Influence of seismic events on shallow geotechnical structures

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This paper deals with a summary of possible seismic loading of shallow geotechnical structures. It is known that seismic loading influences the underground structures much less than the structures on the surface, therefore, it is not usually taken into account. However, cracks or damage in lining occur due to vibration from time to time. Two effects of earthquakes are documented on these structures: an effect due to faulting and an effect due to vibration. At present, FEM is the most popular method to solve the above problems. Integrated earthquake simulation is the most frequent task that has a significant impact on seismic hazard and seismic risk estimations, and human actions against earthquake disasters. Three types of rock massif were defined for this study: soft rock, medium hard rock, and hard rock. More detailed description and sensitivity analysis are performed for circle cross-section of those structures. Sensitivity analysis was performed using soil interaction method according to Wang´s methodology; change of lining diameter and elastic modulus of lining were tested. Thrust force must also be calculated for the no-slip condition. Graphs presented in this paper document individual relations between individual studied parameters. These results can be used as sufficient accurate final analysis while idealised conditions can be accepted.

Keywords: *shallow geotechnical structures, seismic loading, ground shaking, sensitivity analysis, cross-section deformation, bending moment*

Introduction

The so-called "fourth dimension" of any metropolis is the underground space beneath the city which includes typical structures such as tunnel facilitating transport, as well as providing sewage, gas, water and other supplies. Underground space may also be utilised for a living, working and recreational facilities and provide storage for industrial materials. Construction of municipal underground structures in the central parts of large towns started at the turn of the 20th century, initially, and above all, in the form of sewers. Utility tunnel networks in the historic centres of cities are permanent elements of protection and development of the sustainable environment because they allow a long-term and nearly absolute exclusion of digging open trenches for laying, maintaining and refurbishing utility services. To a lesser extent, similar structures are built as parts of dams and hydroelectric schemes to serve both construction and operational purposes, (for example, as headrace, tailrace, diversion, intake, outlet or inspection tunnels/galleries). Although not usually in the public eye, these are geotechnical structures with high utility values, which are in many cases very complicated and provided with high-quality equipment (for example, Barták et al., 2007a, 2007b; Ceylanoğlu and Gül, 2016; Ghazvinian et al., 2010; Klepsatel, 2005).

Stability of all these underground structures is regularly or occasionally observed or permanently monitored using different geodetic and geotechnical methods (for example, Rozsypal, 2001; Pitilakis and Tsinidis, 2014). The necessity for monitoring depends on the significance of a structure, possible loading and motion of staff, and especially other people. In addition to static loading, account must also be taken of the dynamic one when evaluating the stability of underground structures (for example, Towhata, 2008). The problem of dynamic loading is important for structures that were not designed to withstand vibrations. Typical structures representing this category are caves and old mines open for public as museums (for example, Kaláb and Lednická, 2011; Knejzlík et al., 2011; Singh et al., 2015). Measurements and evaluation must be conducted for these structures.

The influence of earthquakes on underground structures is described mainly for seismically active areas. Generally, two effects of earthquakes are documented: an effect due to faulting and an effect due to vibration. Detailed geological survey documents are faulting in the surrounding of underground structures; damage of these weakened places is described as a slippage occurring along the fault (for example, Stevens, 1977). Every earthquake causes some unique motions, the characteristic of which depends on several factors including the disruption mechanism of fault at earthquake source, the wave propagation media and geological features of an earthquake site. Porous rock and unconsolidated materials, in which usually discussed constructions are located, are more compressible in comparison with solid rock. Therefore, with decreasing speed of wave energy, the kinetic energy flux in the wave is maintained by increasing amplitude that rises into increased vibration and increased intensity. The existence of discontinuities makes underground structures vulnerable to collapses, particularly in the case of a shallow position. Many papers describe the impact of earthquakes on the underground structures, and they discuss problems of responses, namely stability and collapses (for example,

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Aydan et al., 2010; Aydin, 2016; Kontogianni and Stiros; 2003, Lenhardt, 2009; Stevens, 1977). A similar vibration effect generated by earthquakes is observed in regions with induced seismicity. For example, mining-induced seismic events have a similar wave pattern as weak natural earthquakes, only the frequency range of signal may be different. Shallow underground structures in undermined areas are loaded due to the sinking of the surface also.

Dealing with the seismic effects on shallowly located tunnels, this paper describes only a small part of this topic.

