MECHANICAL BEHAVIOR OF FRACTURED ROCK MASS – CASE STUDIES FROM BÁTAAPÁTI RADIOACTIVE WASTE REPOSITORY

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Rock mechanics, deformation, extensometer, modelling

INTRODUCTION
The Hungarian National Radioactive Waste Repository is being built in the neighborhood of the village called Bátaapáti. The program of the new disposal facility for the low- and intermediate-level wastes (L/ILW) is conducted by PURAM (Public Limited Company for Radioactive Waste Management).
The building contractor of the Bátaapáti project is Mecsekérc Ltd., and Mott MacDonald Magyarország Ltd. (MMM) designed the underground excavation method and rock support system.
The Bátaapáti underground research program began in February 2005, with the excavation of the two inclined exploratory tunnels. These tunnels have with 30 m distance between their axes, 10% inclination and 1.7 km length. The tunnels reach the 0 m Baltic sea-level in the Mórágyi Granite Formation. The inclined tunnels are connected with 7 cross tunnels (approx. 250 m between their axes). The main horizontal access tunnel system and two repository chambers which area is called as repository level. The overburden of the repository level varies between 240-270 m B. sea level. The tunnel excavation was carried out with drill and blast method. The average advance length were 1-3 metres depended on the excavated rock mass quality. In the tunnel construction, sections of 21 m^2, 25 m^2 and 36 m^2 were used. Tunnelling has been preceded by pilot or probe holes drilling from the beginning of the construction, which enables geological and geotechnical prognoses to be provided. The drill cores provided a large number of core samples. These core samples were used for rock mechanical laboratory tests. Thanks to the continuous sampling and testing results cover the whole excavated tunnel system. The two repository chambers excavation, with section of 96 m^2 were completed in September 2011.
The safety of nuclear repository mainly is influenced by the ground behaviour and it's fracturing.
Beside the laboratory test results were collected as well basic information on the rock mass with in-situ rock measurements. So far fourteen mechanical convergence arrays and nine arrays with multipoint borehole extensometers were installed and monitored. Three of them were not radial arranged, but installed in a „passing" type arrangement. In these arrays the tunnel excavation effects were studied depending on the excavation face position. In a separated research Hydro-geomechanical (HGM) chamber (built by PURAM), the effects of the tunnel driving were studied using hydrogeological, rock mechanical and geophysical monitoring systems. The 3D CSIRO-HI cells have been also used parallel with the convergence arrays and extensometers for tunnel deformation measurements (note: we had separately CSIRO HI cell measurements for the in situ primer stress overcoring observations).
Significant amount of data were collected from the large number of samples of the high accurate measurements on the field geotechnical and rock mechanical characteristics (Table 1.). In many cases the results of these measurements revealed new problems. The behavior of the rock mass could not be explained by continuum mechanical approach. In order to understand the observed behavior continuum and discontinuum models were implemented of the selected measuring arrays.

The calibration model of the main designer experts carried out using UDEC (Universal Discrete Element Code, Itasca, 2004) based on the Ext-3 extensometer array results. This model was constructed without the geotechnically documented fractures (Váró et al. 2009, Váró et al. 2011). For using limit equilibrium calculations, the designers were based on UNWEDGE results. The design was based on continuum mechanical approach (Flac – Fast Lagrangian Analyses of Continua – 3D and 2D, Phase^2 - without discontinuities).

Table 1: Main rock mechanical input parameters of intact monzogranite
(used in the presented models)

UCS	MPa	108
Young's modulus	GPa	47
Poisson's ratio	-	0,2
Density	Kg/m^3	2700
m_i	-	18

EXPERIMENTAL DESIGN

Because of the long-term environmental and radiological safety, the design, construction and monitoring had to be able to describe and predict the Mórágy Granite Formation's geotechnical-rock mechanical characteristics and behaviour. The information were collected on the site parallel with the underground construction work. These information were used by "design as you go" principle to optimize the tunnel driving and the support technology and ensure the long term safety. The most important part of this process is to get to know how the surrounding rock reacts to the tunnel excavation. As the rock losses its self-support, the stresses start is changing around the tunnel and cause movements until reaching the new state of equilibrium. Following this process with measurements and the interpretation of the results provides important information on the realistic rock behaviour for the design and construction.

