Experimental examination of erosion threatened waterfalls on tuff beds protection : natural landscape, historical and cultural values on the example of the town Jajce

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EXPERIMENTAL EXAMINATION OF EROSION THREATENED WATERFALLS ON TUFF BEDS PROTECTION – NATURAL LANDSCAPE, HISTORICAL AND CULTURAL VALUES ON THE EXAMPLE OF THE TOWN JAJCE

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Preliminary notes

The possibilities of technical interventions in waterfall area formed in heterogeneous tuff sediments are described in this paper. The river Pliva's waterfall was chosen for the test site, as it is a unique natural phenomenon placed in the middle of the old town of Jajce. The applicable methods for technical stabilization of waterfall are conditioned by natural, urban, architectural, historical and specific values of the town landscape. That is why that concrete or reinforced concrete structure should be avoided and priority given to binders for natural tuff detritus that do not change the shape or color of naturally hardened tuff are preferred. Laboratory experiments on a large number of samples have shown good results when micro-cement was injected into tuff beds, but the usability of other injection suspensions was also examined on the research region. The injection suspensions were adjusted to the tuff lithological composition. Comparisons of the control samples in laboratory and on site have shown acceptable results of the applied methods.

Key words: *Experiment, erosion, possibility of injection, Jajce, tuff, waterfall*

Eksperimentalno istraživanje zaštite erozijom ugroženih vodenih slapova na naslagama sedre - prirodne pejzažne, povijesne i kulturne vrijednosti na primjeru grada Jajaca

Prethodno priopćenje

U članku se opisuju mogućnosti prihvatljivih tehničkih intervencija u prostoru slapova formiranih u heterogenim naslagama sedre. Kao istražni poligon odabran je slap rijeke Plive, izuzetan prirodni fenomen smješten u samom središtu povijesnog grada Jajca. Metode istraživanja primjenjivosti tehničkih rješenja stabilnosti slapa uvjetovane su prirodnim urbanističkim, arhitektonskim, povijesnim, te specifičnim pejzažnim vrijednostima gradskog prostora zbog čega betonske i armirano betonske konstrukcije treba izbjegavati a prioritet dati stabiliziranju prirodnog sedrenog detritusa vezivima koja ne mijenjaju izgled i boju prirodno očvrsle sedre. Laboratorijski eksperimenti na velikom uzorku pokazali su dobru injektibilnost mikrocementa u sedreni detritus, a primjena ostalih suspenzija ispitivana je na istražnom poligonu gdje su injekcijske suspenzije prilagođavane litološkom sastavu sedrenih naslaga. Kontrolna ispitivanja u laboratoriju i na istražnom poligonu potvrdila su uspješnost primijenjenih metoda.

Ključne riječi: *Eksperiment, erozija, injektibilnost, Jajce, sedra, slap*

1 Uvod
Introduction

Natural beauties of waterfalls give special ambient markings to water flows. On some locations, especially carbon detritus, in waterfall regions tuff beds are created and with their specific shapes enrich artistic impression of nature. Rarely can such phenomena be found in the very centre of a city. The Pliva river waterfall is in the centre of the town and represents one an example of natural phenomena that enrich the values of hundreds of years of the city construction. It is a symbol of the historical town of Jajce (Figure 1).

Technical interventions in the waterfall region formed out of heterogeneous tuff sediments are conditioned by:

- Natural, landscape, urban-architectural and historical values of the town Jajce, but also the landscape's cultural values of the town's wider region and surroundings of Jajce [1, 2].
- Natural markings of the Pliva river waterfall.
- Lithological composition and geotechnical characteristics of tuff beds on which the town Jajce is built and which form the Pliva's waterfalls in the centre of the town [3].
- Continuous erosion and the Pliva waterfall degradation especially during the time of special hydrological occasions [4].