Possible seismic loading of underground structures

The influence of technical seismicity on underground structures is a specific task that is not usually taken into account, although the number of the vibration sources and their effects increase. Technical seismicity is represented especially by quarry blasts; however, vibrations closely connected with human-made activity occur in the surroundings of vibration sources. It includes dynamic phenomena caused by man and his machines, by piling, compaction, traffic and equipment which are used for various activities. Blast operations done during driving tunnels or in the surroundings of quarries are the most frequently evaluated technical vibrations. Special measurements were realised in a near zone to determine a vibration effect on the temporary or final lining (for example, Qiu et al., 2008; Kaláb et al., 2013, 2014; Kaláb and Hrubešová, 2015; Varnusfaderani et al., 2015, 2017). The effect of technical seismicity (industry, traffic, forging shop, vibration roller, etc.), excluding blasts, is usually at a lower limit of a possible negative impact on underground structures (for example, according to Czech Technical Standard 73 0040). However, cracks or damage in lining occur due to vibration from time to time.

Furthermore, vibration effects on underground structures can be divided into two categories (for example, Dowding and Rozen, 1978):

1. Ground shaking: The major factors influencing shaking damage include: the shape, dimensions and depth of the structure, the properties of the surrounding soil or rock, the properties of the structure and the severity of the ground shaking.
2. Ground failure: It represents effect such as liquefaction, fault displacement, and slope instability.

To evaluate vibration and its effect in rock massif on line underground structures, three types of deformations occur due to ground shaking (see Figure 1):

1. Longitudinal axial deformation due to compressional or tensional forces;
2. Longitudinal bending of structures;
3. Ovaling of tunnel section (circle profile) or racking of tunnel section (rectangular profile).

Hashash et al. (2001) describe: Axial deformations in tunnels are generated by the components of seismic waves that produce motions parallel to the axis of the tunnel and cause alternating compression and tension. Bending deformations are caused by the components of seismic waves producing particle motions perpendicular to the longitudinal axis. Design considerations for axial and bending deformations are generally in the direction along the tunnel axis (Wang, 1993). Ovaling or racking deformations in a tunnel structure develop when shear waves propagate normal or nearly normal to the tunnel axis, resulting in a distortion of the cross-sectional shape of the tunnel lining. Design considerations for this type of deformation are in the transverse direction. The general behaviour of the lining may be simulated as a buried structure subject to ground deformations under a two-dimensional plane strain condition.

General observations regarding the seismic performance of underground structures were published by Hashash et al. (2001). The most significant point is that underground structures suffer appreciably less damage than surface structures and that damage decreases with increasing overburden depth. It also documents several field tests and measurements (for example, Lednická and Kaláb, 2013).

Approaches to evaluation of seismic loading

Seismic loading on the underground structure can be evaluated by different methods. The most used methods are (Hashash et al., 2001; Pescara, 2011; Wang, 1993):

1. Calculation of ground pressures (small depth of structures only);
2. Free field deformation method (structures and rock massif with identical rigidity);
3. Soil-structure interaction method (line structures in simple geological conditions);
4. Numerical modelling using different accesses (wide using but the quantity of input parameters and time-consuming method).

