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Design of shallow tunnel linings under seismic effects of earthquakes

Calcul des blindages des tunnels froids sur l'action du treblement sismique de terre

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ABSTRACT

The paper presented describes a new analytical method of designing shallow tunnel linings of an arbitrary cross-section shape under seismic effects. According to this method the design includes determining the most unfavourable stress state which may appear in every lining normal section at any combinations and directions of long longitudinal and shear waves propagating in the plane of the tunnel cross-section. With this aim the sum and difference of general expressions for circumferential stresses on the internal lining outline obtained from new analytical solutions of corresponding quasi-static problems of the elasticity theory simulating the actions of long arbitrary directed longitudinal and shear waves are investigated on the extreme relatively to the angle of the waves falling. It allows the envelope diagrams of normal tangential stresses on the internal lining outline to be obtained analytically.

RÉSUMÉ

L'article décrit une méthode analytique nouvelle du calcul des blindages des sections certains des tunnels froids sur l'action sismique. La méthode en question consiste dans détermination d'état de contrainte le plus défavorable dans chaque section normale des blindages due à n'importe quelle combinaison et direction des ondes longues longitudinales et transversales qui se rependent dans la section transversale du tunnel. Dans ce but la somme et la différence des contraintes circonférentielles agissant sur le contour intérieure de la section transversale du blindage et due à l'action des ondes longitudinales et transversales de n'importe quelle direction sont examinées en extrémum selon l'angle d'incidence des ondes.

1 INTRODUCTION

At the design and construction of tunnels in seismic areas it is necessary to take into account that these structures besides usual static loads may be subjected to the Earthquakes effects consisting in a spreading of long longitudinal (compressive-tensile) and shear seismic waves in the rock (soil) mass, the combinations and directions of which respectively to the tunnel are unknown in advance. That is why the original approach to the problem of designing tunnel linings under Earthquake effects has been proposed (Fotieva, 1980). According to that approach the design includes determining the most unfavourable stress state which may appear in every lining normal section at any combinations and directions of long longitudinal and shear waves propagating in the plane of the tunnel cross-section. On that basis using different design schemes the analytical methods and corresponding computer programs for the design of linings of deep underground structures including tunnels of an arbitrary cross-section shape constructed with the application of grouting (Fotieva et al., 1998; Fotieva & Bulychev, 1999), sprayed concrete tunnel linings (Fotieva & Bulychev, 1996), multi-layered circular tunnel linings (Bulychev, 1994), linings with layers of a variable thickness (Fotieva & Sammal, 2000), linings of parallel circular tunnels (Fotieva & Kozlov, 1992) under seismic effects have been developed. The above approach and the basic principles of designing deep tunnel linings under seismic effects have been included in the Russian standards (Instruction, 1982; Guide, 1996) and widely applied in projects of transport and power-stations tunnels in seismic areas (Fotieva, 1999). Further similar methods have been created for the design of shallow circular tunnel linings (Fotieva et al., 2001) including the case of multiple parallel mutually influencing tunnels (Fotieva et al., 2003). The paper presented describes a new part of those investigations namely a method of designing shallow tunnel linings of an arbitrary cross-section shape (with one axis of symmetry) under seismic effects.

2 THE METHOD OF THE DESIGN

The method 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 an opening of an arbitrary shape (with the one axis of symmetry) supported by a ring simulating the tunnel lining. The design schemes are given in Fig.1 a, b.

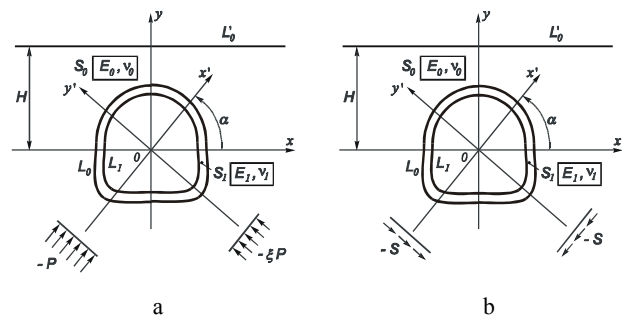


Figure 1. Schemes for the design of tunnel linings under the actions of long arbitrary directed longitudinal (a) and shear (b) waves

The medium is subjected on the infinity to a biaxial compression with non-equal components directed under an arbitrary α angle to the horizontal and the vertical simulating the action of a long arbitrary directed longitudinal wave (Fig.1 a) and to a pure shear simulating the action of a long arbitrary directed shear wave (Fig.1 b). The stresses on the infinity are connected with parameters of waves by well known formulae (Guide, 1996):

$$P = \frac{1}{2\pi} AK_1 \gamma c_1 T_0, \quad \xi = \frac{v_0}{1-v_0}; \quad (1)$$

$$S = \frac{1}{2\pi} AK_1 \gamma c_2 T_0,$$

where A = coefficient corresponding the earthquake intensity, K_1 = coefficient taking admissible damages into account, γ = soil unit weight, v_0 = Poisson's ratio of rocks (soils), T_0 = prevailing period of soil particles oscillations, c_1, c_2 = velocities of longitudinal and shear waves correspondingly.

