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MODELLING THE STABILITY OF A VERY LARGE CAVE ROOM; CASE STUDY: BREZNO PRI MEDVEDOVI KONTI

MODELIRANJE STABILNOSTI ZELO VELIKE JAMSKE DVORANE; NA PRIMERU BREZNA PRI MEDVEDOVI KONTI

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Jože Kortnik & France Šušteršič: Modeliranje stabilnosti zelo velike jamske dvorane; na primeru Brezna pri Medvedovi konti

Dvorana v Breznu pri Medvedovi konti (Pokljuka) je s svojim razponom okrog 150 m, višino prek 50 m in prostornino 62,0 × 10^4 m^3 druga največja znana v Sloveniji. S pomočjo računalniškega programa FLAC smo modelirali stabilnost oboka pri hipotetičnem denudacijskem tanjšanju stropa. Uporabili smo dva nabora mehanskih parametrov kamnine. V obeh primerih so deformacije v stropu najmanjše pri debelini stropa 20 m do 30 m, do zrušenja pa pride pri debelini okrog 4 m. To dobro ustreza terenskim opazovanjem delno zrušenih jamskih dvoran. Skladanje z realnostjo nas opogumlja k nadalnjim simulacijam.
Ključne besede: stabilnost jamskih dvoran, podor, udornice, speleogeneza, denudacija, Brezno pri Medvedovi konti, Pokljuka, Slovenija.

Abstract UDC: 551.44:551.24(497.4)

Jože Kortnik & France Šušteršič: Modelling the stability of a very large cave chamber; case study: Brezno pri Medvedovi konti

The big chamber in Brezno pri Medvedovi konti (Julian Alps, Slovenia), about 150 m wide, over 50 m high and with a volume of about 62 × 10^4 m^3, is the second largest cave chamber yet discovered in Slovenia. Application of FLAC computer software enabled modelling of the stability of the chamber's arched roof during hypothetical denudational lowering of the overlying surface. Modelling was based on two sets of rock property parameters generally attributed to the local parent rock. In both cases the modelled deformation within the arch was at a minimum at a residual ceiling thickness of 20 to 30 m, whereas collapse occurred when the residual ceiling thickness reduced to about 4 m. These modelling results fit well with field observations of partly collapsed cave chambers.
Key words: stability appraisal of large cave rooms, cave room collepse, collapse dolines, speleogenesis, denudation, Brezno pri Medvedovi konti, Pokljuka, Slovenia.

INTRODUCTION

It is well known (A. Scheidegger, 1962) that secondary spalling of rock from the ceilings of large cave chambers should lead to the development of stable (parabolic) arches (cf. Ph. Renault, 1967) and, eventually, to a state of mechanical equilibrium. Ignoring the fact that rock weathering within some arches may not permit total stabilisation, eventual collapse remains inevitable, due to the effects of surface denudation and a consequent gradual thinning of the cave roof.

To enable monitoring of the mechanical behaviour of a cave ceiling during gradual surface lowering, a theoretical model has been built using the FLAC computer program, which is designed primarily for mechanical studies of artificial underground caverns. A large room in Brezno pri Medvedovi konti[1] (2330[2]) was chosen as the test site. This cavern is ideally suited for several reasons, the most obvious of which are that it is relatively large, a good plan exists, and there is evidence that, though the profile appears to be elliptical rather than parabolic, a stable arch has been achieved[3]. During modelling, denudation effects were simulated by a stepwise decrease of the overburden thickness, and the results of the simulation agree reasonably well with field observations. This is taken as an indication that the idea is productive and, consequently, the present model is seen as the first step towards more sophisticated modelling. In the next version of the model the surface configuration, as well as 3D relationships must be considered.

