Rock failures in tunnels

Zruški v predorih

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Abstract: Rock failures of various extents are common in tunnel construction. The source and form of a rock failure depend on actual geological conditions at the time of excavation. Regarding the type of rock there are gradual failures in ductile rocks and sudden failures in stiff rocks. For the purpose of my study I chose rock failures the V Zideh Tunnel and Trojane Tunnel as examples of failures in ductile rocks, and rock failures in the Pletovarje Tunnel, Golo rebro Tunnel and Tabor Tunnel as examples of failures in stiff rock. The results of analysis of some extensive failures in different (stiff and soft) rocks show that rock failures appear mostly in geologically unfavourable areas, such as fault zones and zones with unfavourable distribution of bedding, fissility and joints with additional presence of water. Rock failures often appear in parts of tunnels with thin overburden. Markland's test helps us determine whether a rock failure is due to sliding or is it a gravitational failure. In stiff rocks sliding and falls (gravitational failures) of blocks of rock are characteristic. Failure of tectonically disturbed soft rocks appears in a form characteristic for soils.

Izvleček: Pri gradnji predorov prihaja do različno velikih zruškov. Nastanek zruškov in način porušitve sta povezana z dejanskimi geološkimi razmerami v času izkopa. Glede na vrsto kamnine ločimo postopno porušitev v duktilnih kamninah in trenutno porušitev togih kamnin. Za primer zruškov v duktilnih kamninah sem izbrala predora V Zideh in Trojane, za primer zruškov v togih kamninah pa zruške iz predorov Pletovarje, Golo rebro in Tabor. Pri analizi nekaterih večjih zruškov v različnih (togih in mehkih) kamninah se je izkazalo, da do zruškov prihaja večinoma na območjih z neugodnimi geološkimi razmerami kot so prelomna cona, neugodna medsebojna lega plastnatosti, skrilavosti in razpok ob prisotnosti vode. Zruški so pogosti tudi na območjih z nizkim nadkritjem nad predorsko cevjo. S pomočjo Marklandovega testa ugotavljamo, ali je prišlo do zdrsa ali gravitacijskega zruška. Za toge kamnine so značilni zdrsi ali padci (gravitacijski zruški) kamninskih blokov. Močno tektonsko poškodovane mehke kamnine imajo obliko porušitve, ki je značilna za zemljine.

Scientific paper

Key words: rock failure, tunnel, Markland test, slide, gravitational failure
Ključne besede: zrušek, predor, Marklandov test, zdrs, gravitacijski zrušek

INTRODUCTION

Rock failures are common in the construction of underground openings. They often appear during the excavation works. Causes of rock failures during tunnel construction with NATM are unexpected geological circumstances, errors in design, construction faults and poor excavation management[1].

The subject of my study was rock failures caused by unfavourable geological circumstances. Regarding the type of rock there are gradual failures in ductile rocks (compression, swelling, loosening) and sudden failures in stiff rocks (fall, burst and stroke). For the purpose of my study I chose rock failures in the V Zideh Tunnel and Trojane Tunnel as failures in ductile rock and rock failures in the Pletovarje Tunnel, Golo rebro Tunnel and Tabor Tunnel as failures in stiff rock.

All tunnels that were subject to my study were constructed within the frame of a programme of motorway construction in Slovenia in the last ten years. Excavation and construction works were carried out according to the New Austrian Tunnelling Method (NATM). The Pletovarje Tunnel and Golo rebro Tunnel are located on the Celje – Maribor motorway, the Trojane Tunnel and V Zideh Tunnel on the Ljubljana – Celje motorway, and the Tabor Tunnel on the Razdrto – Fernetiči motorway. They all have one or two tubes with a diameter of 10 m and run through different types of rocks.

GEOLOGY AROUND THE CHOSEN TUNNELS

The northern part of the Pletovarje Tunnel runs through the Donačka fault zone within which tectonic lenses of various lithology (sandstone, dolomite, marl, keratophyre, limestone) and age (Carboniferous, Permian, Lower Triassic, Tertiary) are caught. The second part of the tunnel runs through tectonically disturbed dolomite of the Lower Triassic age and sandstone, marl and tuff of the Oligocene age[2]. The Golo rebro Tunnel runs through carbonate rocks of the Middle Triassic age and clastic rocks of, probably, the Tertiary age[2]. The Tabor Tunnel runs through carbonate rocks of the Cretaceous age[2].