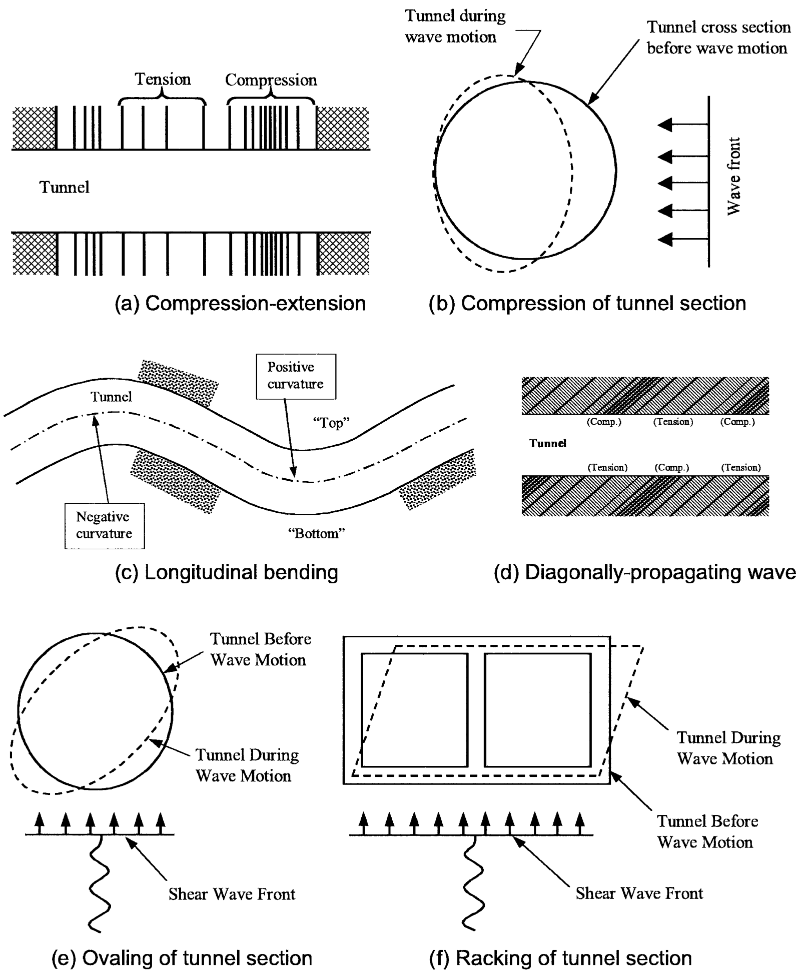

Fig. 1. Deformation modes of tunnels due to seismic waves after Owen and Scholl (1981 in Hashash et al., 2001).

The advancement of computational approach (i.e. No. 4) enables us to solve numerous problems. Usually, these problems are described as a boundary value problem or an initial boundary value problem (from mathematical viewpoint). The foundation of computational methods consists of solid continuum mechanics, finite element method, and stochastic modelling. Numerical analyses of strong ground motion and faulting represent the most frequent tasks. When a well-developed method of numerical analysis is used, modelling of a target body determines the quality and reliability of the results of the numerical analysis. Numerical methods based on FEM (finite element method), FDM (finite difference method) or BEM (boundary element method) provide very detailed and very precise results in the case of top quality and sufficient input data; however, it is the time-consuming approach. It is important to distinguish three parts, namely physical problem (field equations of physical principles), the mathematical problem (a boundary value problem for displacement) and the numerical problem (a matrix equation for unknown displacement). To solve the numerical problem, an approximate solution of the mathematical and physical problems is made (for example, Berr, 2003; Hori, 2006; Villaverde, 2009).

At present, FEM is the most popular method to solve the above problems. In general, FEM follows three basic procedures (Hori, 2006):

1. Input data of a boundary value problem, decompose the domain of analysis into a set of elements and define nodes so that a function is discretised.
2. Compute the discretised function, by solving a matrix equation which is transformed from the boundary value problem.
3. Output results of computation, retrieving the solution of the boundary value problem from the discretised functions.

These processes are called (1) pre-processing, (2) computation and, (3) post-processing. It is necessary to add that advanced topics in computational earthquake engineering are solved. Integrated earthquake simulation is the most frequent task that has a significant impact on seismic hazard and seismic risk estimations, and human actions against earthquake disasters.

Analytical methods (i.e. 2 and 3) enable pre-estimate and simplified estimation of vibration effect on the underground structures.

Free field deformation approach describes strains in the rock massif due to seismic waves. Only the estimation of possible deformations can be obtained because this calculation is made for the rock massif without underground structure. Therefore, mutual interaction between these two environments is not taken into account; structures and rock massif have to have the relative identical rigidity.

The second approach, i.e. soil-structure interaction, extends the calculation to include the influence of structure. It means that interaction between rock massif and structure enables the determination of resulting values of vibration effect with higher certainty degree.

More detailed description of both methods including mathematical equations can be found in the cited literature.

Sensitivity analysis of selected parameters

This sensitivity analysis is focused on line underground structures with a circular profile. Only driven structures in rock massif were modelled, which means that structures with other profiles and/or buried structures were not taken into account. Three types of rock massif were defined for modelling. Their specific parameters are presented in Table 1; seismic parameters are determined using Eurocode 8 for maximum acceleration value a_{gR} = 2 m.s^{-2}. Maximum ovaling or racking deformations (see Fig. 1 - e, f) indicates the chamfering of the rock massif/tunnel. It is represented by the ratio between the maximum of S-wave velocity V_S and the apparent S- wave velocity C_S in a particular massif. The apparent S-wave velocity is calculated with the shear modulus Gm and the bulk weight γp at a given depth *Cs* = (Gm/γp)^½, for example, Wang (1993) or Paolucci and Pitilakis (2007).