ABOUT BREZNO PRI MEDVEDOVI KONTI

The cave lies in the northern part of Pokljuka, a plateau that is just one of several encircling the Julian Alps. Its closest neighbour, Jelovica, lying on the opposite (eastern) side of the Sava canyon, is little different, and caves of similar dimensions[4] are found there. Several theories have been put forward about the origin of Pokljuka. On the evidence of its general form, as well as its degree of karstification, it appears that it could be compared to the Miocene karst plateaus of the Northern Alps (W. Frisch, & alt., 2000). However, until the tectonic relationships between the Austro-alpine and Adriatic micro-plates are known in more detail, some caution must be exercised. Presently Pokljuka is 1200 m to 1400 m high. Much of its parent rock is of Norian and Rhaetian (T^3) age, with the stratigraphically lower parts (such as in the neighbourhood of the Medvedova konta) comprising reef limestone, and the higher parts well-bedded Dachstein limestone.

At first glance Pokljuka does not appear to embody significant karstic shaping, because of its morainic cover. However, some underground phenomena reflect through the cover, and carbonate material within the moraines is also locally karstified. In general, surface karst phenomena are less numerous and less pronounced than in adjacent areas. Pokljuka is densely forested and is not popu-

[1] *In English, the name literally means: "the pothole near the bear's* konta*", where* "konta" *is a local expression for a very large doline. In this case it is probably a collapse doline.*

[2] *Numbering is according to the central cave registry of Slovenia, maintained by the Speleological Association of Slovenia and the Karst Research Institute, ZRC SAZU.*

[3] *This holds true only if considered at any particular instant. In reality there appears to be ongoing cryoclastic loosening of the ceiling during the winter months.*

