Comparison of Analytical Solutions with Numerical Ones for Seismic Design of Tunnels in the Case of Heterogeneous Formations

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Abstract: Application of different continued tunnel sections which pass through heterogeneous geological formations brings large additional forces near the plan of changing sections connection. The tunnel section change in homogeneous and heterogeneous environment has been analysed by analytical and numerical modelling explaining design principles, design methodology and practical methods for structural detail construction. Analytical and simplified dynamic analysis can give predictive values only in the case of soft soil upon rock formation and gives unrealistic values for inverted cases. Based on the results obtained by seismic numerical calculation of the Qaf Murrizi tunnel are given the recommendations for effective methods of design of the section change and the environment treatment to overpass this difficulties. In normal heterogeneity with less than three times stiffness difference between geological formations(soft rock upon rock) a continued section doesn’t seems to have any problem for resisting additional deformations and internal forces but for inverted geologic formations and greater stiffness difference the only practical solution is the separation of the tunnel lining. The influence of heterogeneous geological formations especially the contact zone plan can be taken into account by generated time histories of acceleration in the longitudinal model and not by applying a scale factor to time history of acceleration or internal forces in the linings

Key words: Tunnel, seismic design, cross section, numerical analysis.

1. Introduction

The calculation of underground tunnels is still one of the most difficult problems of engineering, especially in very seismic regions. The tunnels as underground structures must withstand both static and seismic loads. Seismic response of tunnels and underground structures is generally very different from that of the above surface structures as the total mass of the structure is usually small compared to the mass of the surrounding ground and terrain confinement provides high values of geometric damping. Because of these two effects an underground structure reacts in accordance with the surrounding terrain response without resonance.

This article presents a simple practical approach for the design of tunnel linings using longitudinal models to generate the seismic input for lateral models and estimate the deformation and curvature based on which we can judge for applying plastic hinges or seismic joints. In our application, from the longitudinal model we have estimated a scale factor that can scale the internal forces or time history of acceleration. We have also generated in longitudinal model a time history at the level of transversal model which serves as input for the transversal models [1, 2]. Different continued section which passes through heterogeneous geological formations brings large additional forces near the plan of changing sections.
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Connection. Using a plastic hinge at the lining in connection zone is a very efficient way but not sufficiently studied [1]. A simple way to solve the problem is to do seismic joints in order that the sections work separately.

This solution is more problematic because of the possibility of permanent deformations at connection zone but also is a very practical solution for the problem.

From analytical and simplified dynamic analysis (beam on springs) model for known geometric shapes are taken the results of peak ground strains and are compared with the results of numerical analysis. Based upon these comparisons are given recommendations for normal and over thrust heterogeneous conditions influence in the seismic design of tunnels.

2. Calculation Methods

The seismic design of tunnels can be made by different methods. The choice of appropriate method depend upon several factors such as: tunnel importance, complexity of geological structure, available geotechnical and seismicity parameters, etc.

Cross section changes can be met in one of the following conditions:
- Tunnel traverse heterogeneous areas;
- Tunnel connection to station or shaft;
- Junctions;

Calculation methods that can be used also for cross section change are:
- pseudo-static analytical analysis;
- simplified dynamic analysis (beam on springs);
- detailed numerical dynamic analysis.

Three approaches can be used for the solution of these problems [3].
- A movable joint;
- Rigid connection with adequate strength;
- Seismic isolation.

2.1 Pseudo-Static Analytical Analysis

These methods for continuous medium consider different modes of deformation (compression/extension; longitudinal bending; ovaling of the cross section) for longitude in alwaves, transverse, and Reyleighwave taking into account the soil-structure interaction by the flexibility coefficients.

In the case of taking into account the soil-structure interaction are introduced the coefficients of relative flexibility and relative stiffness (compressibility). This interaction [4] should be taken into account in cases where the relative flexibility coefficient is $F < 20$. Simple equations that are derived from numerical analysis are given in the case of strong heterogeneities [5]. In these cases, the design must be based upon numerical analysis. In the case when a rigid connection is used additional bending and shear stresses will developed near the interface of cross section change [4]. Some simplified formulas are given by Yeh and Hetenyi for moment and shear due to differential transverse deflections. In our case we have used two simple approaches (Liu & M.O’Rourke 1997, L. Scandella 2007) that are given for ground strain calculation in the case of strong heterogeneities.

