ADECO-RS PRÍSTUP A PLNOPROFILOVÉ RAZENIE TUNELA VIŠŇOVÉ

THE ADECO-RS APPROACH AND THE FULL-FACE EXCAVATION FOR VISNOVE TUNNEL

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ABSTRAKT
Príspevok popisuje základnú koncepciu návrhového prístupu ADECO-RS, aplikovanú pri projektovaní a razení tunela. Je tu uvedené, ako bolo vyvinuté a vylepšené plnoprofilové razenie prostredníctvom skúseností získaných pri výstavbe cestných i železničných tunelov v posledných tridsiatich rokoch. Hlavnou črtou ADECO-RS je, že sa projektant zameriava predovšetkým na deformačnú odozvu masívu vo vzťahu k pôsobeniu raziacich prác. Deformačná odozva je najprv analyzovaná a predpovedaná za použitia rôznych nástrojov (in situ a laboratórnych skúšok, matematických modelov, a pod.) a potom je riadená pomocou vhodných stabilizačných opatrení. Na rozdiel od tradičných prístupov, ktoré berú do úvahy iba deformáciu za čelbou, ADECO-RS skúma deformačnú odozvu veľmi starostlivo už od jej vzniku pred čelbou. V dôsledku tohto prístup riadi odozvu deformácie predovšetkým pred čelbou, za použitia predzaisťovacích opatrení a nielen obyčajných vystrojovacích prvkov ako u tradičných prístupov. Týmto spôsobom je ADECO-RS schopný úspešne riešiť akýkoľvek typ geotechnických a napäťovo-deformačných podmienok, a to najmä v ťažkých podmienkach. Použitie metódy je prezentované na skutočnom prípade dvojrúrového tunela Višňové na diaľnici D1 Lietavská Lúčka - Višňové - Dubná Skala s dĺžkou razenia cca 7450 m v žilinskom regióne.

ABSTRACT
The paper describes the basic concepts of the approach ADECO-RS, for the design and construction of tunnels. It is shown how full-face excavation has been developed and improved through the experiences gained for construction of both road and railways tunnels in the past thirty years. The main feature of the ADECO-RS approach is that the design Engineer focuses primarily on the deformation response of the ground to the action of excavation. This deformation response is first analysed and predicted using a variety of instruments (full scale and laboratory tests, mathematical models), then it is controlled by using appropriate stabilisation measures. As opposed to traditional approaches, that only consider deformation behind the face, the ADECO-RS approach investigates the deformation response very thoroughly, right from its onset where it starts ahead of the face. As a consequence, the approach controls the deformation response acting first and foremost ahead of the face, using pre-confinement action, and not just ordinary confinement action as in traditional approaches. In this way the ADECO-RS approach is able to successfully tackle any type of ground and stress-strain conditions, especially in difficult ground. The application for the real case of "Visnove Tunnel" in D1 Motorway will be presented.

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1. Introduction

Between the end of '800 and the beginning of '900 no established method was available for the design and excavation of tunnels in difficult ground conditions and for different models of ground behavior. It must be recognized however that, in order to meet the needs posed by the new transportation means and the increasing mobility requests, spectacular tunnels were excavated and completed, such as Frejus and Simplon railway tunnels through the Alps and "La Grande Galleria dell'Appennino" through the Apennines between Bologna and Firenze. This was achieved although a number of workers lost their lives for the sake of reaching the objective. In the absence of established methods, different ways of tunneling were applied such as the Belgian, Austrian and Italian methods, etc. which were essentially characterized by significant differences in the choice of the section where to initiate excavation. It was only between 1920 and 1960 that landmark contributions in tunneling took place by Terzaghi (the "rock load" due to the weight of the broken ground resulting from the excavation of the tunnel), Kastner and Fenner (the development of a "plastic zone" in the rock mass surrounding the tunnel), and Rabcewicz (the New Austrian Tunnelling Method), to mention a few.

In line with the session topic of the 38th Geomechanics Colloquy, one may address the great merit of Rabcewicz who pointed out: (1) *the importance of conserving and mobilizing the inherent strength of the ground surrounding the tunnel,* (2) *the need to minimize ground loosening and excessive deformations by means of a primary support system, flexible rather than rigid, and placed to remain in physical contact with the ground and deform with it*, (3) *the installation of instrumentation to monitor tunnel deformation and build-up of load in the support, for gaining information on tunnel stability and optimizing the load bearing rock mass ring*. Naturally, the tools available to Rabcewicz were those of the time when his "approach or philosophy" was developed, by integrating the principles of rock mass behavior and the monitoring of this behavior. Use was still made of ground classes (Lauffer-Pacher, Bieniawski and so on) and the analyses to understand the ground behavior were performed in two-dimensional conditions and limited to the tunnel cross section. No sophisticated and advanced three dimensional computational tools were available at that time as presently adopted. To control tunnel stability during face advance, the only option was to adopt sequential excavation.

Rabcewicz was well aware of the need to improve the way of thinking of the time, when he pointed out that "*Tunnels should be driven full face whenever possible, although (today) this cannot always be done....*" (Rabcewicz, 1964). It is indeed in this context that in the mid '80s Lunardi (2000) pointed out the importance of the stability of the "core-face" and conceived the ADECO-RS approach. He suggested that understanding and controlling the behavior of the ''core'' ahead of the advancing tunnel face is the secret to successful tunneling in difficult ground conditions.