The V Zideh Tunnel and Trojane Tunnel run through Permo-Carboniferous clastic rocks, which show characteristic interchange of shales, siltstones and sandstones. Those rocks are tectonically disturbed, crushed into tectonic clay or millonite[2],[3]. From engineering geological and geomechanical point of view, the rocks in the area around the Trojane Tunnel belong to a special group of rocks representing a passage between soils and rocks. They are called soft rocks and hard soils, respectively. In an undisturbed state they behave as rocks and show a structure of rock. As a consequence of construction works or water intrusion, however, they start behaving as soils. They are very susceptible to physical and chemical changes. Soft rocks often cause engineering geological problems. The behaviour of soft rocks can be generally characterized as anisotropic, elastoplastic, dilatational and time dependent[4].

INVESTIGATIONS OF ROCK FAILURES

Different causes, such as exceeding of shear strength of rock, sliding along discontinuities, unfavourable distribution of joints, fault zones, presence of water, or a combination of some or all of these factors, can lead to a rock failure. Even though rock itself is strong enough, rock failure may start in those parts of rock mass where tensions are high, and are further transmitted to planes of weakness. When local shear strength is exceeded, a rock failure appears.

For the purposes of my study I chose those rock failures that exceeded the volume of 10 m^3. They appeared in the Pletovarje Tunnel, Golo rebro Tunnel, V Zideh Tunnel and Trojane Tunnel.

Due to the crushed state of rock, the rock failures in the Tabor Tunnel were not very extensive, only some smaller pieces fell off locally. The majority of the Tabor Tunnel runs through fissured, partly crushed, zones of limestone. The major problem in this tunnel was the appearance of large karstic caverns.

All rock failures, with the exception of the failure in the V Zideh Tunnel between chainages 0+713 and 0+722, were sudden and appeared at the time when the tunnel face was being opened. The rock failure in the V Zideh Tunnel could have been predicted by means of geotechnical measurements, as the easily observable deformations of the lining on the tunnel appeared a few days before the rock failure appeared. At that time, unfortunately, there weren't any measurement profiles built in. In the Trojane Tunnel surface measurements had also indicated progressive rock failure, which later spread up to the surface.

Data on location and extension of a rock failure, system discontinuities and geological circumstances are shown in Table 1. The data in the table were compiled from inventories of the faces of tunnels. The last column shows the type of a failure determined by Markland's test.

Table 1. Characteristics of the investigated rock failures
Tabela 1. Značilnosti obravnavanih zruškov

Tunnel	Chainage	Estimated size of rock failure (m^3)	Systems of discontinuities	Rock	Geological circum-stances	Type of rock failure
Pletovarje	30+ 329	18	5/85, 30/85, 200/75	fine sandstone, tuff sandstone	fault zone, water seepage	gravitational
Pletovarje	30 +407	12	270/90, 340/80, 210/50	fine sandstone, tuff	fault zone	slide
Golo rebro	27 +599	12	10/60, 80/85, 290/60	crushed dolomite	fault zone, moisture	slide
Golo rebro	27 + 909	10	115/60, 285/60, 250/80, 85/80	dolomite breccia	fault zone	gravitational
Golo rebro	27 + 974	20	145/85, 270/70, 110/40	dolomite	thin overburden	slide
V Zideh	0 + 572	17	250/90, 170/80, 170/30	siltstone, shale	fault zone, moisture	slide
V Zideh	0 +713 to 0 +722	25	45/65, 350/30, 230/55, 15/35	crushed siltstone and finely laminated shale	fault zone, moisture	slide
Trojane	79 +720 left tube	75	340/30, 160/40, 40/30	crushed finely grained sandstone, siltstone, shale	tectonic zone, thin overburden, thick soils, moisture	slide

ANALYSIS USING MARKLAND`S TEST

Hemispherical projection techniques or stereographic projection offer a graphical method for analyzing three-dimensional problems (involving planes, lines and points) in a convenient and easily interpreted two-dimensional form. The Markland test on Schmidt diagram is very valuable tool for identifying those discontinuities that (could) lead to failure[5]. A wedge slide is triggered when the intersecting line of at least two systems of joints appears in a critical area. It depends on the position of the systems of joints if rock wedge sliding or gravitational failure appears. The test also considers the shear angle φ of the rock. Figures 1a and 1b show the conditions leading to sliding and the conditions leading to gravitational failure.

