Designing linings of mutually influencing parallel shallow circular tunnels under seismic effects of earthquake

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Abstract. The paper deals with seismic design of parallel shallow tunnel linings, which is based on identifying the most unfavorable lining stress states under the effects of long longitudinal and shear seismic waves propagating through the cross section of the tunnel in different directions and combinations. For this purpose, the sum and difference of normal tangential stresses on lining internal outline caused by waves of different types are investigated on the extreme relative to the angle of incidence. The method allows analytic plotting of a curve illustrating structure stresses. The paper gives an example of design calculation.

1. Introduction
The challenges in seismic design of tunnel linings are due to the fact that during earthquakes different types of seismic waves are propagating: compressive-tensile (longitudinal) and shear (transverse) waves. These waves propagate with different velocities and due to numerous refractions and reflections (from both free-field surface and the boundary between rocks with different mechanical properties), they may affect tunnel linings in different combinations and directions. Therefore, designing an underground structure upon the action of only one wave type, longitudinal or shear wave of the specified direction, is a priori inefficient. An original approach to seismic design of underground constructions was developed at Tula State University [1, 2, 7]: according to this approach, the design consists in determining the most unfavorable lining stress states for each standard section under the effect of different seismic waves propagating through the cross section of the structure in different directions and combinations. This approach was applied to design a number of large underground constructions in seismic areas and is prescribed by the effective regulations [2].

The aim of the paper is presenting a new analytical design method for parallel mutually influencing shallow tunnel linings constructed in seismic regions.

2. The design method
Currently, there are several analytical methods of deep underground construction design, which are developed on the basis of the above-mentioned approach. The methods are as follows: multi-layer linings of circular tunnels and vertical shafts; cast-in-place linings with arbitrary cross section shape, which are designed for closed-loop tunnels, including those with the application of grouting; shotcrete linings, including those in combination with anchors; multi-layer linings of mutually influencing parallel circular tunnels of different radii and centered with respect to the right line, with the optimal distances between them being determined. All these method of underground tunnel design upon
Seismic effects are realized by means of a computer program and specified in technical guidelines [3, 4].

The method proposed is based on the new analytical solutions of the two plane quasi-static problems of the elasticity theory for a semi-infinite linearly deformable medium simulating the rock (soil) mass weakened by a number of arbitrary located circular openings of different radii supported by the rings simulating tunnel linings made of different materials. The design schemes are given in Figure 1 a, b.

The problem of compression on the infinity with respect to two axes (fig. 1 a) is solved applying the theory of complex variable analytic functions suggested by I. G. Aramanovich [5], via analytical continuation of the complex potentials characterizing the lower semi-plane beyond the openings in the upper semi-plane across the straight boundary $L^0$ (the method introduced by Kolosov-Muskhelishvili [6]), and using the apparatus complex series. It allows an original iteration process to be formed, when in every approximation of the process a closed solution for a double-layer ring supporting an opening in the extended plane is obtained. The boundary conditions include additional terms reflecting the straight boundary of the semi-plane, which are represented in Laurent series with unknown coefficients specified on the basis of previous iterations.

The problem of pure shear on the infinity (fig. 1 b) is solved as a particular case of the previous one, where $P = S, \xi = -1$, with the angle $\alpha + \pi/4$ instead of $\alpha$. Based on the first problem solution, the $\sigma^{(P)}$ stresses are obtained (hereinafter the $\sigma$ symbol signifies all components of the stress tensor), which are caused in the linings by a long longitudinal wave falling under an arbitrary angle $\alpha$. Based on the second problem solution, the $\sigma^{(S)}$ stresses attributed to the long shear wave propagating at the angle $\alpha$ are obtained.

Then the sum and the difference of general expressions for $\sigma^{(P)}_{\theta}$ and $\sigma^{(S)}_{\theta}$ normal tangential stresses characterizing the lining stress state due to the mutual action of simultaneously passing longitudinal and shear waves (the worst case) are investigated in every point of the internal lining cross-section outline on the extreme relative to the $\alpha$ angle of incidence. With this aim, the following equations are solved:

$$\frac{\partial}{\partial \alpha} \left[ \sigma^{(P)}_{\theta} \pm \sigma^{(S)}_{\theta} \right] = 0 \quad (1)$$
and for every point such a combination of longitudinal and shear waves and such an angle of their falling are determined at which normal tangential stresses in the given point are maximal by their absolute. This allows analytical construction of a curve showing normal tangential stresses on the internal outline \( L_{i,j} \) of each \( j \)-lining \( (j = 1, 2, \ldots, N) \). As for the stresses on the external lining outline, the longitudinal forces \( N \) and bending moments \( M \) in every lining radial section are determined at such a combination and such a direction of waves at which the normal tangential stresses \( \sigma_{\theta} \) on the internal lining outline in the given section have a maximum absolute value. The obtained stresses and forces are assumed to have signs “plus” and “minus” and are summed up with stresses and forces caused by other loads in their most unfavorable combinations. Then the section strength is tested upon compression and tension.