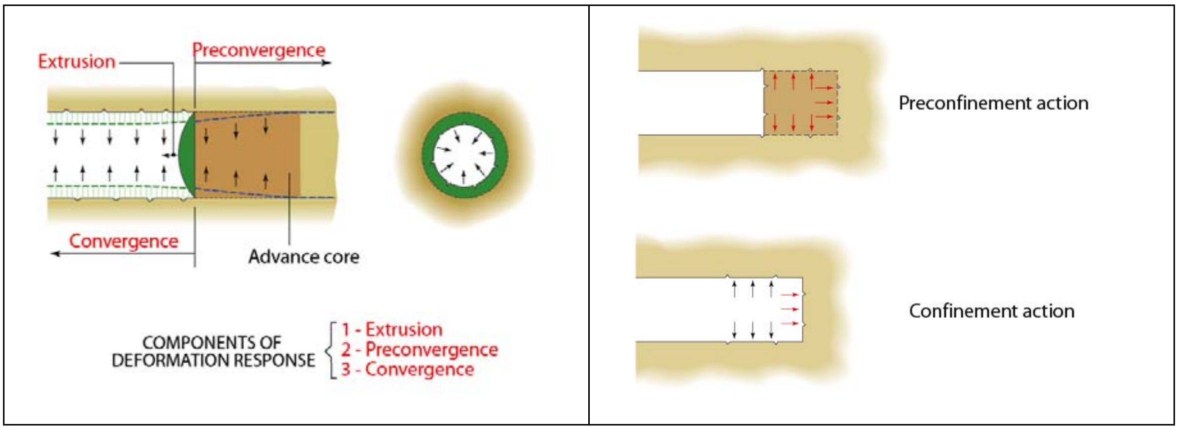
2. The principles of the ADECO-RS Approach

The ADECO-RS approach, which stands for "Analysis of controlled deformations in rock and soil", has shared the concepts of Rabcewicz by applying them to the "extreme":

- the ground considered as a construction material
- the importance of the ground deformational response during excavation
- the advantage of driving the tunnel always full-face in every stress-strain situation
- the importance of the invert in difficult ground conditions (to "close the ring")
- the relevance and value of stress-strain monitoring during face advance.

It is important to highlight how the above concepts are the fundamental components of ADECO-RS. These were agreed upon and further developed. Where possible, the "inherent" weaknesses associated with NATM, mainly due to the limited knowledge, at the time of development, on the control of the ground response during excavation were "corrected".

In order to be successful in this task, the Deformation Response of the ground and rock-mass, subject to excavation action, in terms of "Analysis and Control" should be carefully studied (theoretical forecasting in the design phase and experimental verification during the actual excavation). Deformation response is complex and involves not just the tunnel cavity, but also the volume of ground that lies ahead of the face, virtually cylindrical in shape, with dimensions quite similar to that of the diameter of the tunnel to be excavated. This region, called the "advance core", is affected by a primary component of the deformation response: "extrusion", which manifests on the surface of the face along the longitudinal axis of the tunnel (bellying or rotation of the face), and "preconvergence" of the cavity, i.e. the convergence of the theoretical profile of the tunnel ahead of the face (Fig. 1). These primary components depend on the relationship between the strength and deformation properties of the advance core and its original stress state (Lunardi, 1997). Research has found that:



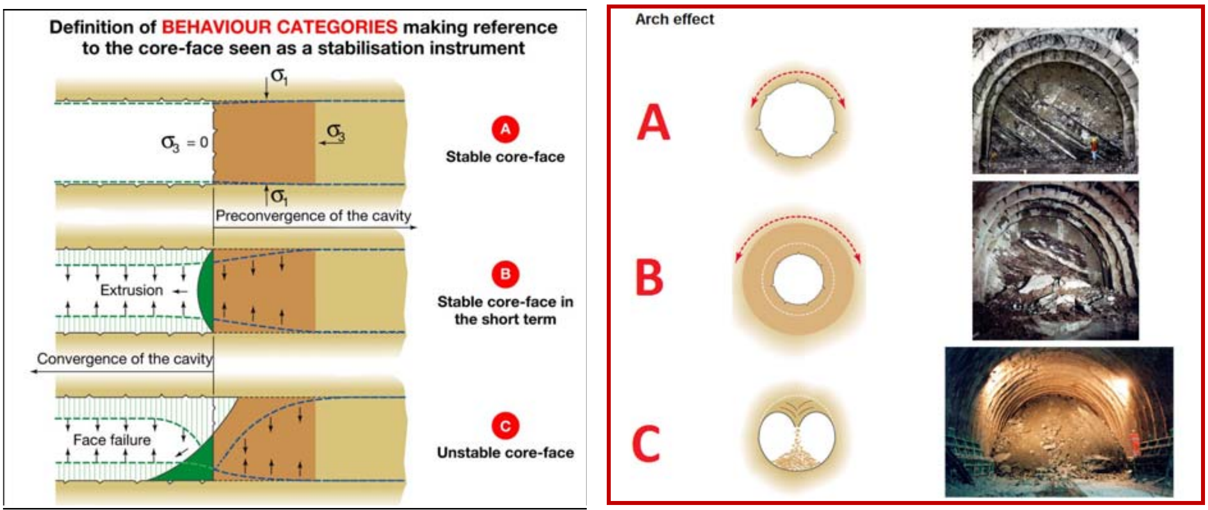
Obr. 1. Prvky deformačnej odozvy a účinky

Fig. 1. Components of deformation responce and actions

- there is a close connection between extrusion of the advance core at the face and preconvergence and convergence of the cavity. Also, deformation in the cavity normally follows and is strictly dependent on deformation in the advance core, which is the true cause of the whole deformation process in all its components;
- it is possible to control advance core deformation (extrusion, preconvergence), and as a consequence also to control cavity deformation (convergence), by acting on the rigidity of the core with measures to protect and reinforce it (Fig. 1);
- the rigidity of the core plays a determining role in the stability of a tunnel both in the short and long term.