[4] *Pižovo brezno (4475).*

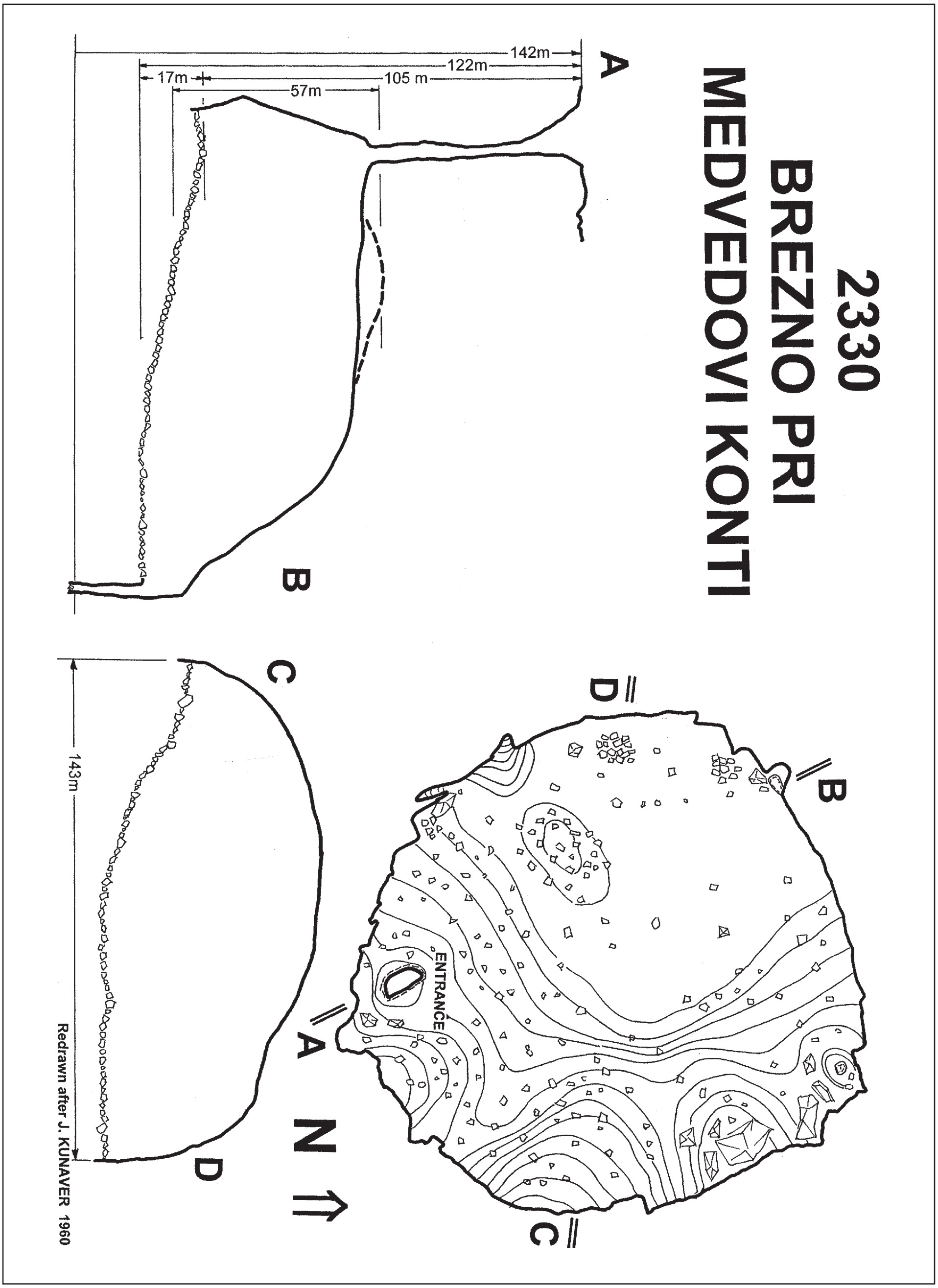

Fig. 1: Brezno pri Medvedovi konti.
Sl. 1: Brezno pri Medvedovi konti.

lated, especially its northern part, which contains Brezno pri Medvedovi konti. Winters are severe, and it is evident that cold winter air can penetrate down the entrance shaft of Brezno pri Medvedovi konti into the cave chamber below. This influence must have been much stronger during Pleistocene cold periods.

The cave entrance lies at 13° 57' 58" E and 45° 28' 23" N, at an elevation of about 1390 m a.s.l., where the Pokljuka plateau begins to rise into the Pokljuka ridge. The cave's existence was first reported to cavers just before the Second World War, but it remained unexplored until 1956, when it was visited for the first time, a survey was carried out and fundamental speleological research commenced (J. Kunaver, 1960). A plan of the cave was drawn at 1:500 scale, based on a closed circular survey traverse along the walls. The height of the chamber was measured using helium-filled balloons.

The present vertical entrance shaft (Fig. 1) has developed along a local fault, which runs NNW-SSE and is clearly visible at the surface. At a depth of 45 m the walls of the rectangular, 6 × 3 m to 9 × 5 m-wide vadose shaft widen out dramatically into the top of a very large chamber. This is nearly circular, with a maximum diameter of 152 m and minimum diameter of 132 m. The foot of the entrance shaft is 105 m below its surface opening, whereas the bottom of the circular chamber is 17 m deeper. Its ceiling is quite regular and of approximately elliptical shape.

Though the fault along which the entrance shaft developed is recognisable across the ceiling and in both sidewalls, it does not seem to have influenced roof stability significantly. The shaft does not penetrate the centre of the chamber's ceiling, but enters its southern sector, not more than 10 m from the nearest wall. At two locations in the walls there are entrances to vertical shafts, presumably formed along relaxation fractures, and the total depth of the cave is 142 m. About a third of the floor between the northern and the western part of the hall is relatively level, and the entire floor area is covered by fallen gravel, slabs and larger rocks.

STABILITY APPRAISAL

Stability appraisal of the Medvedova konta pothole was made using the FLAC (Fast Lagrangian Analysis of Continua) numerical software. FLAC is a two-dimensional explicit finite difference program for engineering mechanics computation, offering a wide range of capabilities to solve complex mechanics problems. The user adjusts the grid to fit the shape of the object being modelled, and each element behaves according to a prescribed linear or non-linear stress/strain law in response to applied forces or boundary conditions. The material can yield and flow, and the grid can deform and move with the material that is represented. The program is based on a Lagrangian calculation scheme that is well suited for modelling large distortions and material collapse.