Basic parameters of modelled underground structure (below referred to as a tunnel) are presented in Table 2. Lining diameter d was tested in range 2 – 12 m and elastic modulus of lining E_t was tested in range 12,000 – 40,000 MPa. Depth is considered as a change of S-wave velocity V_s only; it decreases with depth.

Tab. 1. Parameters of rock massif.

	Soft rock	**Medium hard rock**	**Hard rock**
Bulk weight	γ = 18 [kN.m^{-3}]	γ = 23 [kN.m^{-3}]	γ = 27 [kN.m^{-3}]
Poisson´s ratio	ν = 0,4	ν = 0,2	ν = 0,15
Elastic modulus of rock massif	E_p = 20 [MPa]	E_p = 200 [MPa]	E_p = 2000 [MPa]
S-wave velocity	V_s = 1,056 [m.s^{-1}]	V_s = 2,100 [m.s^{-1}]	V_s = 3,584 [m.s^{-1}]
Apparent S-wave velocity	C_s = 250 [m.s^{-1}]	C_s = 750 [m.s^{-1}]	C_s = 2000 [m.s^{-1}]
Angular distortion	γ_{max} = 0,0042	γ_{max} = 0,0028	γ_{max} = 0,0018

Tab. 2. Parameters of tunnel lining material.

Lining diameter	d = 6 [m]
Lining thickness	t = 0,3 [m]
Length of tunnel	l = 100 [m]
Depth below surface	h = 20 [m]
Elastic modulus of lining	E_t = 20 000 [MPa]
Poisson´s ration of lining	ν_t=0.2

Sensitivity analysis was performed using soil interaction method according to Wang´s methodology (1993). This sensitivity analysis in transverse direction deals with ovaling, which is expressed in this study as deformation of circular cross-section Δd. Other observed parameters are maximum bending moment M_{max} and maximum thrust T_{max} developing in tunnel lining. For both parameters Δd and M_{max} it is possible to calculate only full-slip condition (it means slip along the entire length of lining – rock contact). Thrust force must also be calculated for the no-slip condition. A detailed description of calculation methodology including main equations can be found, for example, in Hashash et al. (2001). Results mentioned above were obtained using analytical relations (Wang, 1993) in Excel environment.

To evaluate obtained results in ranges of lining diameter *d* and elastic modulus of lining E_t mentioned above, selected relations are presented. Behaviours of cross-section deformation in relation to increasing lining diameter for all three types of rocks are presented in Figure 2. Linear relations were obtained for hard and medium hard rocks. Also, the linear relation can be accepted for soft rock from *d* = 4 m. Generally, no significant changes can be documented between different rocks from this numerical modelling.

Figure 3 presents relations between cross-section deformation Δd and elastic modulus of lining E_t. Obtained relations have a different character for different rock types. More significant decreasing of Δd is detected for soft rock, while Δd has comparatively stable values for the above range. Change of E_t from about 10 GPa to 40 GPa evokes decreasing of Δd about 10 mm, i.e. harder lining must be used for soft rocks.