The "advance core" can be seen as a "stabilisation instrument" and its analysis is very important at the design stage, just as the monitoring of the deformation response of the core-face, and not just of the cavity, is very important at the construction stage. The definition of the behaviour of the core-face, in the absence of stabilizing procedures and referring to the intrinsic carachteristics of the ground and rock-mass, allows to define the following categories of the core-face, reported in Fig. 2 and explained in detail in Lunardi (2000, 2008):

- **Category A "Stable core-face"**: is identified when the state of stress in the ground at the face and around the excavation is not sufficient to overcome the strength properties of the medium: the “arch effect” occurs naturally. Deformation phenomena develop in the elastic range, occur immediately and are negligible. The face as a whole is stable. Local instability only occurs due to the fall of isolated blocks caused by an unfavorable configurations of the rock mass. The stability of the tunnel is not affected by the presence of water even under hydrodynamic conditions, unless the strength properties of the ground are mechanically or chemically affected by the water. Stabilisation techniques are mainly employed to prevent deterioration of the rock and to maintain the profile of the excavation.

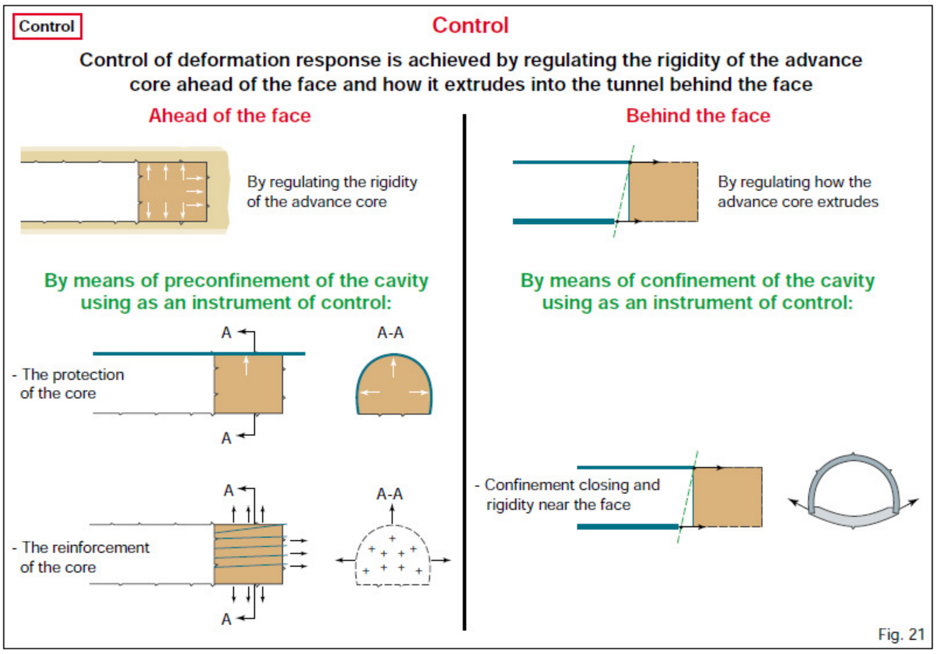


Obr. 2. ADECO-RS kategórie jadra čelby
Fig. 2. ADECO-RS Core-face categories

- **Category B “Stable core-face in a short time”**: is identified when the state of stress in the ground at the face and around the cavity during excavation is sufficient to overcome the strength of the ground in the elastic range. An “arch effect” is not formed immediately around the excavation, but at a distance from it that depends on the plasticization ring. The deformation that occurs is in the elasto-plastic range, is deferred and measurable in centimetres. The tunnel is stable in the short term; extrusion does not affect the stability of the tunnel because the ground is still able to muster sufficient residual strength. Instability manifesting in the form of loose material breaking away is widespread at the face and around the cavity, but allows sufficient time to employ traditional radial confinement measures after the passage of the face. In some cases it may be necessary to resort to preconfinement of the face, balancing stabilisation measures between the face and the cavity so as to contain deformation within acceptable limits. The presence of water, especially under hydrodynamic conditions, reduces the shear strength of the ground, and therefore increases the entity of instability phenomena. It must therefore be prevented by channelling the water away from the advance core.
- **Category C “Unstable core-face”**: is identified when the state of stress in the ground is considerably greater than the strength properties of the material even in the zone around the face. An “arch effect” can be formed neither at the face nor around the excavation because the ground does not possess sufficient residual strength. The deformation is unacceptable because it develops immediately into the failure range giving rise to serious instabilities such as failure of the face and collapse of the cavity without time for radial confinement operations: ground improvement operations must be launched ahead of the face to develop preconfinement capable of creating an artificial arch effect. The presence of water favors the extension of plasticisation and increases the entity of deformation.