The medium and ring undergo deformation together i.e. conditions of a continuity of vectors of stresses and displacements are satisfied on the contact line L_0 . The internal outline of the ring L_1 is free from loads.

The first problem (Fig.1 a) has been solved with the application of the complex variable analytic functions theory (Muskhelishvili, 1966) applying the analytical continuation of complex potentials regular in the lower semi-plane out of the opening into the upper semi-plane across the straight boundary L'_0 (Aramanovich, 1955). It allows to come to the iteration process (Fotieva et al., 2001) in every approximation of which the solution for a ring of an arbitrary shape supporting an opening in a whole plane is being obtained (using the apparatus of conform mappings and complex series) at the boundary conditions including some additional members reflecting the influence of the straight boundary of the semi-plane. Those members are represented in the form of the Laurent's series the unknown coefficients of which are specified on the basis of previous iterations. The solution of the second problem is obtained as a particular case of the first problem assuming $P=S$, $\xi = -1$ and applying the angle $\alpha + \pi/4$ instead of α .

From the solution of the first problem the stresses $\sigma^{(P)}$ in the lining (here a symbol σ signifies all the components of the stress tensor) are determined, caused by a long longitudinal wave falling under an arbitrary α angle ; from the solution of the second problem the stresses $\sigma^{(S)}$, caused by a long shear wave directed under the α angle are obtained.

Further the sum and the difference of general expression for normal tangential stresses obtained from the two above problems characterising the lining stress state caused by mutual actions of longitudinal and shear waves passing simultaneously (the worst case) are investigated in every point of the internal lining outline on the extreme relatively the α angle of the waves falling. With this aim the following equations are solved

$$\frac{\partial}{\partial \alpha} [\sigma_{\theta}^{(P)} \pm \sigma_{\theta}^{(S)}] = 0 \quad (2)$$

and for every point such a combination of waves and such of their direction are determined at which normal tangential stresses in the points considered are maximal by their absolute. It allows the envelope diagram of normal tangential stresses on the internal lining outline to be obtained analytically. The stresses on the external lining outline, bending moments and longitudinal forces in every lining normal section are determined at such a combination and such a direction of waves at which the stress on the lining internal outline in that section has

a maximal absolute value. The stresses and forces obtained are assumed with signs "plus" and "mines" and summed up with the ones caused by the other loads determined by methods published in the paper by Fotieva et al. (2004) in their most unfavourable combinations. After that the control of linings sections strength on the compression and tension is being made.

If the lining is not anchored to the soil and is designed with the allowance of a cracks formation we assume that tensile normal loads are not transferred on the structure. In this case the action of longitudinal waves in the phase of tension is excluded from the consideration and the lining design is fulfilled on the basis of the two different envelope diagrams for maximal absolute values of compressive (negative) and tensile (positive) stresses caused by a joint action of shear waves and longitudinal waves in the compression phase.

The method has been realized in the corresponding computer program allowing to determine both stresses in the lining caused by a separate action of the longitudinal or shear wave of a certain direction and maximal compressive and tensile stresses which may appear in every lining normal section due to all variety of seismic effects in the plane of the tunnel cross-section.

It is necessary to note that the method proposed is based on the position of applying the solutions of quasi-static problems for determining the dynamic stresses in the shallow tunnel linings if the length of seismic waves is more than 3 tunnel diameters. For a checking of this hypothesis the analytical results of quasi-static solutions were compared with the data of a numerical modeling of dynamic problems by the finite elements method applying the FLAC program (Lemos et al., 2001).

With this aim the circular lining with outer radius $R_0 = 5$ m and thickness $\Delta = 0.5$ m of the tunnel located on the depth $H = 15$ m in the soil mass possessing the $E_0 = 50$ MPa, $v_0 = 0.3$ has been calculated. The characteristics of the lining material are $E_1 = 20000$ MPa, $v_1 = 0.25$. The action of vertical longitudinal and shear waves has been considered.

