Earthquake influences during exploitation of diversion tunnel

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SUMMARY:
Even though tunnels are considered as one of the safest structures, worldwide studies show that huge damages can occur in tunnels and underground structures during and after earthquake. Some of many risks that can arise during tunnel exploitation are: contamination of ground water, air pollution and negative consequences in cases of eventual tunnel failure.
This paper presents some of the analyses performed for the diversion tunnel of one tailing dam located in Republic of Macedonia. The tailing dam is a part of the hydro system constructed for exploitation of the lead and zinc mine "Sasa". Formerly, three tailing dams were constructed, and up till now they have been used for deposition of the waste material obtained by the technological flotation processes of leads and zinc minerals.
Performing an engineering tunnel assessment is of huge importance for these structures, both from geotechnical and structural engineering point of view. The designing process for tunnels has to include the calculations considering their safety under different applied loads: temporary and permanent static loads and seismic loads.

Keywords: diversion tunnel, earthquake, collapse, environmental impact

1. INTRODUCTION

The tailing dams are specific structures with high level of risks on the environment. The risks are connected with possible contamination of the ground water, air pollution and extreme consequences in cases of eventual failure.
This paper presents one specific case where a partial collapse of diversion tunnel bellow system of tailing dams which is a part of all structures in a frame of lead and zinc mine "Sasa" in Makedonska Kamenica. Formerly, tree tailing dams were constructed, and they are used for deposition of the waste material obtained by the technological process of flotation of lead and zinc minerals till present moment (Figure 1).

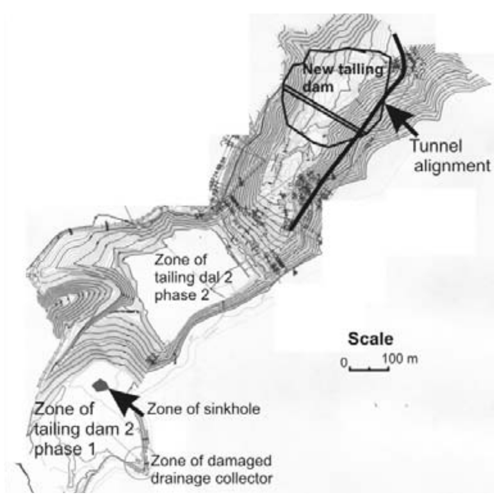

Figure 1. General layout of tailing dams for the lead and zinc mine “Sasa”

During 2005, a specific collapse at the area of Dam Lake had happened, connected with destruction of the diversion tunnel, occurence of the sinkhole at the waste area and partial contamination along river Kamenicka. (Figures 2 and 3)

a)

b)

Figure 2. Partial collapse of diversion tunnel and occurrence of sinkhole for the waste surface area of tailing dam 2

Figure 3. Contamination along Kamenicka river with waste material

Having in mind this specific case, after that, starting from 2007, the tailing dam 3 was designed and with all necesary remedial mesaures for future safe exploitation. It is insured with remediation of the old and construction of new section a new diversion tunnel.

Now, the process of design of tailing dam no 4 is in progress, so some elements of the technical solutions are given in a frame of this article. Briefly, geological and geotechnical elements of the environment are explained.

2. GEOMETRIC PARAMETERS OF THE DIVERSION TUNNEL

On the larger part of the length (≈70%), the tunnel is cut through gneisses that are jointed into blocks with dimensions from decimeters up to meters. The Rock Mass Rating for this sections belongs to so called III-category according to Bieniawski RMR classification. On the other part of the length of the tunnel's route (≈30%), the tunnel passes through gneisses that are cracked into smaller block and in a III-IV category according to Bieniawski. The input parameters for numerical analyses are given in a Table 1:

Table 1. Input parameters for the Hoek-Brown classification

Rock category according to Bieniawski	σ_{ci} (MPa)	GSI	mi	D
III	50	47	10	0.8
IV	50	30	10	0.8

Using the input parameters that are given in Table 1 and the equations used for the calculation of the strength-deformability rock parameters, according to the Hoek-Brown's failure criteria, the global strength of the rock material (σ_{cm}), cohesion (C), angle of the internal friction (φ) and the deformability module of the rock (E_{rm}) are given in a Table 2.