Analyzing the previously mentioned conditions and events, basic demands for technical interventions in the very body of the waterfall are gained. Technical interventions must not degrade the ambient integrity and composition of natural beauty of the waterfall, its meaning in the perception

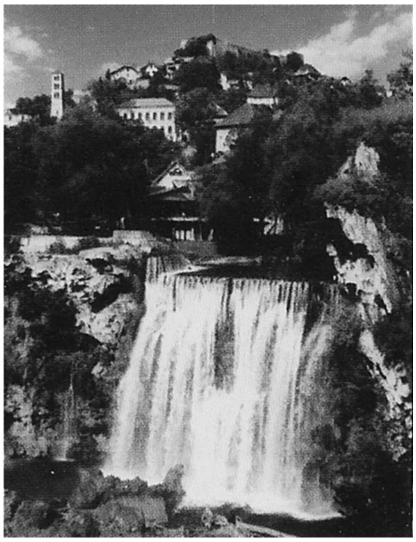

Figure 1 *The Pliva river waterfall in the centre of the town Jajce*
Slika 1. *Slap rijeke Plive u gradu Jajcu*

of the wider landscape as recognizable cultural region and urban-architectural marking of the narrow town region. Concrete or reinforced concrete constructions that could help stabilize the waterfall would impact the shape of the waterfall and ambient integration of architectural, urban and natural markings of the whole region.[1] Even the underwater concrete constructions built in the past present a

1) About the meaning of cultural landscape, and about the condition of protection of cultural landscapes in Croatia, which has by signing Convention of European landscapes taken over the duty of taking care of landscapes, as a part of European landscape differentiality – more in: [1] Bilušić Dumbović, B.; Obad Šćitaroci, M, 2007.: 260-271.

devastation of the region, and what is more, they are not efficient in stopping the devastation of a great part of the waterfall.

Taking into account the named restrictions, the choice of the waterfall stabilization methods is seriously narrowed, especially because of the high lithological heterogeneous and geotechnical characteristics of tuff sediments.

As technical erosion protection solutions of the waterfall, the following choices are available:

1 Tuff beds' injection with adequate suspensions
2 Jet Grouting.

By using comparative analysis of usability for these methods of tuff beds stabilization with complex lithological and geotechnical characteristics it is necessary to find the optimal technical solution that will meet all the named restrictions. This analysis has been performed experimentally by conducting injection experiments on large numbers of tuff detritus in laboratory, by tests on the testing area on the left side of the waterfall and also by examining jet-grouting success in materials with similar geotechnical characteristics.

Advantages and disadvantages of the examined methods mostly depended on geotechnical characteristics of tuff beds and their changeability in space.

2 Review of natural, historical and urban-architectural values of the town Jajce

Osvrt na prirodne, povijesne i urbanističko-arhitektonske vrijednosti grada Jajca

The town Jajce is situated on diluvia and recent tuff beds with thickness of up to 60 m, within which the Pliva river formed its bed and a fabulous 18 m high waterfall. A large number of constructions, in that unique surrounding, that were built recently or in the past, are characterized by their being composed of local materials – picturesque stone with specific porous structure, cut out of compact and petrified tuff. Even after the wars and the devastation and rebuilding of the city in the last two centuries, the town has kept its urban characteristics with evident marks of earlier times. On the area of the city core, findings in caves, formed in tuff beddings, prove the past existence of prehistoric settlement. Late antique tombs, leftovers of Roman brick factory, numerous Roman buildings and money from 2nd, 3rd and 4th century are showing that the antique settlement was city-like [2]. By constructing on Roman leftovers Jajce has created its current shape during the Middle ages. That happened during the 14th and 15th century, mostly by the efforts of Hrvoja-Vukčić Hrvatinić, and it became a royal town during the kingdom of Kotromanić. Then the intensive cultural, trade, but also construction and art contacts with Italian and Croatian towns near the Adriatic coast were established. During the 14th and 15th century the Roman tower and church were built influenced by Dalmatian tradition (St. Lucas tower and St. Mary church). The early and late Roman, Gothic and Renaissance markings are visible on many architectural fragments, like the relief decoration in the St. Mary's church portal and the royal emblem on the entrance into the fortification, etc.

The fortress and the city walls date from the 13th, 14th, 15th and following centuries with three city gates and fortresses, square shaped wooden houses typical for residential buildings in Bosnia and Herzegovina since the Middle ages, plenty of watermills and columns with other specific urban-architectural marks of that time, especially sacral buildings (churches, monasteries and mosques), make harmonious and picturesque town unit characterized by, besides traditionally used wood, tuff as main construction material. The trend of building with these materials was continued during the Austro-Hungarian rule and reduced after the 2nd World War. Because of these facts, conservation of this fundamental building material, used specifically and uniquely by man and nature, is of greater importance when approaching the renewal of the Pliva waterfall, which is generally the main condition of urban revitalization of Jajce. Some designs carried out after the 2nd World War received prestigious world recognitions on account of great landscaping designs that harmonized with traditional architecture of the city. Since the 1970's on lands of Bosnia and Herzegovina the construction has been characterized by a quite aggressive approach to historical heritage, which has partially been the will of the ruling structures of that time. Still, Jajce has the best preserved urban picture of the city in Bosnia and Herzegovina. The word is about the shopping centre "Jajce" in the centre of the town designed by a group of Croatian architects (R. Jandrić, DŽ. Karić, N. Kurt i G. Ferušić from Zagreb) and winning the 2nd place on International congress of architects UIA ("Unité international des architectes") in Mexico, in 1978.