Primary stress state

The average rock thickness above the chamber ceiling at Medvedova konta is something like 55 m, if local details such as surface undulations are ignored. Thus, the ceiling lies relatively close to the surface. In such cases, the ratio of horizontal to vertical stress varies considerably, but in general the horizontal stress σ_H exceeds the vertical stress σ_V. Diagrams of coefficient *k* versus depth were made on the basis of numerous measurements in different types of rock (Brady, B.H.G., Brown, E.T., 1985).

Model of the Brezno pri Medvedovi konti

One model was constructed, using two different sets of material properties that correspond to laboratory data for the Triassic limestone. Tests based on these sets of material properties (Table 1) confirm the stability of the model before the start of ceiling thinning.

The model simulates the gradual thinning of the chamber ceiling (by denudation of material from the overlying surface), until its eventual collapse. The grid size is 223 × 162 elements, and the Mohr-Coulomb plasticity model was used.

Table 1: Sets of rock material properties used in the model.

Designation	Unit		Set 1	Set 2
E	(GPa)	Modulus of elasticity	8	25
ν		Poisson's ratio	0.25	0.25
T	(MPa)	Tensile strength	1.85	4
γ	(kg/m^3)	Density	2732	2732
C	(MPa)	Cohesion	1.1	1.1
φ	(°)	Friction angle	35	35

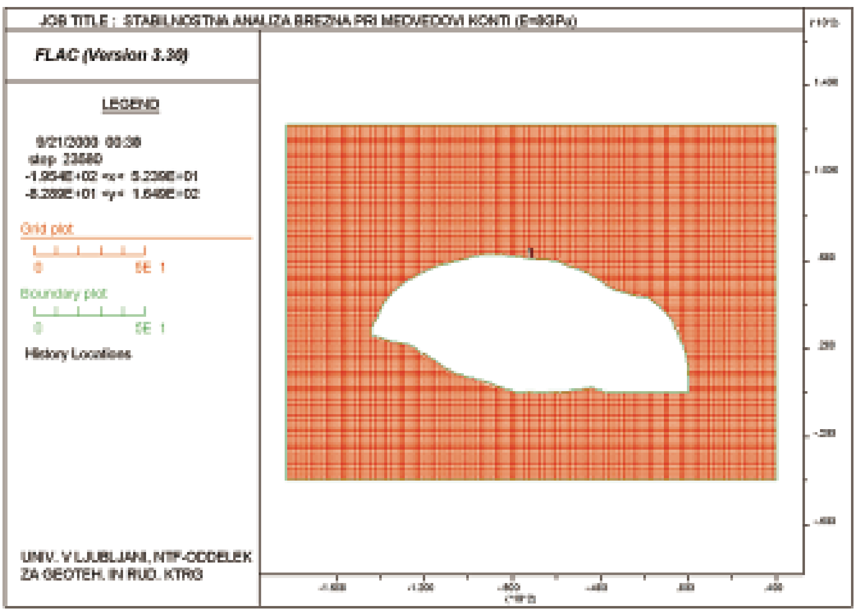

Fig. 2: Model of the Brezno pri Medvedovi konti - profile A - B.
Sl. 2: Model Brezna pri Medvedovi konti - profil A - B.

Development of displacements was monitored at three chosen control points in the rock above the chamber ceiling. The model was considered to be stable if the displacement values at the control points converged towards an end value. The corollary is that increasing displacement values presaged the imminent collapse of the ceiling.

Results of modelling

During modelling, thinning of the chamber ceiling was simulated by a gradual (10 step) reduction of the cover thickness from the surface downwards. The results are shown in Table 2.