The measurement arrays were designed by MMM and RockStudy Ltd. The installations of instruments were made by RockStudy Ltd. We have got an assignment to interpret and explain the measurement results based on the installation circumstances, the geotechnical characterisation of the tunnel mapping, the core logging and the field observations. Different trial models were used to confirm the measurement concept. The detailed 3D modelling was carried out by the designer.

Radial arrangement extensometer arrays have been installed close to the front face (around 1.5-2.5 m) in order to investigate the measurable maximum range of deformation caused by tunnel excavation. In these arrays 6 radial extensometers were installed with its ends fixed at 18 m depth from the tunnel wall (around triple tunnel diameter). These extensometers were combined with mechanical convergence measurements with 6 directions around the arrays.

In the case of the "passing" type arrangement, the instruments were installed into boreholes drilled outside passing toward the investigated tunnel. In this configuration the displacements caused by the oncoming excavation was also measurable. Another advantage of this arrangement was measure the displacement several metres in front of the excavation face, and to calculate its ratio to the total displacement. This measurement has a great importance because in most cases there is just the possibility to measure a rate of the whole displacement range by devices installed from the given excavated tunnel.

Knowing the deformation is useful also during the modelling process, because in the 2D models the tunnel excavation is separable into more phases. The supporting effect of the tunnel face is taken into account as well. The rock self-support decreases until the stresses can be accurately modelled with a two-dimensional plane-strain approach, as the tunnel face advances away from the area of interest.

Geokon A-5 type of extensometers with logarithmic anchor positions were installed in the way that the last anchor is as close to the tunnel as possible with overblasting taken into account as well.
The analyzed extensometer arrangements are shown on Figure 1. The extensometers at the array Ext-6 are installed towards the "7OK" cross tunnel, the instruments at Ext-7 towards "KAV" repository access tunnel, and the ones are installed at Ext-9 towards EPZS (fork tunnel).

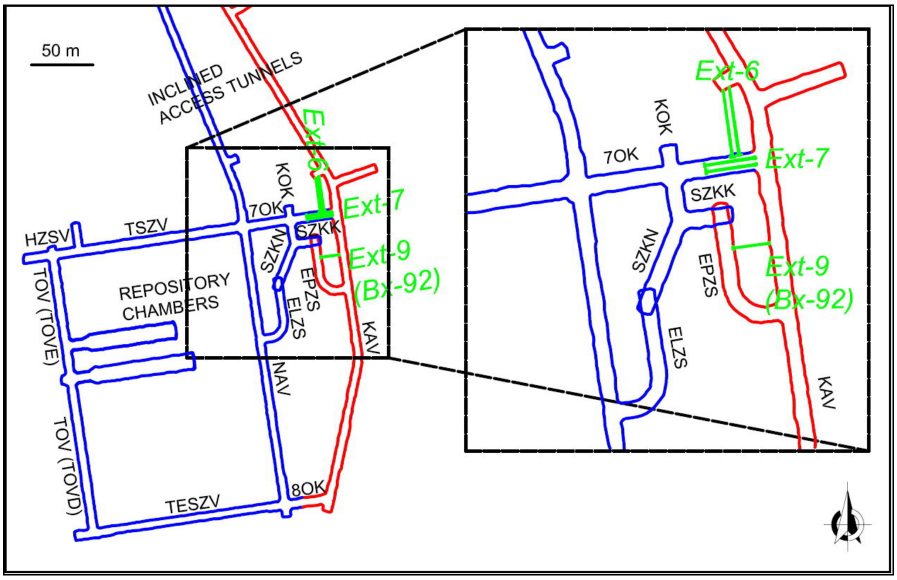

Figure 1. General layout of the repository facility level with the analyzed extensometer arrays