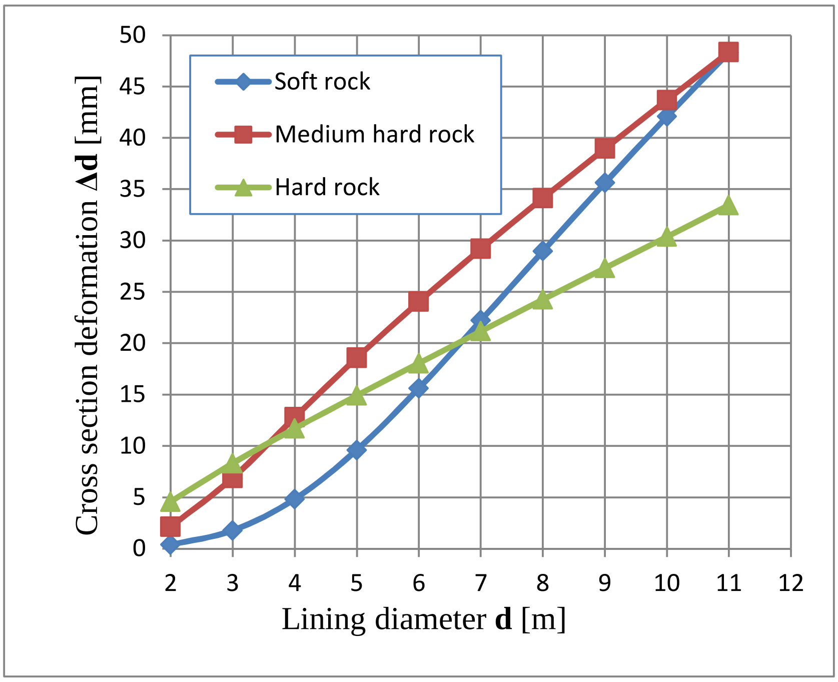

Fig. 2. Behaviours of cross-section deformation in relation to increasing lining diameter for all three types of rocks.

Very different curves were calculated for graphs of diameter lining d versus maximum bending moment M_{max} (Figure 4). The almost parabolic decrease of M_{max} depending on the increase of d for hard rock was obtained, and reversely, an increase of M_{max} depending on the decrease of d for soft rock was also obtained. Relation to medium hard rock is a combination of previous curves: sharp increase of M_{max} up to lining diameter d = 4 m and more gradual decrease from this value of d. It is possible to derive that underground structures with lining diameter d < 6 m have to be carefully observed for the evaluation of M_{max}.

Changes of maximum bending moment M_{max} are linearly dependent on the elastic modulus of lining E_t (Fig. 5). The greatest values were calculated for medium hard rock, a line of hard rock has the same angular coefficient (corresponding individual values are less rather 50 kNm). Value increments of soft rock are less than for the previous ones.

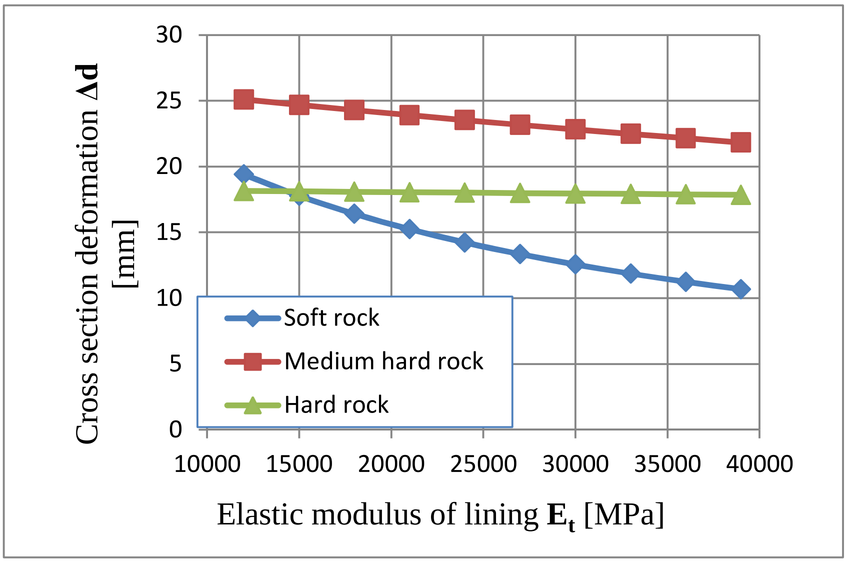

Fig. 3. Behaviours of cross-section deformation in relation to increasing elastic modulus of lining for all three types of rocks.

The last two presented graphs show differences for numerical models with full-slip (Fig. 6) and no-slip (Fig. 7) conditions. Thrust forces T_{max}, also for all three rock types, are calculated for these conditions. To accept the full-slip condition, thrust force increases with the increase of the elastic modulus of lining totally pursuant to maximum bending moment (cf. Fig. 5 and 6). Rock massif behaviour has more significance in case of the no-slip condition. The thrust force is with low values, and stable for hard and hard medium rocks, high values and a slight increase of T_{max} values were obtained for soft rock. However, the calculation of thrust force condition does not provide generally correct (realistic) values. The main reason is nonlinear nature of friction on the contact, and analytical methods are not possible to use to solve this problem.