The diagrams of normal tangential stresses $\sigma_{\theta}^{(in)}$ along the internal lining cross-section outline caused by the action of the vertical longitudinal wave obtained from solutions of quasi-static (analytical results) and dynamic (numerical results) problems are given in Fig.2 by solid and dash lines correspondingly.

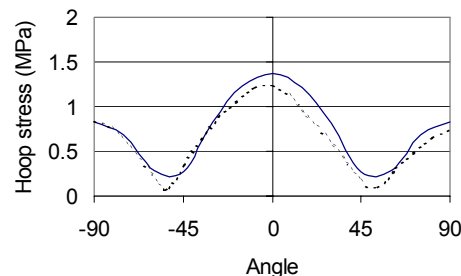


Figure 2. Stresses caused by a vertical longitudinal wave determined from the solutions of quasi-static and dynamic problems

The same stresses caused by the action of vertical shear wave are shown in Fig.3.

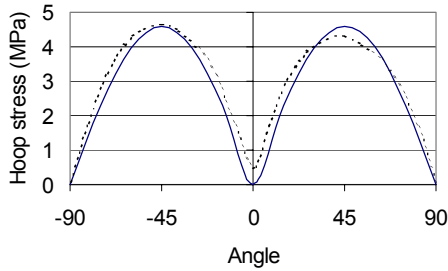


Figure 3. Stresses caused by a vertical shear wave determined from the solutions of quasi-static and dynamic problems

As follows from Figures 2, 3, the difference between results of analytical and numerical calculations is not significant. It confirms the possibility to apply solutions of quasi-static problems for determining the dynamic stresses caused by seismic effects of the Earthquakes in shallow tunnel linings including the ones located in soft soils.

3 EXAMPLES OF THE DESIGN

The example of the design of concrete lining of 0.3 m thickness for a non-circular tunnel of 6.6 m height and 4.6 m width is given below. The input data are the following: $H = 6$ m (the thickness of the overburden is $H' = 2.5$ m), $E_0 = 500$ MPa, $\nu_0 = 0.3$, $E_1 = 23000$ MPa, $\nu_1 = 0.2$, $\gamma = 0.019$ MN/m³, $AK_1 = 0.1$ (corresponds to the 9 degree of the Earthquake intensity on MSK scale), $T_0 = 0.5$ s.

Diagrams of maximal compressive and tensile normal tangential stresses $\sigma_{\theta}^{(in)}$ (in MPa) which may appear on the internal outline of the lining cross-section are correspondingly shown in Fig.4a by solid and dash lines. The corresponding them stresses $\sigma_{\theta}^{(ex)}$ (in MPa) on the external lining outline are given in Fig.4b.

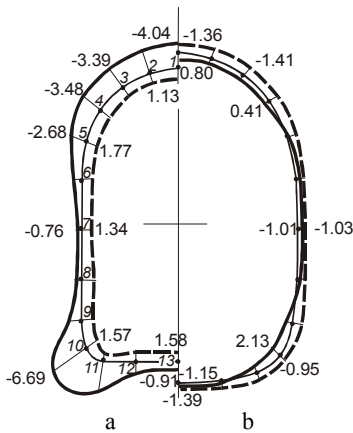


Figure 4. Diagrams of maximal compressive and tensile stresses which may appear on the internal lining outline (a) and corresponding them stresses on the external lining outline (b)

The results of investigations of the tunnel depth influence on the lining stress state are shown in Fig.5 where diagrams of maximal compressive and tensile circumferential stresses which may appear along the lining internal outline are given by curves 1, 2, 3 correspondingly at $H = 4$ m, 8 m and 32 m.

As it follows from Fig.5 maximal compressive and tensile stresses which may appear along the internal outline of the lining due to the Earthquake decrease practically in all points of the outline with increasing the tunnel depth especially in the top of arch.

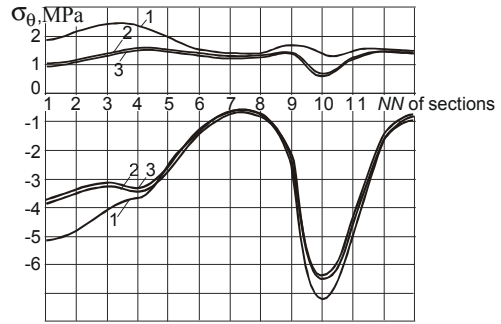


Figure 5. Maximal compressive and tensile circumferential stresses which may appear in points of the internal lining outline at different tunnel depths

Dependencies of extreme stresses $\sigma_{\theta_{extr}}^{(in)}$ i.e. maximal compressive and tensile stresses along the perimeter of lining internal outline with may appear at the Earthquake on the tunnel depth are shown in Fig.6. Curves 1, 2, 3 correspond the cases when $E_0 = 50$ MPa, 500 MPa, 5000 MPa.