Table 2. Estimated values of the strength-deformability rock characteristics

Rock category according to Bieniawski	σ_{cm} (MPa)	C (MPa)	$\varphi^{(0)}$	E_{rm} (MPa)
III	4.2	0.246	43	3400
IV	2.3	0.135	34	1480

Based on this assumption, the designed procedure is briefly explained bellow.

3. STATIC AND DYNAMIC ANALYSES FOR THE DIVERSION TUNNEL'S LINING

3.1. Numerical model

Numerical model of the continuum, as well as the primary and secondary lining of the diversion tunnel, were made using the finite element method (FEM) which is also implemented as a part of the software package PHASE 2 (www.rocscience.com). Using the failure criteria of Hoek-Brown and the assumption that the surrounding rock material is elastic-plastic, numerical analyses were performed. A range of five diameters (5D) of the continuum, left, right and under the tunnel, was analyzed. The upper edge of the model is included in the analyses as it is the real terrain in the section with the maximal above layer. The following boundary conditions were adopted for the numerical model: flexible bearings in vertical direction on the left and right boundary, fixed bearings on the bottom boundary and free (without displacement limitations) upper boundary of the model. The numerical model is shown on the Figure 4.

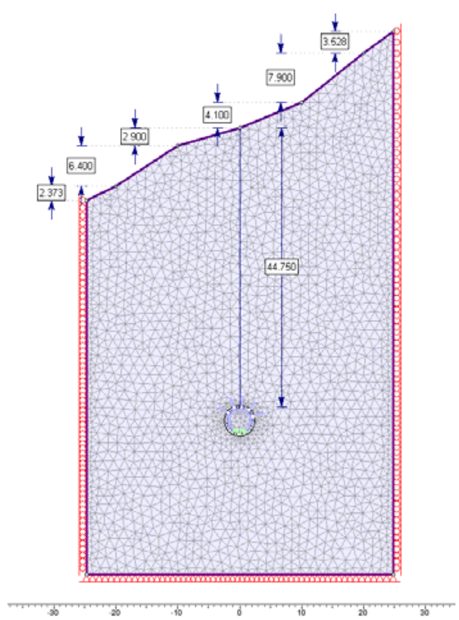

Figure 4. Numerical model

The tunnel construction is a process that happens during some period of time, so the analyses were performed in few phases as follows:

- **Phase-1:** the primary condition of the stresses in the massif, before any intervention;
- **Phase-2:** tunnel excavation;
- **Phase -3:** support placement;
- **Phase -4:** earthquake influences during the tunnel exploitation.

3.2. Loads

The most unfavorable section, aka the section where the largest primary stresses in the rock are expected, is the section of the route of the diversion tunnel extension that has a maximal above layer. The value of the above layer's height in that section is H_{nmax}=44.75m (Figure 4).
When the diversion tunnel's profile is excavated, it is expected that the primary stress condition of the surrounding rock mass will be disturbed, and that a concentrated stresses will occur in the opening area, which will lead to deformations appearance. In order to prevent large deformations in the walls of the tunnel excavation and uncontrolled increasing of the plastic zone around the unsupported tunnel excavation, as well as for the prevention of potential unstable blocks falling, the tunnel excavation has to be stabilized. The predicted stabilization, in this case, is formed of shotcrete support and anchors. Apart from the basic loads, that come from the size of the above layer mountainous material, analyses also include an earthquake influence (through the inertial forces) that occur when the earth's acceleration in horizontal direction is a_H=0.3g and when the earth's acceleration in vertical direction is a_V=±0.15g.