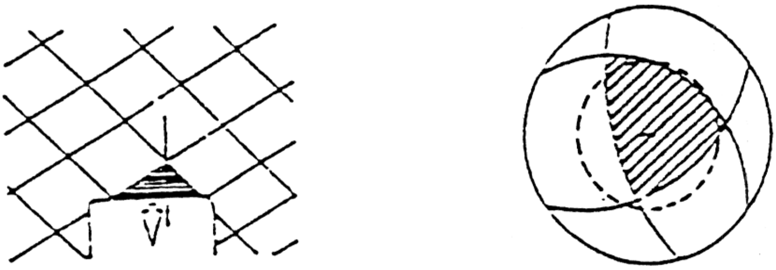

Figure 1a. Conditions leading to gravitational rock failure[5]
Slika 1a. Pogoji pri gravitacijskem zrušku[5]

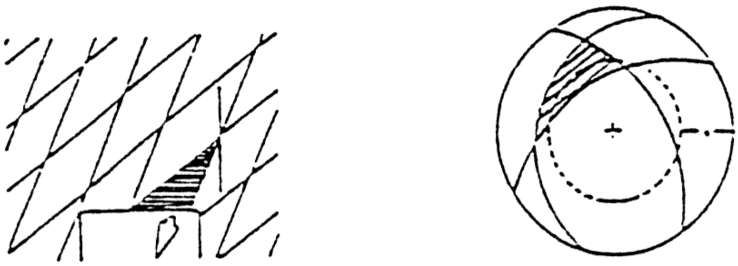

Figure 1b. Conditions leading to rock wedge sliding[5]
Slika 1b. Pogoji pri drsenju klina[5]

The mentioned failures were analysed using Markland's test. Figures 2 and 3 show Schmidt diagrams for systems of discontinuity along which failures appeared in the Golo rebro Tunnel, chainage 27+909, and in the V Zideh Tunnel, chainage 0+713.

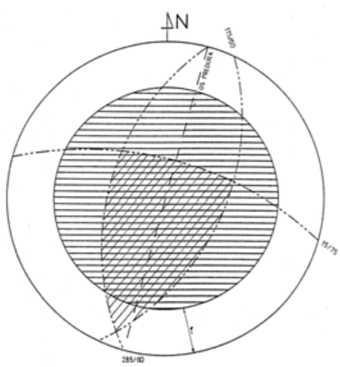

Figure 2. Schmidt diagram for the Golo rebro Tunnel, chainage 27+909
Slika 2. Schmidtov diagram za predor Golo rebro na stacionaži 27+909

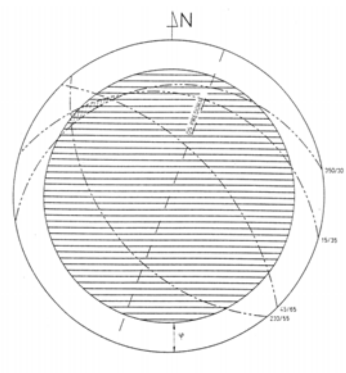

Figure 3. Schmidt diagram for the V Zideh Tunnel, chainage 0+713
Slika 3. Schmidtov diagram za predor V Zideh na stacionaži 0+713

The results show that the majority of the investigated rock failures started with sliding of a rock wedge along a smooth surface. It is especially difficult to discern between sliding and gravitational failure in tectonically disturbed rocks. The test doesn't consider the characteristics of joints, such as roughness, smoothness, fill (millonite and clay have different impact on the shear strength along discontinuities), presence of water and a degree to which the rock has been crushed.

The rock failure in the Trojane Tunnel, shown in Figure 4, had spread to the surface. The form of the sink that can be seen on the surface indicates the presence of pipe flow of crushed and wet sandy silty rock[3]. This form of failure is characteristic of silty soils. The observed type of failure confirms the classification of Permo-Carboniferous clastic rocks into the group of soft rocks – hard soils.

Figure 4. A rock failure in the Trojane Tunnel, chainage 79+720[3]. A sink on the surface can be seen in the upper left corner and centre of the picture, while the rock failure in tunnel is indicated in the lower right corner.
Slika 4. Zrušek v predoru Trojane na stacionaži 79+720[3]. Zgoraj levo in v sredini je viden lijak na površini, spodaj desno pa zrušek v kaloti.

In contrast to the failures in ductile rocks, the rock failure indicated in Figure 5 is characteristic of stiff rocks. The rock failure in the Golo rebro Tunnel appeared during the breakthrough of a tube of the tunnel. A dolomite block slid along joints oriented in directions 145/85, 270/70, 110/40.

Figure 5. Slide of a dolomite block in the Golo rebro Tunnel at chainage 27+974[2]
Slika 5. Zdrs dolomitnega bloka v predoru Golo rebro na stacionaži 27+974[2]

CONCLUSIONS

Regarding the results of the analysis of some extensive rock failures that appeared during tunnel construction we can conclude that a rock failure usually appear in areas characterised by unfavourable geological conditions, such as fault zones, unfavourable distribution of bedding, fissility and joints with the additional presence of water. Failures are especially frequent in the parts of tunnels with thin overburden and thick layer of soils above the tube of a tunnel.