For both sets of material properties, collapse of the chamber ceiling occurs when its thickness falls below 4 m. This fits well with field observation at points where similar chambers have just begun to open to the surface by collapse. Throughout the modelling, areas of plastic deformation appeared in the rock near the ceiling and chamber walls, and were especially common in the area close to the walls of the chamber. As the cover thickness diminishes, the locations of the plastic zones move towards the centre of the ceiling arch and thus towards the surface. Indications of the possibility of ceiling collapse gradually appear at points where the ceiling becomes thinner than 20 m. In places where the ceiling becomes thinner than 20 m, indications of the possibility of ceiling collapse gradually appear. The maximum displacements occur at the edges of the chamber.

Throughout modelling, the maximum displacements appeared in the chamber ceiling and decreased towards the sides. The development of displacements at the model's control points indicated a decrease of maximum displacement with decrease in ceiling thickness to 30 m. With further steps, the displacements gradually increased with the thinning of the ceiling until complete collapse.

Table 2: Maximum displacements during modelled thinning of the chamber ceiling using both sets of materials properties (Table 1).

Step	Cover height (ceiling thickness) (m)	Maximum displacement (Set 1 properties) (mm)	Max. displacement (Set 2 properties) (mm)	Notes
1.	59	68,4	21,9	
2.	50	63,9	20,4	
3.	40	59,9	19,1	
4.	30	57,8	18,4	
5.	20	59,6	19,0	
6.	15	63,7	20,3	Figures 4, 5
7.	10	83,3	26,7	
8.	8	107,7	34,6	
9.	6	154,0	49,4	
10.	4	collapse	collapse	

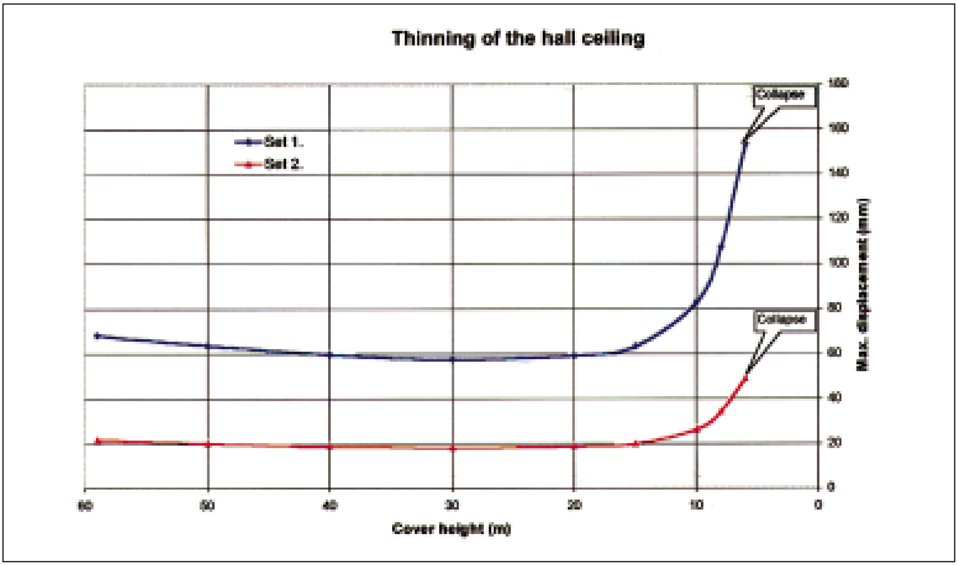

Fig. 3: Thinning of the Medvedova konta hall ceiling.
Sl. 3: Tanjšanje stropa dvorane Medvedove konte.