3.3 Results from the numerical analyses

Tunnel TYPE-4 is applied in the sections of the extension of the diversion tunnel where the rock mass falls into category III-IV, according to the Bieniawski classification. The primary support, made of shotcrete d=10cm; MB-25 (calotte +abutments) reinforced with a net reinforcement in the calotte Q-196 and "SN" anchors Ø22-25mm; La=2.5m; a_p/a_n=1.25/1.5m, completely ensures the tunnel stability. A complete final reinforced concrete lining is predicted for these parts, thickness of the lining is d=40cm and the concrete grade is 30 (Figure 5).

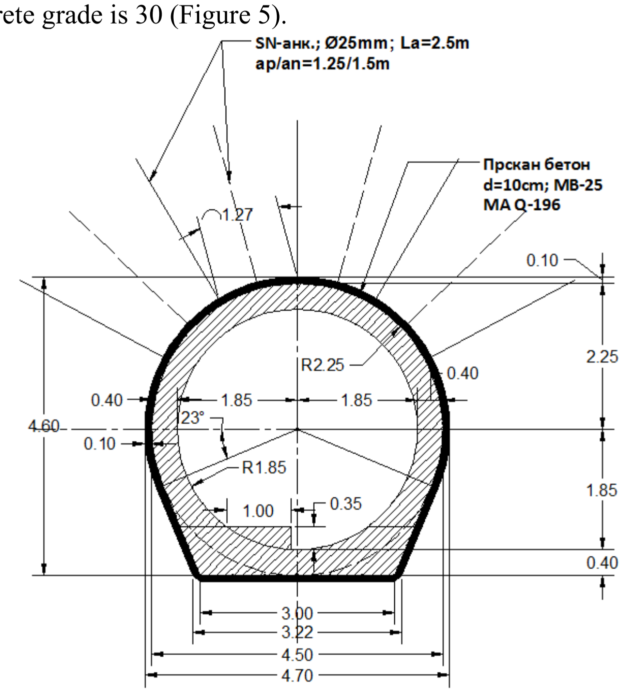

Figure 5. Tunnel TYPE-4 in materials of IV-th category according to Bieniawski

Diagrams and intensity of the axial forces, bending moments and transversal forces that occur in the primary support, are shown in the following Figures.
Measuring units: MN, m, MPa

Sign convention:

(+N)=pressure axial force; (-N)= tension axial force;

(+M)=tension stress from the inner lining side, pressure stress from the outer lining side;

(-M)= tension stress from the outer lining side, pressure stress from the inner lining side;

(+σ)=normal pressure stress; (-σ)= normal tension stress.

The diagrams for static units that occur in the shotcrete lining show that the axial forces are dominant compared to the bending moment which are relatively smaller.

3.3 Static units for the final concrete lining of the tunnel TYPE-4

Few different load cases were analyzed considering the final concrete lining. The goal was to obtain the most unfavourable load case. Analyzed load cases are explained further bellow:

a) The whole rock load affects the final lining (with the assumption that the primary support is not permanent and it doesn't receive any loads during the exploitation) and an earthquake load with horizontal acceleration a_H=0.3g and vertical acceleration a_V=-0.15g (downwards).
b) Same as a) but with vertical acceleration a_V=0.15g (upwards)
c) The whole rock load is accepted by the primary support (according to the NATM principles), and the final lining is affected only by its self weight and by the earthquake with with horizontal acceleration a_H=0.3g and vertical acceleration a_V=-0.15g (downwards).
d) Same as c) but with vertical acceleration a_V=0.15g (upwards)

From these four load cases, the most unfavourable is the load case d), the case when a tensile stresses occur in the concrete lining which leads to the need for an appropriate reinforcement usage. For the other three load cases (a, b and c) only a pressure stresses occur in every cross section of the final concrete lining, and there is no need of a reinforcement. The occurred static units in the final concrete lining, for the most unfavourable load case (d), are shown in the following figures.