Under hydrodynamic conditions it translates into the transport of material and siphoning.

The behaviour of the face is influenced by the geotechnical parameters of the soil (strength and deformability), the overburden of the tunnel (geostatic stresses), the size of the tunnel (diameter and shape) and the excavation system and constructional procedures. By means laboratory tests and numerical analyses, both preliminary evaluation by Analytic Methods, both more refined F.E.M. and F.D.M. Analyses, the core-face categories should be detected and, consequently, the properly interventions defined, with conservative action, by pre-confining of the core-face and confining of the cavity, as showed in Fig. 3.



Obr. 3. Opatrenia na predzaistenie a zaistenie
Fig. 3. Preconfinement and confinement actions

The characteristic features of the approach are:

- the importance of the ground deformational response during face advance (which is strictly linked to the formation of the arching effect, needed for reaching stability of the underground excavation, in the short and long term). The tunnel engineer is to analyze it, make appropriate design predictions with reference to the three dimensional conditions of the tunnel. Essential in this approach is the control of the core deformation, from which originate both the "pre-convergence" of the tunnel contour ahead of the face and obviously the "convergence" of the tunnel behind it;
- the tunnel excavation is to be always carried out full-face, also in difficult ground conditions, when stresses and strains do develop in the tunnel surround, including the "core" ahead of the advancing tunnel face; this is intended to be the main means for reaching the tunnel stability (by using the designed pre-confinement, stabilization and reinforcement measures as appropriate). The ADECO-RS is characterized for having found for the first time the technologies for "protecting" and "reinforcing" the core ahead of the advancing tunnel face, whenever needed (with the use of fiber glass elements, sub-horizontal jet-grouting columns, mechanical pre-cutting full face, etc.);
- the transition from the confinement action due to the "core" ahead of the advancing tunnel face to that of the support along the tunnel perimeter is to take place in the most uniform and gradual way possible, by taking the invert in the near vicinity of the face, if needed;

- the validation and the simple and immediate calibration of the design during excavation is to be carried out in line with the longitudinal and transversal sections and the possible variability of them defined at the design stage, on the basis of continuous performance monitoring and comparison of the predicted and the measured three dimensional displacement components, in line with the iterative observational approach.

The most significant advantages of working in accordance with the ADECO-RS approach are:

- industrialization of the works (with reference to both time and cost), with a few specialized workers into the tunnel, a limited number of large and powerful multipurpose machines and equipment, to be used, given the space which is made available with the full face method, with a clear sequence of operations;
- safety of the workers, due to the limited number of them in each stage, given that the less they are the greater is the safety;
- excellent production rates as demonstrated by the minimum mean daily face advance of 1.5 m/day of a completed tunnel with a cross section of about 160 m^2, which is possible in the most difficult ground, including low cover conditions, with construction time significantly reduced.

After more than 30 years of application of the approach and the excavation of significant tunnel lengths (more than 1000 km), with cross sections ranging in size from 120 to 220 m^2, in different ground conditions, near the surface or at depth, it is well demonstrated that is possible to safely and efficiently drive a tunnel in difficult ground conditions and complex behavior, by excavating the tunnel full-face, according to Rabcewicz intention, by reinforcing the “core” ahead of the advancing tunnel face and, if needed, around the tunnel perimeter, with the most suitable pre-confinement, stabilization and reinforcement measures. It is important to remark that significant efforts have been made during this time to improve the technologies adopted for achieving these objectives. For example, the 30-40 mm diameter pipes, which made it difficult to reach lengths of the core greater than 15 m, were substituted with fiber glass bands of different cross sectional profiles. With the flexibility gained in this way, core lengths of 24 m could be reached. With the understanding that the core-face reinforcement is more effective if the adhesion between the grout and the ground is increased, a significant effort was also made to test the use of expanding mortars to be mixed with the cement. Different methods for measuring the face extrusion were applied such as the incremental extensometer with significant advantages, when associated to the more traditional convergence measurements, for the understanding of the deformational response of the core ahead of the advancing face. This, together with careful three-dimensional modeling, developed with attention to the realistic simulation of the excavation/construction stages, contributed significantly to the understanding of the tunnel response in different conditions.

3. The design and construction of tunnels according to ADECO-RS Approach

In order to frame the design and the construction of underground works in a correct and universally valid manner, the ADECO-RS approach divides them into two chronologically separate moments (Fig. 4): a “design stage” and a “construction stage”. The design stage consisting of:

- “survey phase”, referred to the geological, geomechanical and hydrogeological knowledge of the ground and to the analysis of the existing natural equilibriums;
- “diagnosis phase”, referred to the analysis and the theoretical forecasting of the behaviour

of the ground in terms of Deformation Response, in the absence of stabilizing operations, according to the stability conditions of the core-face (categories A, B and C);

- “therapy phase”, referred, firstly, to the definition of the methods of excavating and stabilizing the ground to control the Deformation Response; and subsequently, to the numerical evaluation of the effectiveness of the solutions chosen; in this phase the section types are composed and the possible variability depending on the actual deformation behaviour of the tunnel in the excavation phase, which will be measured during the operating phase.