ROCK MECHANICAL BEHAVIOR OF A CASE, EXPLAINED WITH CONTINUUM MECHANICAL APPROACH

Measurement results

The increments caused by the blasts can be observed on the displacement-time graph (Figure 2). The installed extensometers were able to measure the realistic displacements of the surrounding rock. The graph shows that the most intensive reaction to the tunnel driving appears when the tunnel face reaches the measuring array as well as at the following 2-3 blasts and after it decreases gradually.
The displacements of the anchors were plotted against the relative distance of the actual face and the measuring array. To these diagrams the average of the measured values between the blasts were used, so the values are related to the face positions. As fitting curves on the points the deformations at the measuring array are drawn up.
The graph shows that the displacement occurs similar to the theoretical process. This means that the measurable displacements in the rock mass begins at a distance of about one-one and half of a tunnel diameter ahead of the face. When the tunnel is coincident with the measuring arrangement, the radial displacement is about one third of the maximum value. The displacement reaches the maximum value when the face has progressed about one and one half tunnel diameters beyond the measuring array or arrangement and the support provided by the face is no longer effective. This theory works well in cases where the only support provided is by the rock ahead of the advancing face in circular shape tunnels, Hoek et al. 1995.
The largest displacement appears at the anchor 5 which is the closest one to the excavated tunnel's side wall. The displacement are less at the farthermost anchor.

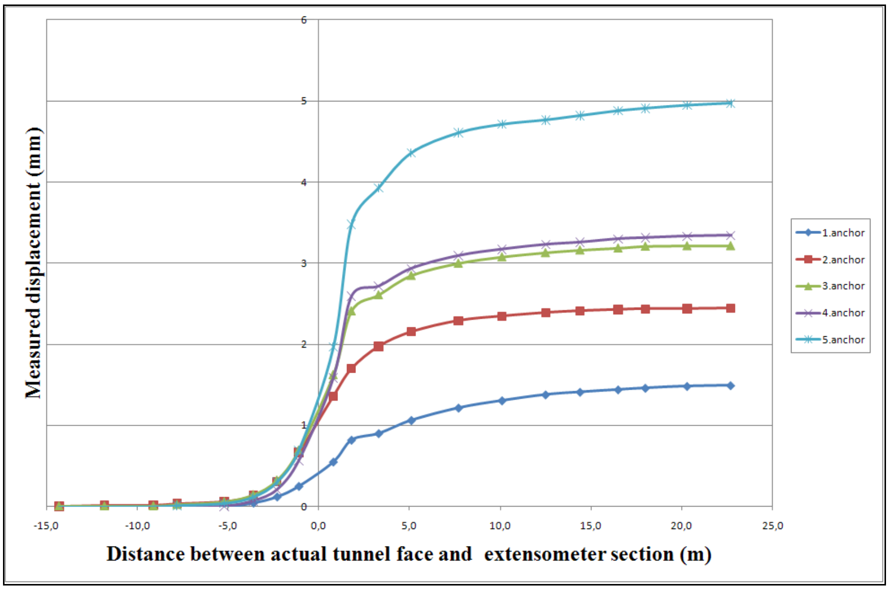

Figure 2. Measured displacement on the anchors of extensometer (MPBX) Bx-71

Modelling results

A continuum mechanical model in Phase[2] was constructed. This is a finite element stress analysis program (Rocscience). The self-support of the tunnel face was taken into consideration with a softened material properties area in the infected area. The excavation damaged zone (EDZ) around the tunnel caused by the blasting was also defined with decreased mechanical properties. The designer defined a Q based rock mass classification system for excavation of the repository area. Based on this classification system the rock mass was distinguished in 6 rock classes. The minimum, medium and maximum Q values of the geotechnically documented rock class interval relating the measuring arrays were taken into account.