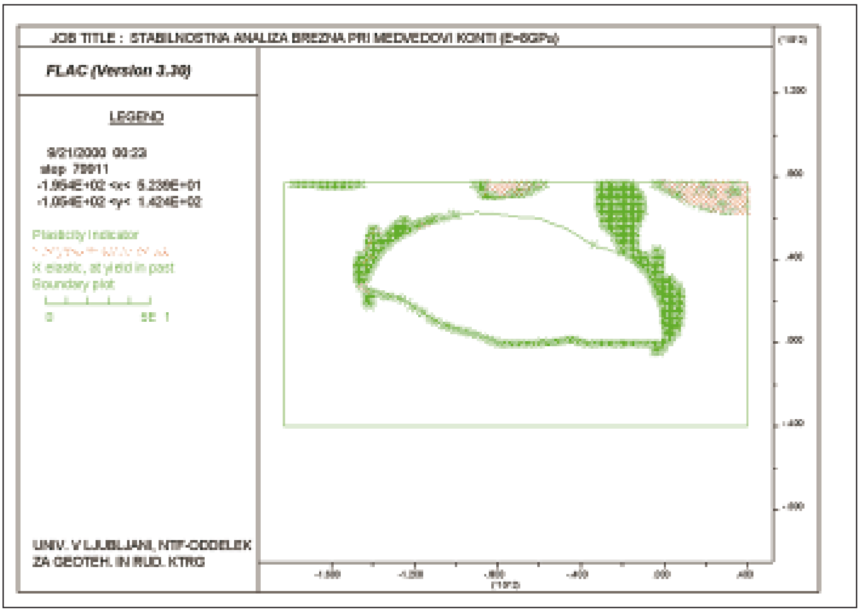

Fig. 4: Plasticy indicators in the surroundings of hall area (ceiling thinner than 20 m).
Sl. 4: Plastična območja v hribini v okolici dvorane (strop tanjši kot 20 m).

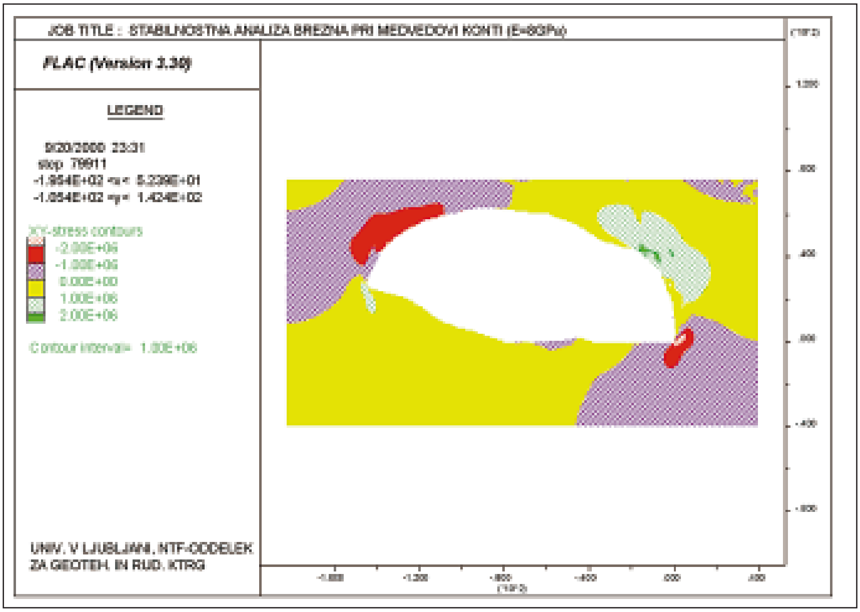

Fig. 5: Shear stresses in the surroundings of hall area (ceiling thinner than 20 m).
Sl. 5: Strižne napetosti v hribini v okolici dvorane (strop tanjši kot 20 m).