Stage	Phase	Description
Design	– Survey	– Analysis of existing natural equilibriums
	– Diagnosis	– Analysis and prediction of deformation phenomena (*) in the absence of stabilisation measures
	– Therapy	– Control of deformation phenomena (*) in term of stabilisation systems chosen
Construction	– Operational	– Application of the stabilisation instruments for controlling deformation phenomena(*)
	– Monitoring	– Control and measurement of deformation phenomena(*) as the response of the rock mass during tunnel advance (measurement of extrusion at the core-face and of convergence at the contour of the cavity and at varying distance from it, inside the mass of the ground)
	– Final design adjustments	– Interpretation of deformation phenomena(*) – Balancing of stabilisation systems between the core-face and the perimeter of the cavity

Obr. 4. Návrhové a realizačné fázy – Plnoprofilové razenie
Fig. 4. Design and construction stage – Full-face excavation

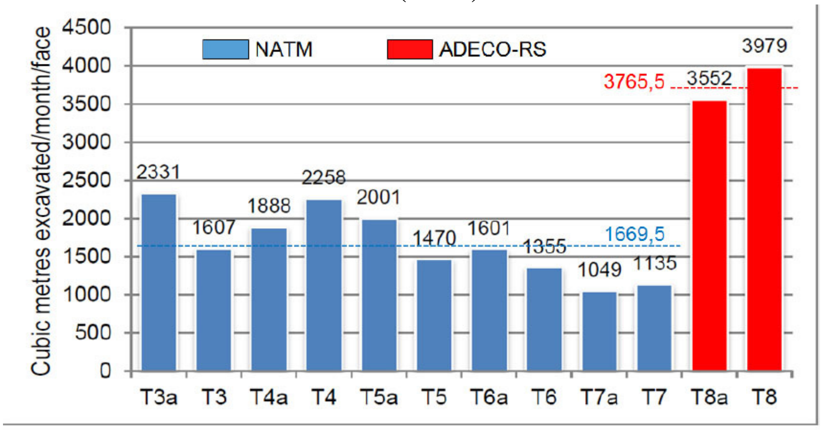
The construction stage consisting of:

- “operational phase”, referring to the actual construction of the tunnel, in which the application of the stabilizing instruments for controlling the Deformation Response is implemented.

- “monitoring and final design adjustment phase” during the course of the work, referring to the measurement and experimental interpretation of the actual behaviour of the ground to excavation in terms of Deformation Response, for the finalization and the balancing of the stabilizing systems implemented between the core-face and the excavation perimeter, and for checking the chosen solutions by means of comparing actually measured deformations with the ones that are expected theoretically.

A recent interesting experience has been achieved for the construction of the T8 e T8A tunnels of the Sochi highways ring, in the framework of the projects developed for the XXII Winter Olympic Games. These tunnels are of interest given that the other tunnels of the same highways ring have been excavated in similar ground conditions by adopting the NATM. For the first time is possible to compare the two methods based on real data and therefore reliable.

The results are commented in Lunardi and Barla (2014).



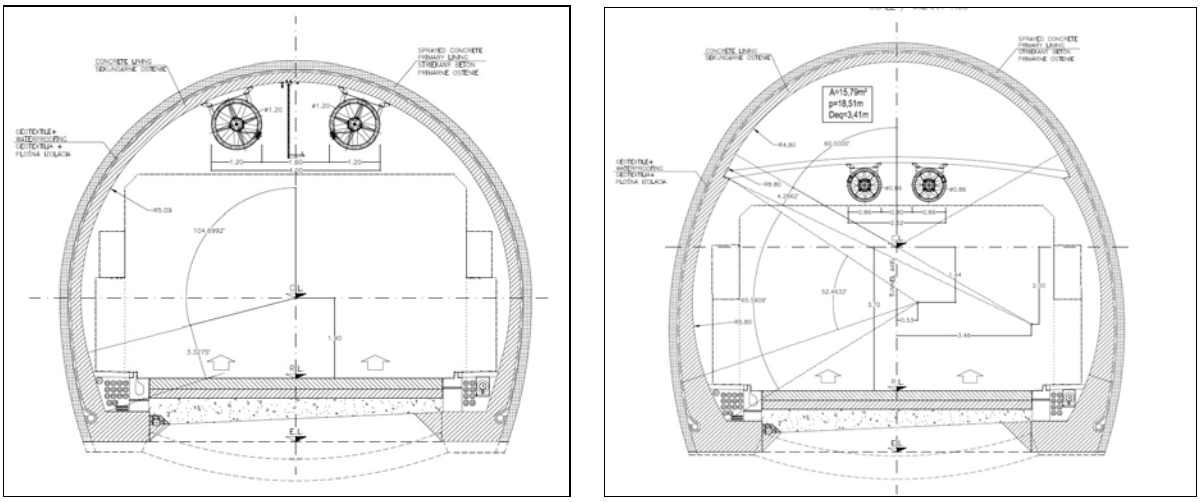
Obr. 5. Porovnanie metód razenia

Fig. 5. Comparison of construction methods

As illustrated in Fig.5, the T8 and T8A tunnels were excavated with a rate of excavation of 40 to 90 meter per month; the better performance of ADECO-RS with respect to NATM in terms of the “volume of rock excavated/month” is clearly showed; an additional it’s interesting to notice that the ADECO-RS is characterized by the very short time for final lining installation (3 weeks approx.) with respect to the NATM (up to 43 weeks maximum).