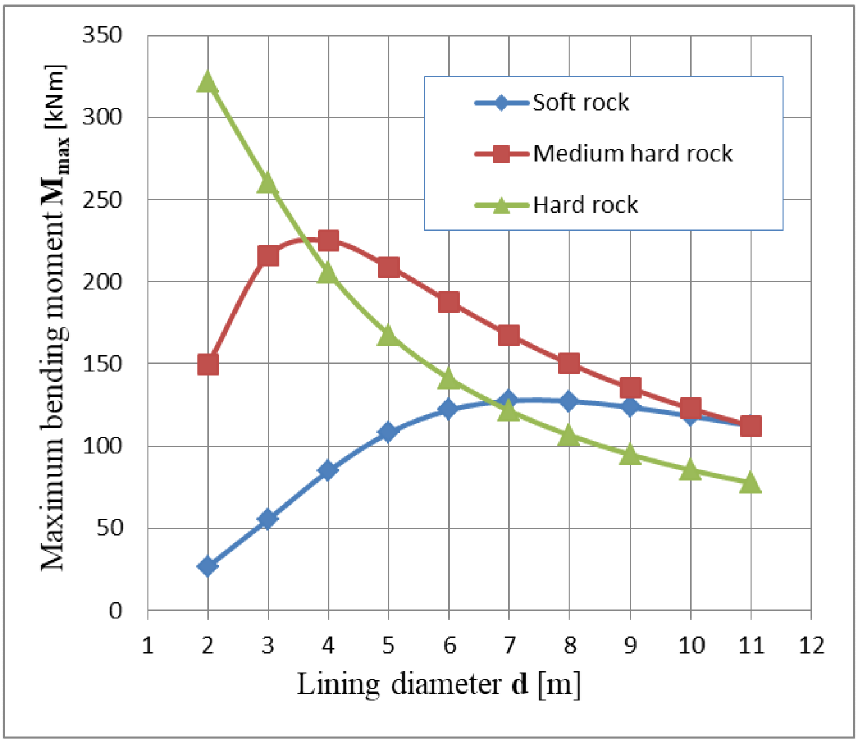

Fig. 4. Behaviours of maximum bending moment in relation to increasing lining diameter for all three types of rocks.

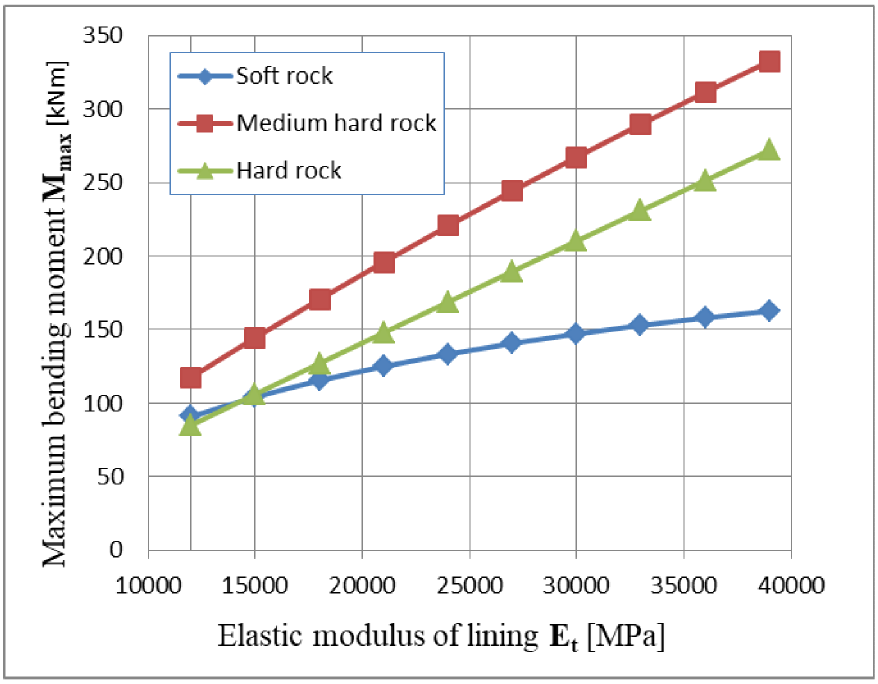

Fig. 5. Behaviours of maximum bending moment in relation to increasing elastic modulus of lining for all three types of rocks.