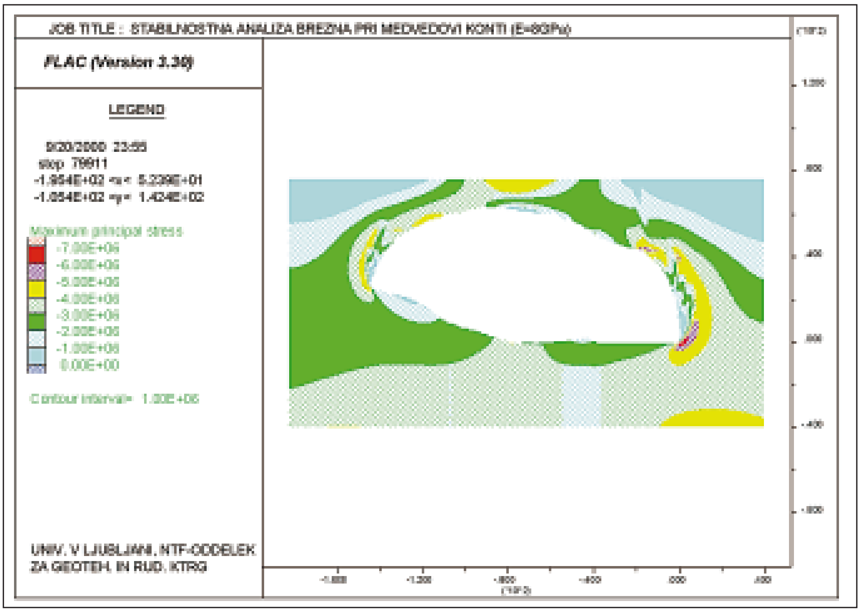

Fig. 6: Maximal stresses in the surroundings of hall area (ceiling thinner than 20 m).
Sl. 6: Največje napetosti v hribini v okolici dvorane (strop tanjši kot 20 m).

Solid rock, such as Triassic limestone, is characterised by brittle fracture. Such rocks can withstand only low plastic strains, so any appearance of plastic areas in the model indicates a potential danger of chamber ceiling collapse.

CONCLUSIONS

The stability appraisal presented in the paper was used for study and research purposes at the Medvedova konta pothole. The results of the related modelling, as described, can contribute to the understanding of the mechanisms of doline formation.

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[5] *The titles of summaries/abstracts (if they exist) are given just to show the foreign reader the contents of the original texts, which are, however, considered in the whole.*

MODELIRANJE STABILNOSTI ZELO VELIKE JAMSKE DVORANE; NA PRIMERU BREZNA PRI MEDVEDOVI KONTI

Povzetek

Teoretski izračuni (A. Scheidegger, 1962) kažejo, da postopno krušenje stropa jamskih dvoran privede do stabilnega (praboličnega) oboka (Ph. Renault, 1967). Če iz obravnave izpustimo možnost, da se zaradi tektonsko preveč poškodovane kamnine stabilen obok v gotovih primerih ne more vzpostaviti, ostaja neogibno dejstvo, da denudacija postopoma stanjša jamski obok do take mere, da se zruši. Da bi dobili boljši vpogled v dogajanje, smo s pomočjo računalniškega programa FLAC, ki je prvenstveno zasnovan za izračunavanje napetosti v hribini ob gradnji umetnih podzemskih protorov, oblikovali teoretski model.

Program FLAC (Fast Lagrangian Analysis of Continua) deluje na osnovi dvodimenzionalnih eksplicitnih končnih diferenc. Uporabnik mrežo sam prilagodi obliki proučevanega jamskega prostora. Med proceduro se vsak posamičen element odziva glede na postavljene linearne/nelinearne zakone napetosti, ki nastanejo kot odgovor na sile, ki jih predpiše uporabnik kot mejne pogoje. Material se lahko deformira elastično ali plastično, mreža pa se sproti prilagaja premikom gmote. Program temelji na Lagrange-ovi računski shemi, ki je zelo ugodna za modeliranje velikih defrmacij oz. porušitev materiala.

Za poskusni objekt smo izbrali dvorano v Breznu pri Medvedovi konti (2330[6]). Vhod v jamo leži na severnem kraju Pokljuke, pri koordinatah 5419 18 / 5137 02 in na nadmorski višini 1390 m. Vhodno brezno se v globini slabih 50 m odpre v skoraj okroglo dvorano, premera okrog 150 m in visoko prek 50 m. S svojo prostornino okrog $62{,}0 \times 10^4$ m^3 je to druga največja jamska dvorana v Sloveniji[7]. Sorazmerno ravno jamsko dno prekriva podorni material.