Tectonically disturbed soft rocks have a tendency to fail in a way that is typical for soils. Failures in soft rocks can be detected by measuring devices (if already installed). Slow and progressive rock failure can be predicted on the basis of speedy subsidence of the high point.

Failures in stiff rocks are sudden and usually appear when the face of a tunnel is being opened. Analysis of failures using Markland's test is more suitable for stiff rocks.

POVZETKI

Zruški v predorih

Pri podzemnih gradnjah pogosto prihaja do zruškov. Pojav zruškov je pogosto vezan na geološke razmere v času izkopa. Vzroki porušitev pri gradnji predorov z NATM so nepričakovane geološke razmere, napake pri projektiranju, konstrukcijske napake ali slabo vodenje izkopa[1]. V članku obravnavam geološko pogojene zruške. Glede na vrsto kamnine ločimo postopno porušitev v duktilnih kamninah (stiskanje, nabrekanje, rahljanje) in trenutno porušitev togih kamnin (padec, izbruh, udar). Za primer zruškov v duktilnih kamninah sem izbrala predora V Zideh in Trojane, za primer zruškov v togih kamninah pa zruške iz predorov Pletovarje, Golo rebro in Tabor.

Vsi našteti predori so bili zgrajeni v zadnjem desetletju v sklopu gradnje avtocest v Sloveniji. Izkop in gradnja sta potekala po novi avstrijski metodi gradnje predorov (NATM). Predora Pletovarje in Golo Rebro sta zgrajena na AC Celje – Maribor, Trojane in V Zideh na AC Ljubljana – Celje ter predor Tabor na AC Razdrto – Fernetiči. To so eno ali dvocevni predori s premerom 10 m, ki potekajo skozi različne kamnine. Predora V Zideh in Trojane potekata skozi permokarbonske klastične kamnine[2],[3], ki s stališča inženirske geologije spadajo v posebno skupino mehkih kamnin, ostali predori pa skozi karbonatne in klastične kamnine različnih starosti, ki jih uvrščamo med toge kamnine.

S pomočjo stereografske projekcije analiziramo prostorske probleme v ravnini. S pomočjo Marklandovega testa na Schmidtovem diagramu ugotavljamo možnost kamninskega zdrsa[5]. Od položaja sistemov razpok je odvisno ali pride do zdrsa kamninskega klina ali do gravitacijskega zruška. Do porušitve pride, kadar sečnica vsaj dveh sistemov razpok pade v kritično območje. V testu upoštevamo tudi strižni kot kamnine. Pri analizi nekaterih večjih zruškov, ki so nastali v času gradnje predorov, se je izkazalo, da je do zruškov prihajalo večinoma na območjih z neugodnimi geološkimi razmerami kot so prelomna cona, neugodna medsebojna lega plastnatosti, skrilavosti in razpok ob prisotnosti vode. Zruški so pogosti tudi na območjih z nizkim nadkritjem in debelejšo preperino nad predorsko cevjo.

Močno tektonsko poškodovane mehke kamnine imajo obliko porušitve, ki je značilna za zemljine. Za zruške v mehkih kamninah je značilno, da jih z meritvami zaznamo (če meritve na tistem območju že potekajo). Na počasno, toda progresivno rušenje kamnine opozarja hitrost posedanja temenske točke.

Zruški v togih kamninah so trenutni in so se zgodili v času odpiranja kalote. Ugotavljanje in analiziranje zruškov z Marklandovim testom je primernejše za toge kamnine.

REFERENCES

[1] ROMERO, V., (2002): NATM in soft-grounds: a contradiction of terms? *World tunnelling*. pp. 338-343. Dostopno na svetovnem spletu: www.jacobssf.com/NATMInSoftGround.html.

[2] ČARMAN, M. (1998): *Metodologija inženir-skogeoloških raziskav in spremljave za gradnjo predorov*: *magistrsko delo*. Ljubljana, GeoZs, 127 str.

[3] AJDIČ, I., ŠTIMULAK, A. (2004): Geološka spremljava in klasificiranje hribinske mase pri gradnji predora Trojane. *Razprave 4. posvetovanja slovenskih geotehnikov*. Rogaška Slatina, pp. 35-44.

[4] JOHNSON, I.W., NOVELLO, E.A. (1993): Soft rocks in the geotechnical spectrum. *Geotechnical Engineering of Hard Soils - Soft Rocks*.; Vol. 1, pp. 177-183, Balkema, Rotterdam.

[5] HOEK, E. & BROWN, E.T. (1994): *Underground Excavations in Rock*. Chapman&Hall, 527 p., London.