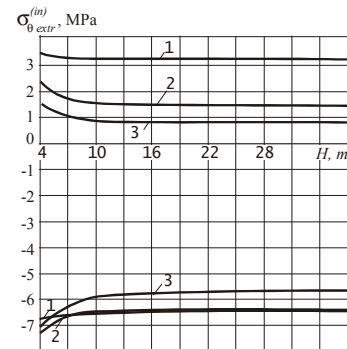


Figure 6. Dependencies of extreme stresses in the lining on the tunnel depth

One can see from Fig.6 that maximal compressive and tensile stresses decrease with the increase of the tunnel depth turning to the ones calculated without taking the influence of the Earth surface into account. Values of these stresses are given in Table 1, where their differences (in percents) from the corresponding stresses obtained for the tunnel depth $H = 6$ m are shown in parenthesis).

Table 1. Extreme stresses calculated without taking the influence of the Earth surface into account

| Maximal stresses $\sigma_{\theta}^{(in)}$, MPa | E_0 , MPa | | | | |
|---|------------------|-----------------|------------------|------------------|-------------------|
| | 50 | 500 | 1000 | 5000 | 10000 |
| Compressive | -6.49 (0.3 %) | -6.40 (4.3%) | -6.28 (5.3 %) | -5.74 (8.8 %) | -5.20 (10.5 %) |
| Tensile | 3.23 (0.6 %) | 1.67 (7.2 %) | 1.35 (5.4 %) | 0.9 (14.0 %) | 0.86 (15.7 %) |

From Table 1 one can see that the design of tunnels located in hard rocks (soils) without taking the influence of the Earth surface into account may result in a substantial mistakes and in irregular estimation of seismic danger.

In the second example the concrete lining of 0.35 m thickness in the tunnel of 4.55 m height and 6.4 m width is calculated at the following input data: $H = 6$ m (the thickness of the over-

burden is $H' = 3.5$ m), $E_0 = 500$ MPa, $\nu_0 = 0.3$, $E_1 = 23000$ MPa, $\nu_1 = 0.2$, $\gamma = 0.023$ MN/m³, $AK_1 = 0.1$, $T_0 = 0.5$ s.

Diagrams of maximal compressive and tensile stresses, which may appear on the lining internal outline (a) and corresponding them stresses on the external outline (b) are shown in Fig. 7a,b by solid and dash lines correspondingly.

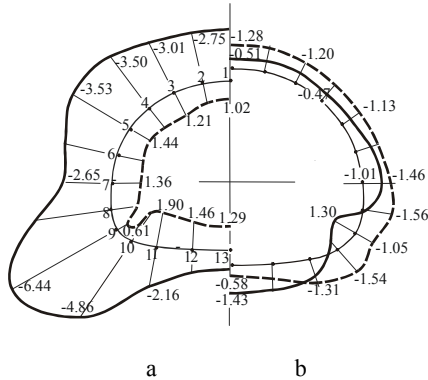


Figure 7. Maximal compressive and tensile stresses on the lining internal outline and corresponding them stresses on the external outline

Similar investigations of dependencies of maximal compressive and tensile stresses, which may appear on the internal lining outline, on the tunnel depth show the same character is as in the first example and in examples considered earlier for a shallow circular tunnels (Fotieva & Shelepov, 2000).

So, the results obtained, confirm well known from practice fact that seismic effects are more dangerous for shallow tunnels than for the deep ones.

4 SUMMARY AND CONCLUSIONS

The new method of designing tunnel linings of an arbitrary cross-section shape under seismic effects taking the influence of the Earth surface into account is described in the paper. The method allows to determine the most unfavourable stress state in every lining normal section which may appear at any combinations and directions of long longitudinal and shear seismic waves propagating in the plane of the tunnel cross-section. Investigations of dependencies of maximal compressive and tensile stresses which may appear along the lining cross-section internal outline, on the tunnel depth shows the increase of these stresses with the depth decreasing, especially for tunnels located in hard rocks. This is why it is necessary to take the influence of the Earth surface into account at the design of shallow tunnel linings in seismically active areas.

In conclusion we can mark that the method described is restricted by requirement that the circle surrounding the external outline of the ring simulating the tunnel lining does not cross or touch the straight boundary of the semi-plane simulating the rock mass. At the same time an increase of the tunnel depth does not restricted, therefore the method may be also applied for the design of deep tunnels.

The method may be generalized for designing tunnel linings constructed with the application of grouting.

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