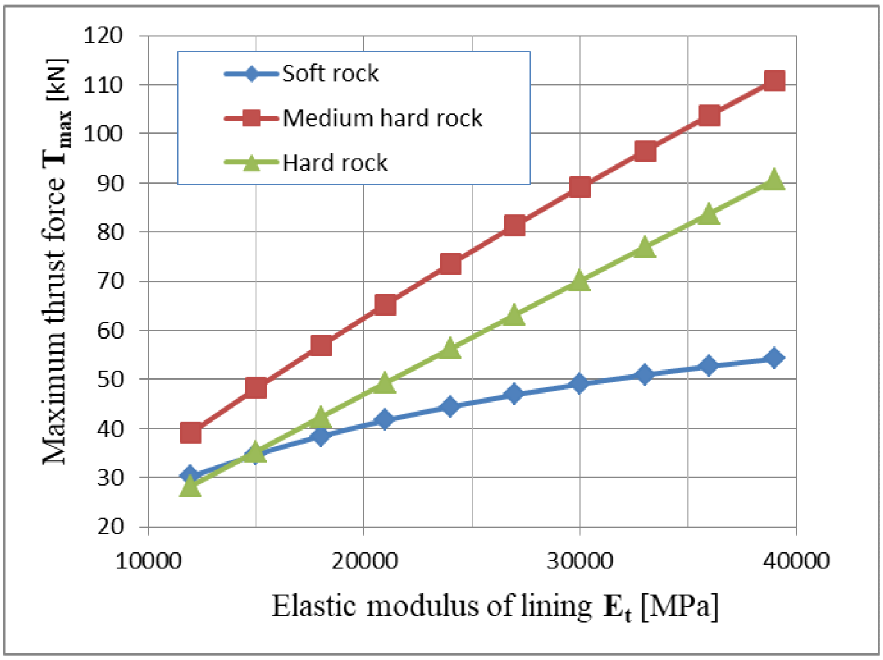

Fig. 6. Behaviours of maximum thrust force in relation to increasing elastic modulus of lining with full-slip condition for all three types of rocks.

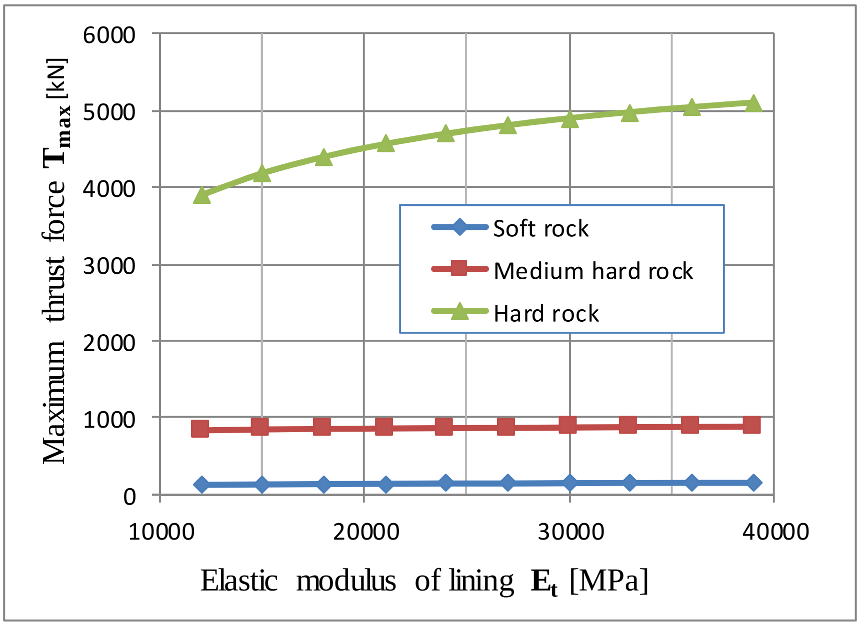

Fig. 7. Behaviours of maximum thrust force in relation to increasing elastic modulus of lining with no-slip condition for all three types of rocks.