In case the lining is not anchored to the ground and designed with an allowance of crack formation, it is assumed that there are no tensile normal loads on it. Therefore, the effect of the longitudinal wave is not considered and the lining is designed on the basis of two curves of normal tangential stresses constructed using the maximal absolute values of the compressive (negative) and tensile (positive) stresses caused by mutual actions of both shear and longitudinal waves in the compression phase.

The above-described method represented as an algorithm of calculations and realized by means of the computer software allows identifying the most unfavorable stresses in every lining radial section of each lining with due regard to all plausible seismic effects. The method also makes it possible to identify the stress states caused by a long, either longitudinal or shear, wave of the specified direction.

Since the method is based on the assumption that quasi-static problem solutions are appropriate to design dynamic stresses in the shallow tunnel lining, with the length of the seismic wave being more than three times as much as the tunnel diameter, we compared the results obtained analytically from quasi-static model with those of numerical simulation of shear and longitudinal waves diffraction in a single tunnel lining via FLAC program [7]. The results comparison showed a satisfying agreement.

3. Examples of the design

Examples of the design of two identical parallel tunnels under seismic effects are given below. The input data are the following: \( H_1 = H_2 = 8 \) m; \( x_1 = 0; x_2 = 9 \) m; \( R_{0,1} = R_{0,2} = 3.0 \) m; \( R_{1,1} = R_{1,2} = 2.65 \) m; \( E_0 = 200 \) MPa; \( \nu_0 = 0.2; E_{1,1} = E_{1,2} = 23000 \) MPa; \( \nu_{1,1} = \nu_{1,2} = 0.2 \) the soil unit weight is \( \gamma = 0.017 \) MN/m\(^3\), prevailing period of a soil particles oscillations is \( T_0 = 0.5 \) s, intensity of the Earthquake is 9 point of the MSK-scale. The linings are designed with the cracks allowance.

Diagrams of maximal compressive (negative) and tensile (positive) circumferential stresses (in MPa) which may appear along internal outline of the left tunnel lining due to seismic effects (a) and corresponding stresses in external lining outline (b) are shown in Figure 2 a, b by solid and dotted lines relatively.
Figure 2. Maximal compressive and tensile stresses along the left tunnel lining internal outline (a) and corresponding them stresses on the external outline (b) (tunnels are situated at the same depth).

The same two tunnels with centers located on a vertical straight line are considered in the next example, here $y_1 = 0; y_2 = 9$ m. Diagrams of maximal compressive and tensile stresses (a) and corresponding stresses along external outline (b) are shown in 3 by solid and dotted lines relatively.

Figure 3. Maximal compressive and tensile stresses along the left tunnel lining internal outline (a) and corresponding them stresses on the external outline (b) (tunnels are situated one under another).

Another example concerns stress state computation performed for a complex of three shallow tunnels. The design scheme is shown in Figure 4.
Figure 4. Tunnel size and layout

The input data are the following: \( E_0 = 700 \text{ MPa} \); \( \nu_0 = 0.27 \); \( E_{1,1} = E_{1,2} = E_{1,3} = 23000 \text{ MPa} \); \( \nu_{1,1} = \nu_{1,2} = \nu_{1,3} = 0.2 \); \( \gamma = 0.017 \text{ MN/m}^3 \); prevailing period of a soil particles oscillations is \( T_0 = 0.5 \text{ s} \); intensity of the Earthquake is 9 point of the MSK-scale. The linings are designed with the allowance of cracks formation.

Diagrams of maximal compressive and tensile stresses \( \sigma_{\theta}^{(in)} \) are shown in Figure 5 by solid and dotted lines correspondingly.

Figure 5. Distribution of maximal stresses \( \sigma_{\theta}^{(in)} \) (in MPa) on the lining cross-section internal outline

Speaking of limitations, the above-described analytical method cannot be used to study Earth surface dynamics and currently the only adequate technique is numerical computer simulation, which was applied in the works [8, 9].

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