4. The application of the ADECO-RS Approach for Visnove Tunnel

“Visnove tunnel” is a double-track tunnel of the D1 Motorway “Lietavska Lucka – Visnove – Dubna Skala”, about 7450 m length. It’s located in the Zilina district. The tunnel will be built with two tubes following the development of the existing pilot tunnel, which will be used as a drainage tunnel during service. The tunnel width category is 2T 7.5, with maximum speed 100 km/h. Two traffic lane, 3.5 m width, are provided with clearance 4.8 m of height. The maximum vertical degree is 3.4%. Owing to the ventilation system, the tunnels present two different sections for the west and the east sides: in the east part a ceiling is present in crown, connected to a ventilation shaft (Fig. 6).

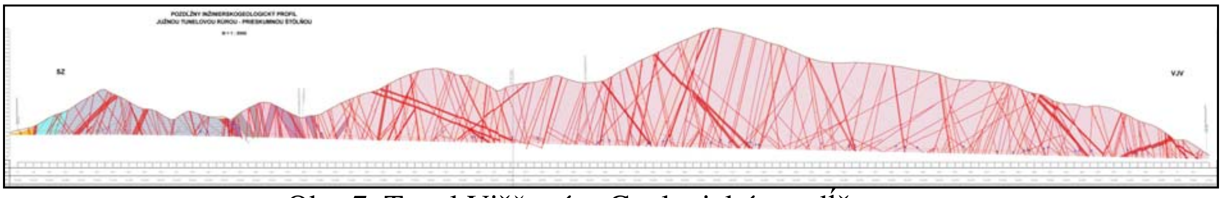


Obr. 6. Tunel Višňové – Vzorové priečne rezy (v úsekoch od západu a od východu)

Fig. 6. Visnove Tunnel – Typical cross sections (west and east)

Višňové tunnel is located on the territory of Mala Fatra. Malá Fatra is 55 km long mountain range in the north-western part of Slovakia, extending southeast of Zilina in the line of the major arc of the Western Carpathians. The main ridge runs from the southwest to the northeast. Middle of the mountain range is divided by Vah river. At this point the river created a 12 km long narrow valley known as the Strečnianska gorge. Altitude of mountain range, on the projected route of the tunnel, ranges from 800 to 1,300 meters. Geological conditions along the alignment of the tunnel are verified by pilot tunnel, excavated in the years 1998-2002, from the west portal in the length of 3.12 km by conventional method of drilling and blasting; from the eastern portal of the length 4.36 kilometers using full-profile tunneling machine (TBM) with a diameter of 3.5 m drill head. Based on survey work carried out, the rock mass, starting from the west portal, are so defined (Fig.7):

- flysch formations represented by claystone complex of central-Carpathian Paleogene
- mudstone–sandstone-limestone complex of formation Upper Triassic and Lower Jurassic (Liassic), with max overburden 90 m
- limestone-dolomite formation, represented by a complex of carboniferous rocks of triassic krížňansky Nappe Mala Fatra, with max overburden od 250 m
- lower terigen formation of the lower Triassic malofatranská unit
- formation of varis granitoids, which is represented at the heart of Mala Fatra (730 m).



Obr. 7. Tunel Višňové - Geologický pozdĺžny rez
Fig. 7. Visnove Tunnel – Geological longitudinal profile

During the pilot tunnel excavation the groundwater inflows mainly stabilize at the interface of carbonate rocks and crystalline basement; after the breakthrough of the two sections of the pilot tunnel, the total amount of water flowing to the east portal represents 150-220 l/s. Taking into account the effect of permanent drainage operated by the pilot tunnel, it is expected to have smaller water inflows during the road tunnel excavation. The strongest water inflows are expected in the zone of carbonate rocks. A constant flow of water is expected in the contact of mesozoic fault zone between the mesozoic and crystalline rocks: it is calculated that, depending on the rate of atmospheric precipitation, will go on the flow of from 20 to 100 l/s. In the other sections it is expected short-term and local inflows from 0,2 to 3 l/s. Nevertheless, not excluding local and isolated inflows of the open karst systems as well as discontinuities and fractures, which in the survey table have not been registered. In the crystalline rock there are expected large inflows in the tunnel tube in the individual sections, in the range of 10 to 20 l / s.

From a geotechnical point of view, the data collected during the pilot tunnel excavation allowed to define seven geotechnical units, from 1 to 6a and 6b, according to rock-mass properties (strength and deformability) and rock-mass discontinuities (fractured zones, faults and tectonic contacts); in the following table a characterization of the geotechnical units present along the tunnel alignment, in term of RMR and QTS, is reported; Mohr-Coulomb parameters are also reported. The 43% of the tunnels is interested by geotechnical unit 1, 2 and 3: these represent good rock-mass condition, intact or little wethered granitoid and limestone, locally fractured, with low deformation. Another 46% by the units 4 and 5, carachterised by wethered and tectonally disturbed rock-mass, fractured to strongly fractured;

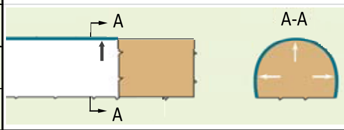
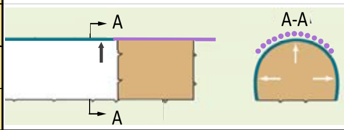
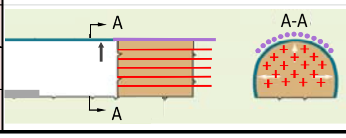
low rock strength due to joints with collapsing of rock from free unsupported surfaces, occasionally squeezing conditions. And finally, just 11% is related to the units 6a and 6b, mainly at the tunnel portals, where weathered and tectonically disturbed claystone sandy and sandstone (6a) and carbonatic breccias and claystone carbonatic (6b) are present; they are strongly fractured, with low interlocking and quickly subsiding (QTS<40).