Discussion

Soil interaction method according to Wang´s methodology (1993) was used for this study. Selected results of sensitivity analysis were presented above. The main knowledge is possible to summarise as follows:

1. The longitudinal sensitivity analysis (results are not all listed in figures):
   a. It has confirmed that the seismic loading is less manifested when the structure (lining) is situated in harder rock massif.
   b. The combined axial strain increases with the increasing lining diameter, and it decreases with the increasing elastic modulus of the lining.
   c. The shear force increases when increasing both the lining diameter and the elastic modulus of the lining.

2. The transverse sensitivity analysis:
   a. Seismic loading is the most manifested in medium hard rocks. In relatively soft or hard rocks, that manifestation is less for almost all studied parameters. Therefore, it is necessary to pay extra attention to the parameters of the rock massif.
   b. The change of the elastic modulus of the lining does not have a major effect on the cross-section deformation. This change does not in practice exist in hard rock massif. Behaviours of cross-section deformation in relation to increasing lining diameter for all three types of rocks are almost linear.
   c. The maximum bending moment is very specific to the varying diameter of the lining; maximum bending moment increases during increasing lining diameter, but it decreases further from a certain diameter. This change on the curve occurs with small diameters in soft and medium hard rocks. The almost parabolic decrease of this curve was obtained for hard rock. Changes of the maximum bending moment are linearly dependent on the elastic modulus of the lining.
   d. The maximum thrust force significantly depends on the condition of defined slip.

3. Sensitivity analysis demonstrates that curves of the hard rocks were very often distinguished from the other rocks. It can not be specified if they will manifest negatively rather than positively.

It is possible to add that Penzien and Wu (1998) represent an alternative approach to calculate discussed parameters, also assuming the full slip and no-slip. To compare mentioned approaches (Wang vs Penzien and Wu), calculation of internal forces were performed in the numerical model using Plaxis software (FEM). Generally, the differences of internal forces and cross-section deformation between results of Plaxis and mentioned approaches are approximately 15 %. Negligible differences were obtained for normal forces of the Wang´s approach. Based on these results, it is not recommended to use Penzien's approach for no-slip conditions between the lining and the rock and values close to these ones. A similar conclusion was presented in a study by Sedarat et al., 2008.

Conclusion

Rigidities of the rock massif and the lining are the main characteristics of the method selection. The ratio of flexibility between rock and structure has great influence on the seismic loading effects in the context of the interacting method. Specification of the interface between the lining and rock has important role for the ovaling of circular cross-section.

A detailed description of calculation methodology including main equations can be found, for example, in Hashash et al., 2001. Our sensitivity analysis of lining diameter and elastic modulus of lining for analytical methods enables the following conclusions to be made:

1. Seismic loading has lesser effect when the structure is executed in harder rock;
2. Transverse sensitivity analysis proves that effect due to seismic loading is maximal for medium hard rocks. This effect is smaller for almost all parameters in harder or softer rocks; therefore, it is advisable to pay special attention to the parameters of the rocks;
3. Change of elastic modulus of lining does not have significant impact on cross-section deformation;
4. Bending moment has specific behaviour depending on the change of lining diameter.

Common information from this study is possible to summarise:

1. The seismic loading is much less on the underground line structures than on the ground structure. Therefore, the evaluation methodology is not clearly specified;
2. Seismic loading is solved separately (from static loading);
3. Seismic manifestations are analysed longitudinally and transversely on the axis of the structure, and simultaneously the combined axial deformations and ovaling of the circular cross-section together with internal forces are observed;
4. Analytical methods are suitable tool for this analysis because of their simplicity and easily available inputs; these methods are very accurate and can be used as a final analysis in idealised conditions;
5. For more complex geological conditions, higher level of analysis is needed, i.e. currently computational programs and numerical modelling; analytical methods can still be used as an approximate estimation;
6. Stiffness of the rock massif and the lining stiffness are the main characteristics used for the selection of methods; the ratio of flexibility between the rock and the structure has a great effect on the manifestation of the seismic loading;
7. Interaction between the lining and the rock plays an important role for ovaling of the circular cross-section; methodologies are developed for both extreme conditions where full slip or no-slip occurs;
8. Two different approaches are possible to use for ovaling definition (according to Wang and Penzien); Wang's approach gives much more realistic results for the no-slip condition.

As mentioned above, seismic loading influences the underground structures much less than the structures on the surface. Analytical methods or numerical modelling are appropriate tools that are used now. Generally, analytical methods can still be used as an information precursor for approximate estimation. However, comparison of results is possible for very similar geological and structural conditions.

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