2.2 Simplified Dynamic Analysis (Beam on Springs)

Modelling as abeam supported on springs is one the most practical methods of solving the problem. In this type of analysis, we can model both transient and non-transient ground movements. In general, the model form will have the appearance shown in Fig. 1, where springs on one side have a shift from the fault displacement. The seismic loading can be applied by time history of acceleration [3]. In this case, springs should be associated with dampers. In the case when a rigid connection is used the stress concentration can be evaluated by a beam on springs model with a fixed end at the connection.

2.3 Detailed Dynamic Analysis (Numerical Methods)

Numerical methods are in many cases the only methods by which you can get the solution. Numerical
methods can simulate the seismic motion and dynamic soil-structure interaction in any condition. The main numerical methods are “finite element”, “finite difference” and the less used “boundary element” method. The numerical methods recently have made significant progress in wave propagation solution techniques, boundary simulation, and material behaviour modelling and soil structure interaction allowing them to solve the complex problem from the source (far field) to the analysed structure including all the possible soil-rock conditions.

In Finite element methods, numerical modelling of wave motion can be performed by means of direct integration in time or through solutions based on frequency calculations. The latter due to their simplicity are widely used in the analysis of structures, but in modelling of ground wave motion are not very suitable. Numerical modelling through time integration allows easier implementation of the laws of advanced material behaviours that take into account the time dependency and material nonlinearity. In all these formulations, we should take into account a number of factors which will influence the numerical analysis such as: formulation of the mass matrix, the determination of the damping matrix, boundary conditions, critical time integration step, finite element size, etc., the damping coefficients must be chosen to match 1D wave propagation in elasto-plastic soil columns [6, 7]. The boundaries can be modelled by adaption of material properties of boundary elements, infinite elements and viscous boundaries. The last two methods are used mostly and the response of the system in both cases is the same [8].

3. Seismic Design of “Qaf Murrizi” Tunnel

3.1 Introduction of Qaf Murrizi

The Qaf Murriz tunnel is part of a new road from Tirana to Dibra in the center of Albania. The position of the tunnel is shown in Fig. 2. The tunnel has two lanes with a cross section of 105-120 m² and a length of 2.6km. It passes through a very disturbed tectonic zone, where the carbonatic rocks (Cretaceous) of Krasta-Cukali zone over thrust the flysch rocks (Paleocene) of Kruja-Dajti zone. It has a closed shape in the flysch zones with a 90cm thick inverter in the most difficult part. The lining thickness is from 50 cm to 90 cm for the section in the flysch and 35-60 cm for the section in the carbonatic rocks.

Fig. 1 Beam on springs model. General case and rigid connection case.

Fig. 2 Position of “Qaf Murrizi” tunnel.
In our case is not possible to define an exact position of the strong rock weak rock interface (tectonic plane) so we have adopted a rigid connection for the suspected zone with two movable joints outside.

The cross sections in the rigid connection interfaces are given in Fig. 3.

### 3.2 Seismic Input

Due to many uncertainties of a seismic event, the best way for seismic input evaluation is performing probabilistic seismic hazard analysis. Based upon the results of this analyse, we can have the desired parameters of seismic input (ground motion parameters) in any point. For numerical analysis, we need the time histories of this motion that are compatible with the design spectra given by the codes.

For important buildings structures, lifetime is 100years and consequently the return period will be \( T_R = 949 \) years [1, 9]. For evaluation of Hazard, we have used the computer program CRISIS2007.

After the evaluation of the PGA, the seismic input is taken as a real accelerograms from ESD database using the software Rexel [10] and scaling the accelerograms with the software Seismosoft [11]. The chosen accelerogram according to EC8 spectra is compatible with PGA taken from probabilistic seismic hazard analysis for \( T_R \approx 950 \) years [12]. For taking into account the convolution from surface to the depth in which is generated the input in the model a scaled factor is applied to the accelerograms. Three components of the selected accelerogram are given in Fig. 4.