Tabuľka 1 Parametre geotechnických jednotiek
Table 1 Geotechnical units‘ parameters

Geotecnhical Unit	QTS (Tesar, 1989)	RMR (Beniawski, 1989)	γ [kN/m³]	c' [kPa]	φ' [°]	υ [/]	E [MPa]	E_{def} [MPa]	σ_c [MPa]
1	> 84	81 ÷ 100	27.1	1 000	60	0.13	10 000	5 000	120
2	68 ÷ 84	61 ÷ 80	27.1	900	60	0.15	4 400	2 200	100
3	54÷ 68	41 ÷ 60	27.1	800	54	0.17	2 500	1 200	80
4	40 ÷ 54	21 ÷ 40	26.9	600	45	0.19	1 700	750	70
5	≈ 40	≈ 20	26.8	400	40	0.21	1 000	400	50
6a	< 40	< 20	24.0	20	33	0.25	60	25	20
6b	< 40	< 20	26.8	100	30	0.25	500	200	40

Considering these rock-mass parameters, the tunnel dimensions and the overburden values, the Deformation Response of the rock-mass - in absence of interventions - has been detected, to defined the core-face categories (diagnosis phase). For geo-units 1, 2 and 3 core-face "stable" conditions occur (category A): the deformation exhibits mainly in the elastic domain, no extrusion and convergence are expected in the range 1.0-3.0 cm; plastic zone is very low (0.0-0.5 m at the face, up to 1.0-2.0 m around the cavity). Just confinement of the cavity is necessary, in order to stabilize wedge and locally fractured rock-mass; interventions are related to shotcrete shell and rockbolts, with different mesh according to discontinuities. **Section types A0 and A1** will be provided, with D&B excavation step in the range 2.2-3.0 up to 4.5 m for good rock-mass conditions; Swellex bolts, 4.0 m length, will be adopted, with transversal spacing of 4.0 m and a C30/37 shotcrete shell, thickness 5 cm, reinforced by steel fibers 25 kg/m^3 or with single steel wire-mesh (therapy phase). The final lining is 30 cm in thickness, without invert.

For geo-units 4 and 5 core-face "stable in a short time" occur (category B): the deformation exhibit in the elasto-plastic domain, with low extrusion and expected convergence and settlement in the range 2.0-6.0 cm; plastic zone at the face is 1.0-2.5 m, and increases up to 4.0-8.0 m around the cavity. No ground reinforcements for the core-face are required, but pre-support in crown could be necessary to maintain the excavation profile and avoid local collapsing of fractured rock-mass. Interventions are related to steel forepolings in crown, shotcrete shell and steel ribs. **Section types B0 and B0V** will be provided, with excavation step in the range 1.0-1.6 by mechanical system (up to 3.2 m if D&B is used for section type B0). The confinement of the cavity is supported by steel ribs: 2 IPN 160 spacing 1.0-1.6 m in 20-25 cm of shotcrete, reinforced by steel fibers 25 kg/m^3 or with double steel wire-mesh. The final lining is 30 cm in thickness, without invert. For section type B0V, steel forepoles, 88.9 mm of diameter and 12-15 m in length, cemented with grout, will be placed; 4 drainages, L=18 m (the first 10 m blind and then 8 m micro-fissured) will be used in unfavorable hydrogeology conditions. Where forepoles will be used, the RC final lining thickness is ranging from 30 to 85 cm, with 50 cm of RC invert.