Povprečna debelina stropa nad jamsko dvorano v breznu pri Medvedovi konti znaša okrog 55 m in strop je - glede na izmere dvorane - sorazmerno blizu površja. V takšnih primerih razmerje med horizontalnimin navpičnimi tlaki precej varira, v splošnem pa horizontalni tlaki (σ_H) prekašajo vertikalne (σ_V). Učinke denudacije smo simulirali tako, da smo pri izračunavanju statike jamskega prostora postopoma tanjšali debelino stropa.

Konstruirali smo en sam model, vendar uporabili dva različna nabora parametrov (Preglednica 1), ki odgovarjajo laboratorijskim preiskavam triasnega apnenca. Lastnosti materiala so izbrane tako, da zagotavljata stabilnost modela preden začnemo tanjšati strop.

Velikost mreže je 223×162 elementov, uporabili pa smo Mohr-Coulombov model plastičnosti. Razvoj premikov smo izračunavali za tri izbrane kontrolne točke v stropu dvorane. Model smo obravnavali kot stabilen, če so vrednosti deformacij v kontrolnih točkah konvergirale k končni vrednosti.

Denudacijo (zniževanje površja) smo v modelu simulirali s tanjšanjm stropa v desetih koprakih. Rezultate prikazuje naslednja preglednica (2)

[6] *Identifikacijska številka jame v katastru jam Slovenije, ki ga vodita Jamarska zveza Slovenije in Inštutut za raziskovanje krasa, ZRC SAZU.*

[7] *Podrobnejše podatke o jami lahko dobi bralec pri J. Kunaverju (1960), od koder jih povzemamo.*

Preglednica 1: Izbrana nabora mehanskih lastnosti materiala, uporabljena v modelu.

Simbol	Enota		Nabor 1	Nabor 2
E	(GPa)	Elastični modul	8	25
ν		Poissonov količnik	0.25	0.25
T	(MPa)	Natezna trdnost	1.85	4
γ	(kg/m^3)	Gostota	2732	2732
C	(MPa)	Kohezija	1.1	1.1
φ	(°)	Strižni kot	35	35

Preglednica 2: Maksimalni premiki med tanjšanjem stropa dvorane, prikazani posebej za vsak nabor parametrov (tip kamnine) posebej.

Korak	Debelina stropa (m)	Največji pomik prvega nabora (mm)	Največji pomik drugega nabora (mm)	Opombe
1.	59	68,4	21,9	
2.	50	63,9	20,4	
3.	40	59,9	19,1	
4.	30	57,8	18,4	
5.	20	59,6	19,0	
6.	15	63,7	20,3	Sliki 4 in 5
7.	10	83,3	26,7	
8.	8	107,7	34,6	
9.	6	154,0	49,4	
10.	4	udor	udor	

V obeh primerih se strop zruši, ko mu debelina pade pod 4 metre. To se dobro sklada s terenskimi opazovanji na krajih, kjer so se jamske dvorane že pričele odpirati na površje. Med simulacijo so se plastične deformacije najprej pojavljale v bližni stropa in sten dvorane, s tanjšanjem stropa pa so se bližale vrhu oboka in površju. Na krajih, kjer se je strop stanjšal pod 20 metrov so se postpoma nakazovale možne porušitve. Največji pomiki so se pojavljali v jamskem stropu in zmanjševali proti stranem. Časovni razvoj na kontrolnih točkah kaže, da so pomiki manjšali od večjih debelin stropa proti debelini okrog 30 m - kjer so dosegli minimum - nato pa z nadalnjim tanjšanjem stropa spet večali do porušitve.

Kamnina, kakršen je triasni apnenec, je krhka. Takšen kamnine se lahko upirajo le nizkim plastičnim deformacijam. To pomeni, da je že vsako pojavljanje omočij plastičnosti objektivna grožnja s porušitvijo stropa.

Stabilnostno študijo dvorane v Breznu pri Medvedovi konti smo izvedli izključno iz znastvene radovednosti. Vsekakor pa rezultati prispevajo k boljšemu poznavanju mehanizmov nastajanja udornic nasploh.