The results from the model and the measurement are plotted on the same diagram in the function of anchors and distance from the tunnel wall (Figure 3). The shape of the deformation on the extensometer is similar to the modelled ones. The values are between the modelling results of the array. Accordingly this area could be explained with continuum mechanical approach.

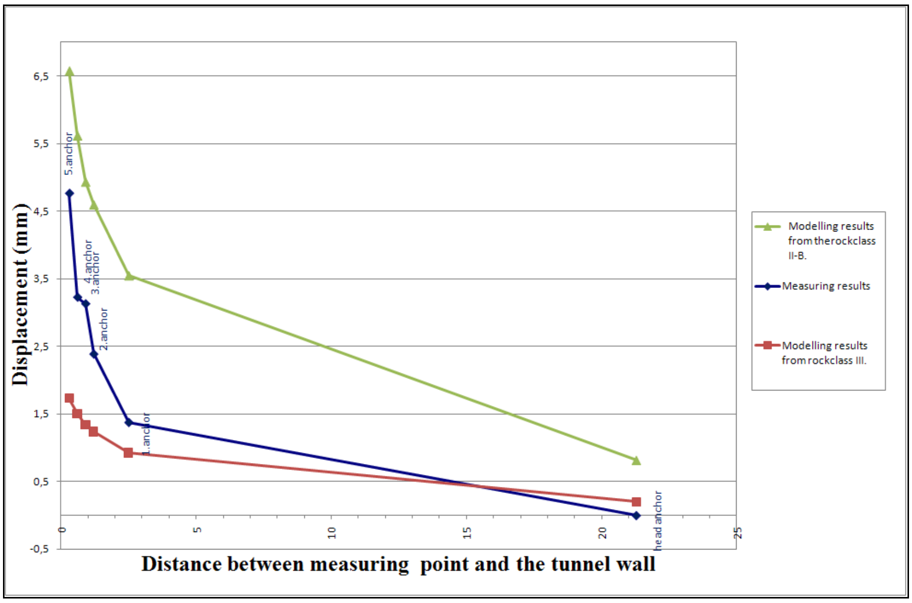

Figure 3. Measured displacement at Bx-71

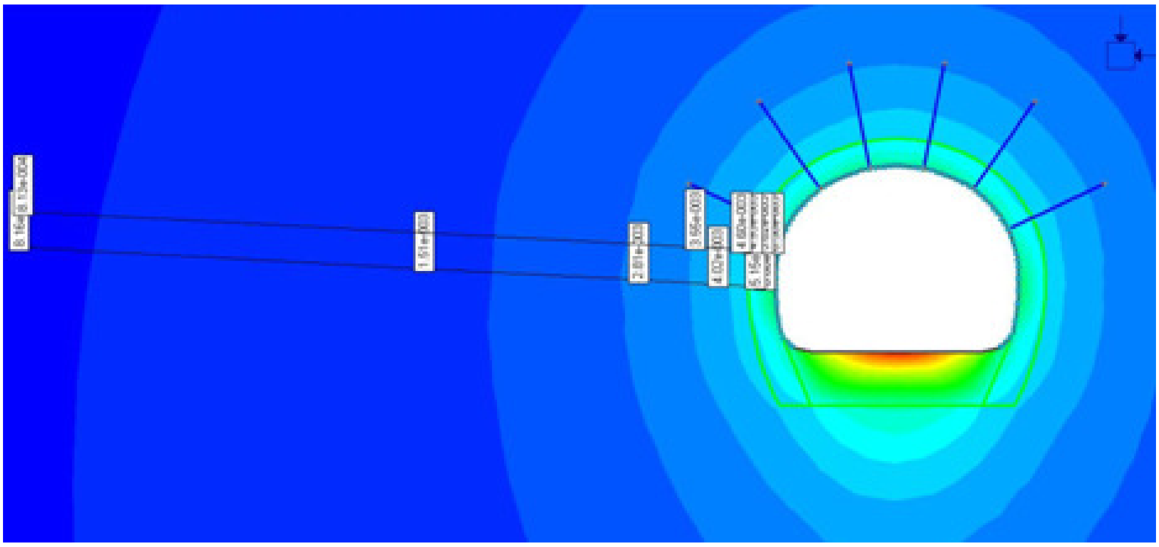

Figure 4. Modelling results and readouts at the anchor points

ROCK MECHANICAL BEHAVIOR OF A CASE STUDY UNEXPLAINED WITH CONTINUUM MECHANIC APPROACH

Measurement results

On further investigation results from the Bx-92 extensometer array (Ext-9 system) have produced some discrepancies by continuum mechanical approach (Figure 5):

-After several blasts it didn't set directly into the equilibrium state, the displacements continuously have been increased.

-The biggest increase of displacement appeared one blast before the face reached the measuring array.

-Advancing the Bx-92 array, the second and third blasts brought on minimal displacements on the anchors, while in continuation the transducers detected significant rock reaction.

-The largest displacements have turned up at anchor 3.

Beside the above mentioned extensometers a mechanical convergence array was installed, where similar deformations were measured. The results of the two measuring methods confirm each other. Consequently conformation of displacements around the extensometer array has close relationship with the geological background, the tectonization of this area.

Modelling results

The modelling work was started with continuum mechanical approach, using the Phase^2 software. However the measured trends could not be described using this approach.

After the first try the real surveyed tunnel section and the mapped fractures by geologists during the excavation were defined (Figure 6). To solve the discrepancies between measurements and modelling Phase^2 and UDEC were used parallel.

The Phase^2 was able to model rock mass problems with explicit representation of discontinuities using special joint elements in the Finite Element Method and it was possible to use this approach for routine (more details in Hammah et al., 2008).