### 3.3 Pseudo-static Analytical Analysis

Simplified formula given by Liu & M.J.O’ Rourke serves only for soft deposits above rock with a particular geometry as in Fig. 5. In our case geometric shapes doesn’t correspond with studied shapes so these formulas cannot be applied.

Also for L. Scandella [5] approach the given formulas only serve for soft deposits above rock with a particular geometry one of which corresponds to the configuration of Qaf Murrizi tunnel at right side, but for the over thrust tectonic zone at the center we can’t use the formulas.

For the right side, peak ground strain will be:

\[
P_{GS_{a}} = r \frac{P_G V}{V_S} \left[ F_1 \left( \frac{\chi}{T}, \alpha \right) + F_2 \left( \frac{\chi}{T}, \alpha \right) \right] \tag{1}
\]

In our case we shall have \( r = 0.872 \).

The value of functions \( F_1 + F_2 \) is obtained graphically considering \( L = 4x \), and \( H = 4x \) as extreme value after which functions do not change. In our case we shall have \( F_1 + F_2 = 0.2 \).

![Fig. 3 The cross sections in the rigid connection interfaces.](image-url)
3.4 Simplified Dynamic Analysis (Beam on Springs)

For each geologic formation we have defined the relevant section and stiffness of springs. For the model through time history of the acceleration analysis are been calculated displacements and internal forces in each segment. The model is given in Fig. 6 and displacements and internal forces in each segment are shown in Fig. 7.

3.5 Numerical Model

For numerical calculation we have used the software “PLAXIS 2D” [13].

The longitudinal model is used to calculate axial strains, deformation and to generate the seismic input for lateral model considering soil-structure interaction and the influence of strong heterogeneities in the modification of time histories of acceleration. The model is taken 2,800 m long and at maximum height 1,000 m. It has 1,668 elements with average length 48m (<1/4-1/8 wave length) [4, 8, 14] with coarse mesh triangular 15node finite elements. The material model behaviour is taken the classic elasto-plastic material model (Mohr-Coulomb). The Mohr-Coulomb material model parameters are estimated from site tests, laboratory tests and geophysical tests. The tunnel lining is modelled as elasto-plastic beam element with normal and bending stiffness (EA, EI) of the concrete lining shape for three typical cross sections. The soil tunnel interaction is modelled by interface elements with assumption of no sliding among them. The construction sequences and water are not taken in consideration [14]. The model boundaries in Plaxis are created by absorbent viscous

So the value of peak ground strain will be: PGSa = 0.00017 << 0.003

Peak ground strain are very small and can be easily resisted by the structure.
Fig. 6 Beam on springs model. 5 different springs with axial and transversal stiffness “kl, kt” every 50 m. 5 different sections for each type of geological formation.

Fig. 7 Moments and displacement for “beam on springs” model.

boundaries that give the same results as infinite element boundaries [8]. In our model, the relaxation coefficients that determined the normal (C1) and shear (C2) stresses absorbed by the damper are taken 1 and 0.25 [7, 13]. The geological formations in our case are rock-poor rock and so the material damping Rayleigh coefficients are taken the default values (\(a_R = b_R = 0\)). The deformation of the tunnel lining in the longitudinal model is shown in Fig. 8.

By choosing different point for graphical presentation, we take the time histories of acceleration that serves as input for transversal model seismic calculation.

We have made three transversals models, one in deep flysch formations, one in carbonatic formations and one in contact zone. The flysch model for the maximum depth (280 m) is represented in Fig. 9. This model has 359 finite elements with average length 6.25 m (<1/4-1/8 wave length) with medium fine mesh triangular 15 node finite elements near the tunnel lining.

