Government of the Russian Federation, contract No. 02.A03.21.0011.