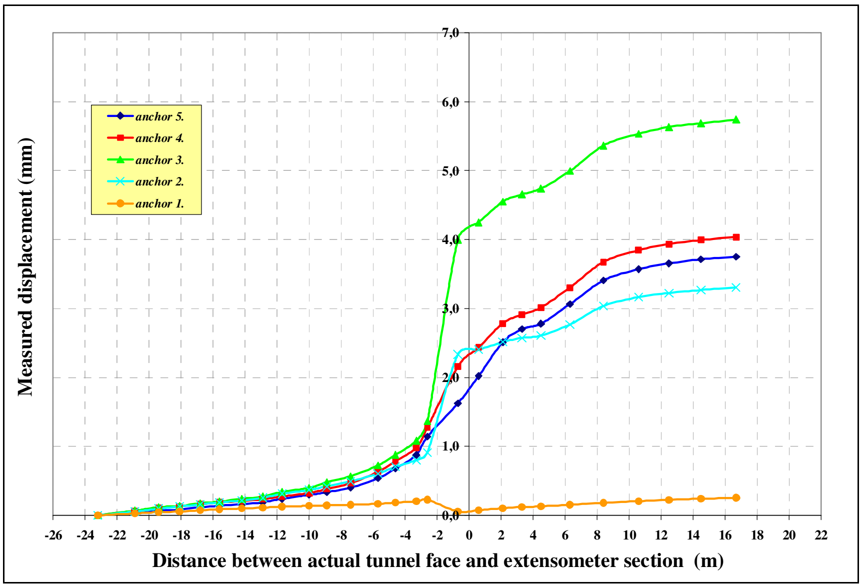

Figure 5. Measured displacements at Bx-92 extensometer

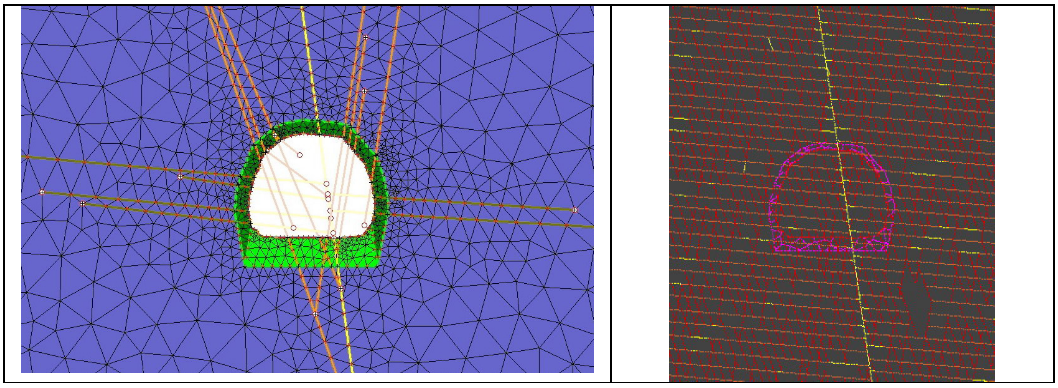

Figure 6. The tunnel section which included the extensometer arrangement with the documented main fractures and EDZ zone (Phase^2 – left, UDEC – right)

The model runs did not bring the appropriate measured displacement values or displacement trends (Figure 7).

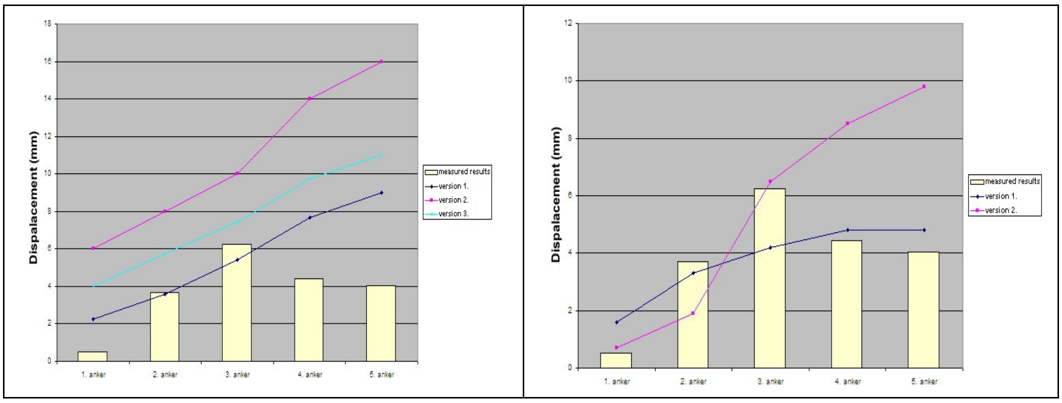

Figure 7. The graphs of modelling results with the measured displacements (Phase^2 on the left side, UDEC on the right side, after Vida, 2010)

Since the structural features from the geological maps didn't explain this behavior, an important clay filled fracture out from the tunnel was introduced. The fracture was found from the Bx-92 drill cores, as a section between 13,09-13,20 m without core recovery. This missing core section could indicate the presence of out-washed clay strata. The depth of this fracture agreed to the rock area beyond the anchor 3 toward the tunnel (Figure 7).

In the next step the clay-infilled fracture has been introduced into the models.

The UDEC model didn't provide similar results as the measurements. In the future these models will be refined. The Phase^2 results had very good correlation with the measured displacements (Figure 8).

The model values were fitting the Bx-92 anchor movements: anchor 1 = 3 mm, anchor 2 = 6 mm, anchor 3 = 7.8 mm, anchor 4 = 4 mm, anchor 5 = 3,3 mm.

The definite reason why the largest displacement increases occur before excavating of the face, were not found yet. It is a 3D problem and could be related to the geology. For example there could be the existence of a steeply dipping weak fracture zone in front of the array loading on this area with a strike northeast-southwest. However it should be emphasized that the geological mapping and the documentation does not show such a weakness zone.