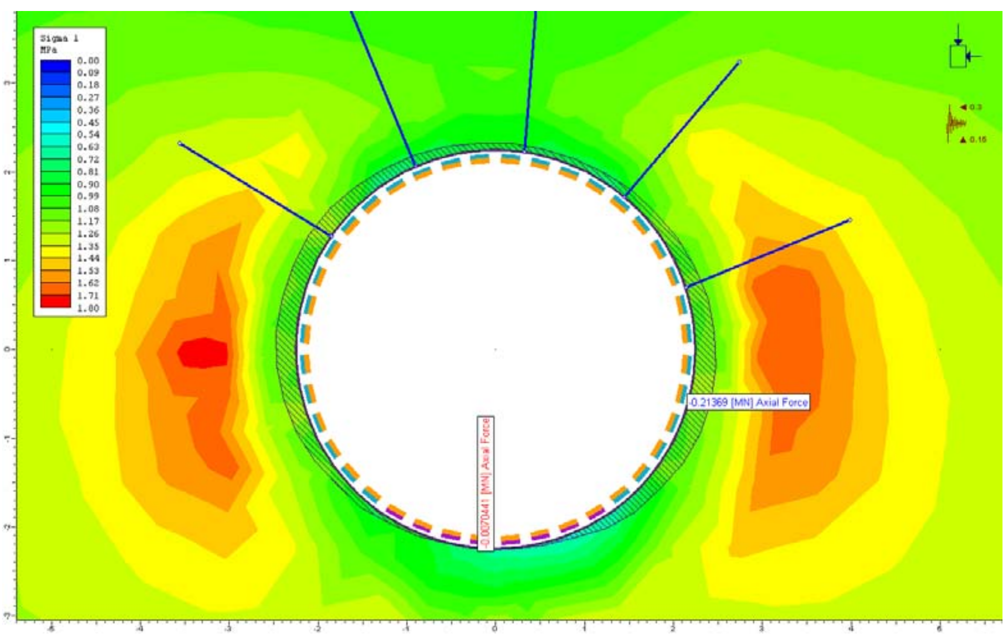

Figure 6. Diagram of the axial forces in the concrete lining for an earthquake influence

N_{max} = -0.214 KN (tension) N_{min} = -0.007 KN (tension)

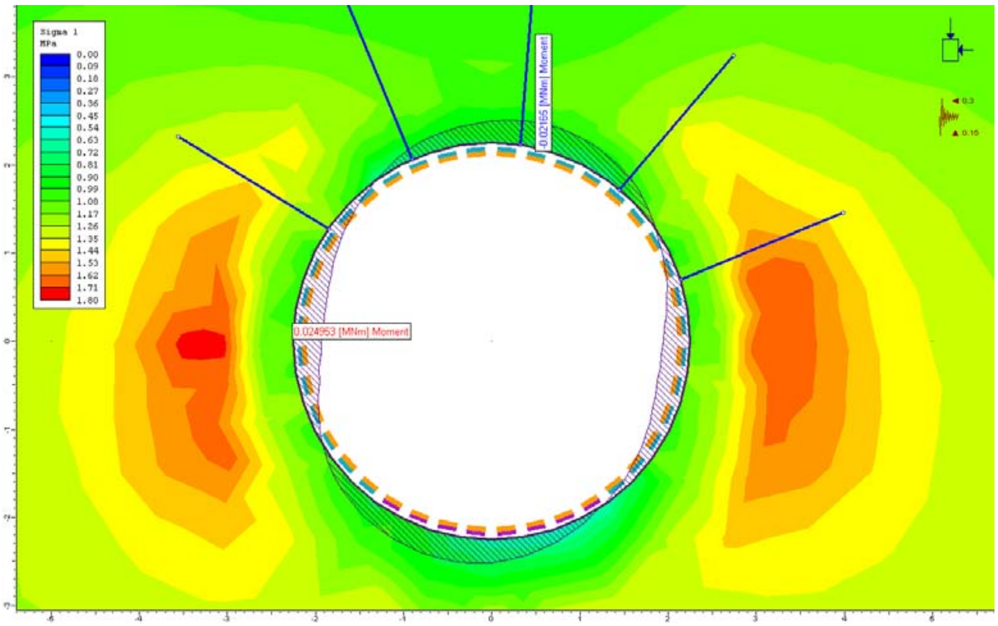

Figure 7. Diagram of the bending moments in the concrete lining for an earthquake influence