The most suitable material model in dynamic analysis in Plaxis is Hardening soil with small strain stiffness (HS small) because it can simulate hysteretic behaviour of the ground and stress level dependency of stiffness. In our case due to lack of appropriate data for generating, the curves of shear modulus dependency from dynamic cyclic small shear strains, we have used Mohr-Coulomb material model with the material damping Rayleigh coefficients values \(a_R = \)
0.08, $b_R = 0.0042$. For small models because we have only considered wave passage effect and not damping in longitudinal model, we must take non-zero values for Rayleigh coefficients. The values of Rayleigh coefficients are taken by assuming the same damping ($z$) for natural soil frequency ($w_1$) and input motion predominant frequency ($w_2$) [6, 13].

All other modelling aspects are the same as in longitudinal model.

Fig. 8  Deformation of the tunnel lining in longitudinal model (concentration of deformation are positioned in inverted heterogeneity, overthrust tectonic zone).

Fig. 9  Trasversal model in flysch.

4. Results and Discussions

For each model are taken strains, deformations, stresses and internal forces in the structure. In longitudinal model, we can control global stability [3], strains and stresses in surrounding terrain and tunnel deformations. The results of the longitudinal model are compared with the results from analytical and beam on springs model and examples of from similar cases [15, 16].

As can be seen in the Fig. 7 we have great moments concentration and deformation in the contact area of inverted heterogeneity and for normal heterogeneity conditions the moments and deformations are greater compare to limestone formations but easily resistible by tunnel structure. Results of the model “beam on springs” in comparison with the numerical model for the inverted case of heterogeneity have great differences and cannot be used.

In transversal models, we can take directly internal forces in tunnel lining. In Plaxis we cannot separate seismic loads from the others so we have to make the difference. The diagram of total envelope moment and axial force for the transversal section at the end of seismic load phase for flysch zone is shown in Fig. 10.

Based on tunnel deformations in longitudinal model is seen that in the contact area for a length of 60-80 m
we have a concentration of deformation, change of direction of curvature and large internal forces in the lining of the tunnel. Also adjacent to the plan of tectonic zone even in the good rock formation (carbonatic) in the model are seen large internal forces due to longitudinal flexural stiffness of tunnel lining and over thrust heterogeneity influence (rock upon soft soil) [12]. By comparing the size of deformation on three sections we have derived scale multiplier, which consider the influence of geological configuration and the change of tunnel section. The values of internal forces for transverse model in tectonic zone are multiplied by this scale multiplier (g = 2.1). From the control of reinforced concrete cross section it is seen that under these forces the section will be destroyed. For these reason we would find a different approach to solve the problem. At the tectonic zone, at a 100m distance, we make 2 seismic joints which divide the tunnel on three segments that behaves like separate parts during the earthquake. With this new configuration we recalculate the longitudinal model and take strains, deformations and forces in the lining in the axial direction.

We have also recalculated transversal models with seismic input that we have generated from modified longitudinal model. Transversal models calculated separately for each segment now depends only on the modification of the time histories of seismic action due to heterogenous geological configuration and ground-structure interactions for each segment separately. In the tunnel lining did not appear inertial forces due to the change of section and influence of sections on each other. Application of different continued sections which pass through heterogeneous geological formations brings large additional forces near the plan of changing sections connection [4].

Using a plastic hinge at the lining in connection zone is a very efficient way [1] but not sufficiently studied how it works, hinge length, plastic rotation etc. due to these uncertainties a simple way to solve the problem is to do seismic joints in order that the sections work separately.

This solution is more problematic because of the possibility of permanent deformations at connection zone but also is a very practical solution for the problem.

5. Conclusions

In normal heterogeneity with less than three times stiffness difference between geological formations(soft rock upon rock) a continued section doesn’t seems to have any problem for resisting additional deformations and internal forces.

Analytical and “beam on springs” models can give comparable results only for normal heterogeneities conditions and in any case serves only as a first step solution before numerical analysis.

The influence of heterogeneous geological formations especially the contact zone plan can be taken into account by generated time histories of acceleration in the longitudinal model and not by applying a scale factor to time history of acceleration or internal forces in the linings.

The study of the use of plastic hinges at connection zone will be one of our objectives in the future.

References

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