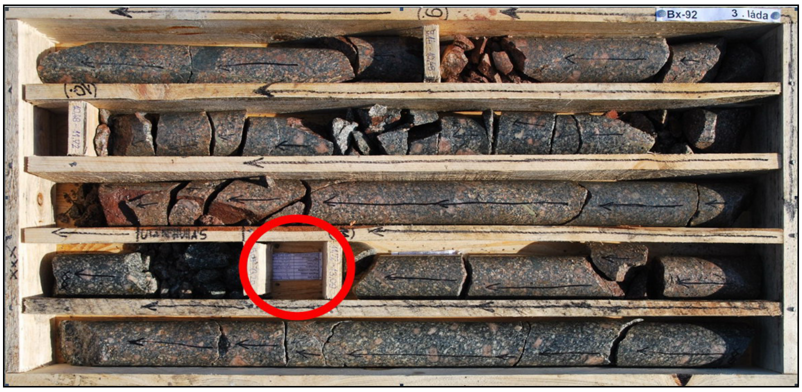

Figure 7. The Bx-92 extensometer drill cores (no core recovery with red circle)

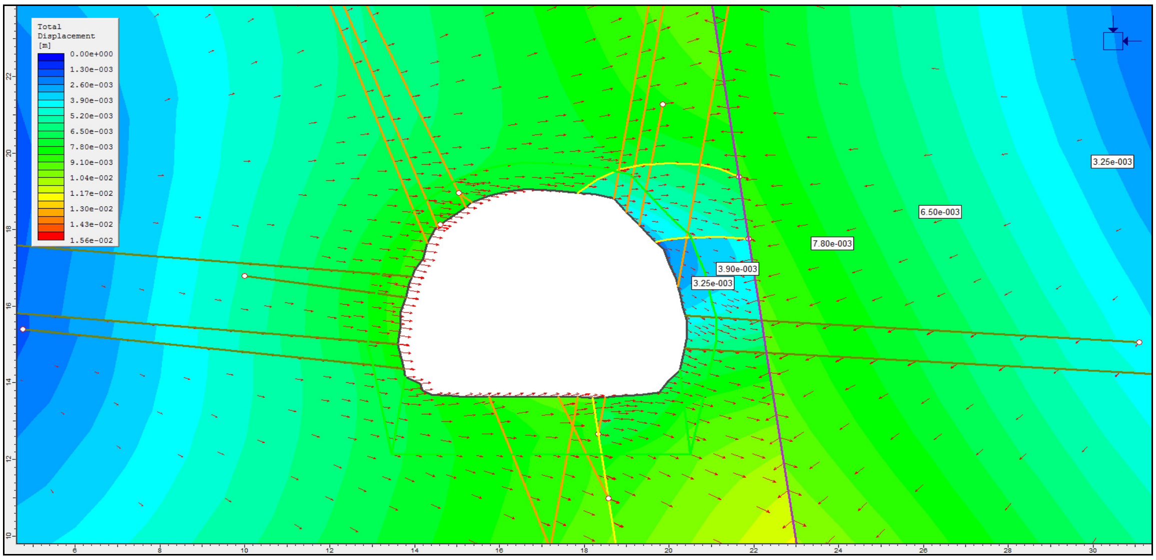

Figure 8. Displacement distribution with the introduced clay-infilled fracture

CONCLUSIONS

The presented two case studies together with other experiences from Bátaapáti reveal the variability of Mórágyi Granite Formation and highlight that it is intersected with fractures, fracture systems. These discontinuities have a great influence on the size and distribution of the tunnel wall displacements. From the mentioned discontinuities, the clay infilled fractures appears to have high priority. Modelling back analyses demonstrated, that it is necessary to use the continuum- and discontinuum mechanical approaches in the case of Bátaapáti project together.

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