M_{max} = 0.025 MNm N_{min} = - 0.0022 MNm

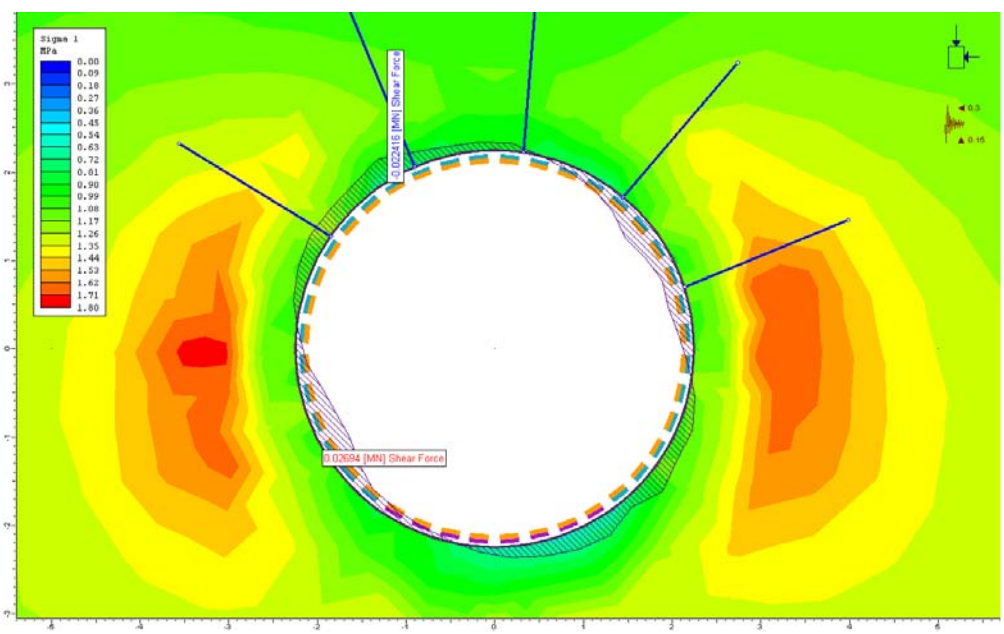

Figure 8. Diagram of the transversal forces in the concrete lining for an earthquake influence

Qmax = 0.027 MN Qmin = 0.022 MN

3.4 Dimensioning of the primary support for the tunnel TYPE-4

The load-bearing capacity diagrams of the concrete with formwork that has a thickness d=40cm and concrete grade MB 30, are shown in the following figures:

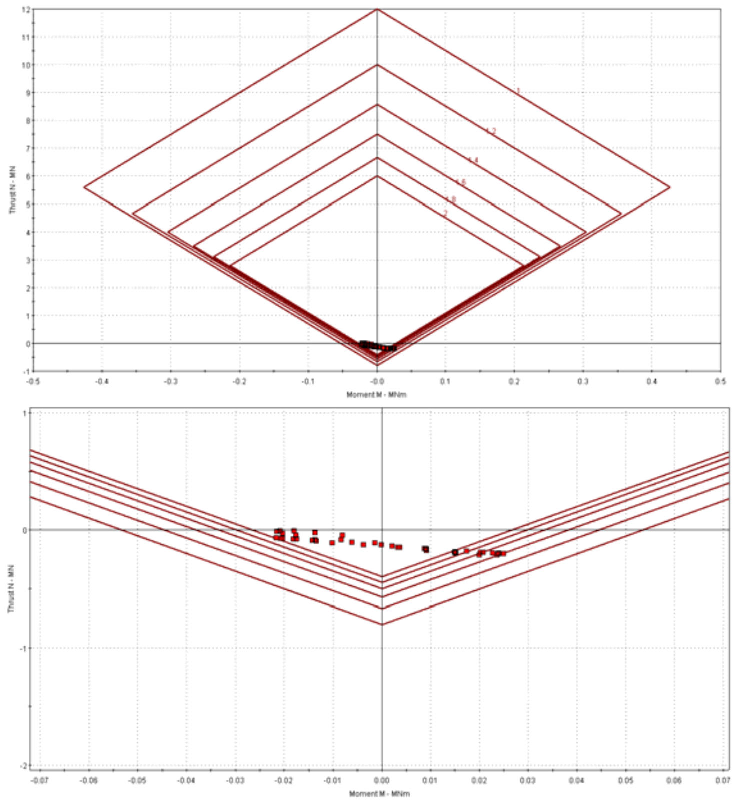

Figure 9. Load-bearing capacity envelope as a function of moments and axial forces, for concrete with formwork that has a thickness of d=40cm, MB-30

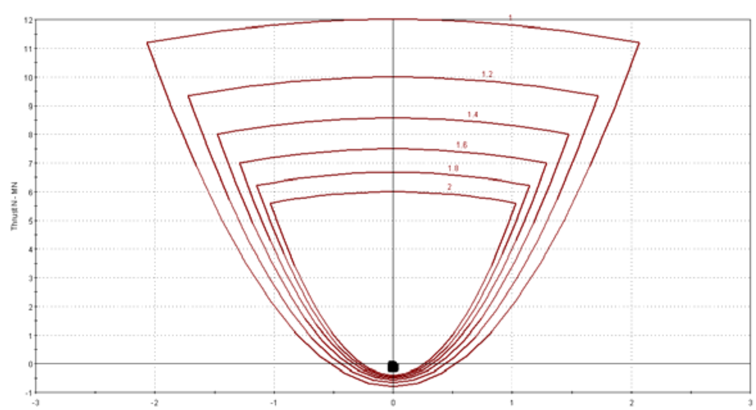

Figure 10. Load-bearing capacity envelope as a function of transverse and axial forces, for concrete with formwork that has a thickness of d=40cm, MB-30

Analyzing the figures 8, 9 and 10, it can be concluded that in some cross sections of the final concrete lining, the safety factor is lower than 2 (Fs<2) which shows that an appropriate reinforcement has to be used for the final lining.

The calculations for the required reinforcement, according to the Macedonian regulative for the limit load-bearing capacity are given by the following equations (Eq. 1):

$$N_{ui} = \gamma_u \cdot N_{max} = 1.3 \cdot 214 = 278\,KN$$
$$\mathrm{M}_{ui} = \gamma_u \cdot \mathrm{M}_{max} = 1.3 \cdot 25 = 32.5\,KNm \quad (3.1)$$

For concrete cross section with thickness Db=40 cm; MB-30; RA-400/500; a=5cm (symmetrical reinforcement):

$$A_{pot} = 2x6.3\ cm^2/m \quad (3.2)$$

For symmetrical reinforcement Φ12/18cm (A=2x6.3cm^2/m) is adopted.

According to Eurocode-2 (for walls):

$$A_{smin} = 0.002 \cdot A_{?} = 0.002 \cdot 100 \cdot 40 = 8\ cm^2/m' \quad (3.3)$$
$$A_s = 2 \cdot 6.3 = 12.6\ cm^2/m' \rightarrow OK$$

4. CONCLUSIONS

The exploitation of the tailing dams is connected with is with high level of risks on the environment. This indicates that design of diversion structures must be done with a great attention, in order to insure safe work during operational phase. The important step in the design is to obtain reliable input parameters for the geological elements along diversion structures, which is basic prerequisite for numerical analyses. Authors believe that the given analyses can be illustrative for similar cases in the practice.

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