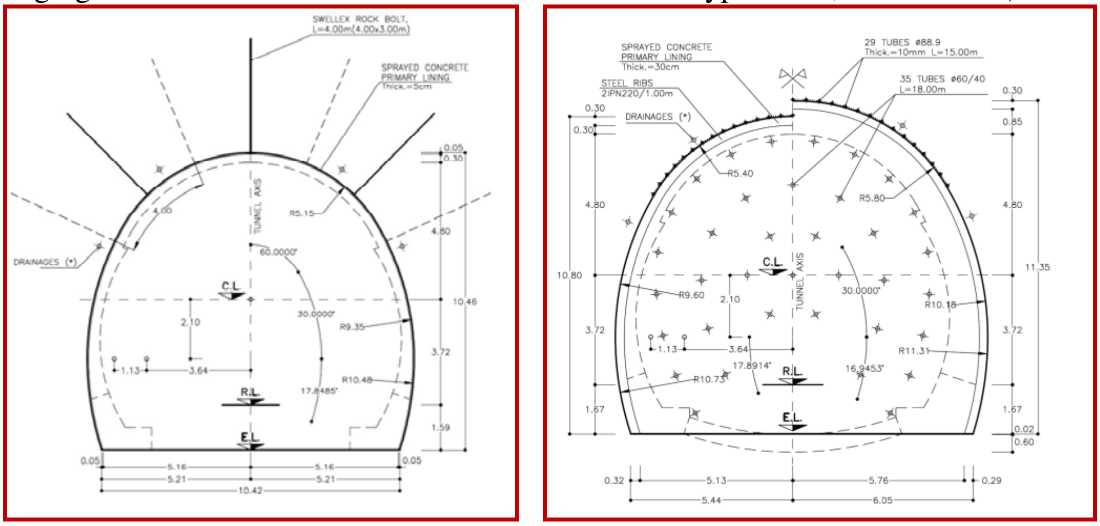
Design concept					
Geomechanical Unit	Expected behaviour		Action	Interventions	Section type
1 - 2 - 3	A	Stable core face	Confinement	Shotcrete shell Swellex Rockbolts	A0/1 A0/2 A1/1 A1/2
		Plastic zone around the face **0,0 ÷ 0,5 m**			
		Plastic zone around the cavity **1,0 ÷ 2,0 m**			
		Expected Convergence **1,0 ÷ 3,0 cm**			
4 - 5	B	Stable core face in the short term	Confinement - Pre-support	Shotcrete shell Stell ribs Steel forepoles	B0/1 B0/2 B0V/1 B0V/2
		Plastic zone around the face **1,0 ÷ 2,5 m**			
		Plastic zone around the cavity **4,0 ÷ 8,0 m**			
		Expected Convergence **2,0 ÷ 6,0 cm**			
6a - 6b	B/C	Unstable core face	Confinement - Reinforcement of advance core - Pre-support	Shotcrete shell Stell ribs Fiberglass elements Steel forepoles Invert casting	B2 B2V
		Plastic zone around the face **2,0 ÷ 4,0 m**			
		Plastic zone around the cavity **9,0 ÷ 12,0 m**			
		Expected Convergence **5,0 ÷ 10,0 cm**			

Obr. 8. Tunel Višňové - Vystrojovacie triedy vs. geomechanické jednotky
Fig. 8. Visnove Tunnel – Section types vs geo-mechanical units

Finally for geo-unit 6a and 6b core-face "stable in a short time" occur (category B); locally, in very tectonised rock-mass, "unstable" condition (category C) could be occur. For these conditions the deformation exhibit in elasto-plastic domain with failure if the necessary intervention are not provided. Extrusion is expected in the range 4-8 cm, with convergence and settlement in the range 5.0-10.0 cm. Plastic zone at the face is 2.0-4.0 m which increases around the cavity up to 9.0-12.0 m. To minimize this Deformation Response, pre-confinement is necessary, reinforcing the advance-core ahead the current face with fiber-glass elements to prevent the extrusion phenomena; pre-support and confinement of the cavity are also necessary. Sections B2 and B2V will be provided with excavation step equal to 1.0 m (range 0.8-1.2 m): 35 cemented fiberglass structural elements, Ø60/40 type L=18 m length, overlap 8.00 m, will be placed in the core-face, steel ribs 2IPN200 spacing 1.0-1.2 m in 25 cm of shotcrete (10 cm shotcrete at the face). Final lining consists in 50 cm of RC crown (30-85 cm for section type B2V with forepoles) and 60 cm of RC invert. The specific section types related to the geo-units are reported in Fig.8; some examples of section types are reported in Fig.9. A typical cycle-work for tunnel construction provides these main phases:

- Pre-confinement of the core-face, by means of fiber-glass reinforcements or grouting activities; pre-support system by forepoles and drainages pipes ahead of the face (where necessary, according to geotechnical units and core-face categories)
- Full-face excavation, with excavation step depending on the geomechanical conditions, ranging from 1.0 m up to 4.5 m. The excavation will be made by drill&blast or by mechanical system, with concave shape.
- Placing of fiber-reinforced shotcrete on the face (if necessary)
- Confinement of the cavity, placing steel bolts or steel ribs
- Completing the pre-lining, placing fiber-reinforced shotcrete (or reinforced with wire-mesh)
- Casting of kickers and invert at a defined distance from the face (ranging from 1 to 6 diameter of excavation for section types B0V, B2 and B2V)
- Waterproofing and drainage system installation
- Casting of the final lining, reinforced if required, at a defined distance from the face

(ranging from 4 to 8 diameter of excavation for section types B0V, B2 and B2V).



Obr. 9. Tunel Višňové – Vystrojovacie triedy A0 a B2V (úsek od východu)
Fig. 9. Visnove Tunnel – Section types A0 and B2V (east tunnel)

The analysis of the monitoring data (mainly geological face mapping and extrusion-convergence measurements) will allow to confirm the predicted section type, the intensity of the interventions and of the executive phases (such as: excavation step, distance from the face for invert and final lining casting …) or to calibrate them according to specific “Guidelines” part of the design, which will be able to fine tune the construction stage.

5. References

Rabcewicz L. (1964), “The New Austrian Tunnelling Method”, Part one, Water Power

Lunardi P. (1997), “The influence of the rigidity of the advance core on the safety of tunnel excavation”, Gallerie e grandi opere sotterranee, n. 52

Lunardi P. (2000), “Design & constructing tunnels – ADECO-RS approach”. Tunnels & Tunnelling International, special supplement

Lunardi P. (2008), “Design and construction of tunnels: Analysis of Controlled Deformations in Rock and Soils (ADECO-RS)”, SPRINGER-Verlag Berlin Heidelberg, 576 pp.

Lunardi P., Barla G. (2014), “Full face excavation in difficult ground”, Geomechanics and Tunneling 7, n. 5.

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