Besides urban-architectural landmarks, the outlook and cultural landscape of the town, its close surrounding is filled with harmonious design of the park on sides of the river and the waterfall that enrich the whole ambient value.

Of all the architectural values, as specially valuable and important sights of the town, actually the urban-architectural values of the narrow region and cultural value of the wider region the following ones should be emphasized (Figures 2, 3, 4, 5, 6 and 7).

- The Bear tower, built at the beginning of the 14th century is one of the oldest fortresses in Bosnia and Herzegovina with walls 6 m thick constructed of tuff stone and chalk and perimeter of 50 m, [2].

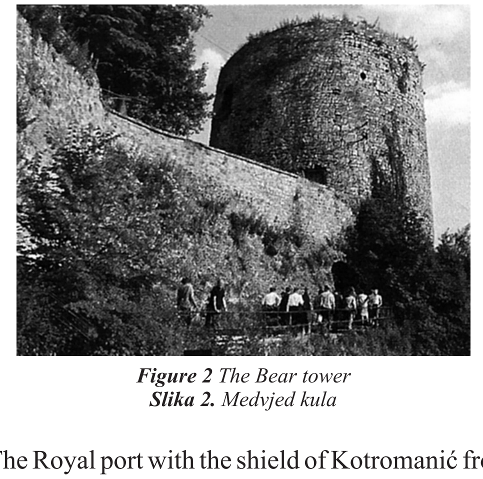

***Figure 2** The Bear tower*
***Slika 2.** Medvjed kula*

- The Royal port with the shield of Kotromanić from 15th century. The emblem was shaped in tuff in Gothic style and is composed of a crown shaped like lily. The Crown, armor and flower bouquet are placed in the middle. The emblem was shaped in tuff in Gothic style, [2].
- The Banjaluka gate, earlier known as Franciscan doors, dating from the bricklaying time of Jajce. The main construction material is shaped tuff, [2].

Figure 3 *The Royal portal and emblem*
Slika 3. *Kraljevski portal i grb*

- St. Mary's church with Roman sculptures of lions is one of the oldest sacral objects of catholic provenance in Bosnia and Herzegovina. It was built during the 14th century and later upgraded and widened in Gothic style. During the mid 15th century Roman tower (St. Luca tower) was built under a strong influence of Dalmatian constructing tradition. This tower was protected as a cultural monument during the year of 1982. The main material is tuff, [2].

Figure 4 *The Banjaluka gate*
Slika 4. *Banjalučka vrata*

- Design of shopping centre "Jajce" in the centre of the town won a 2nd prize on International congress of architects UIA ("Unité international des architectes") held in Mexico in 1978. Authors of this design are R. Jandrić, DŽ. Karić, N. Kurto and G. Ferušić from Zagreb. The shopping centre "Jajce" is an example of harmonious and relatively careful embedding in the existing urban-architectural and landscape unit, [2].
- The town park by the Pliva waterfall with its position and design is bonding the old town's core to the magnificent waterfall. The town's park is the best example of integration in and coexistence of natural regional marks and historical urban-architectural intervention, [2].

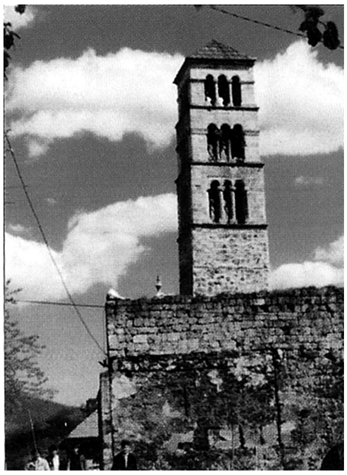

Figure 5 *St. Mary's church*
Slika 5. *Crkva sv. Marije*

Figure 6 *Shopping center "Jajce" built during 1976.*
Slika 6. *Robna kuća "Jajce" izgrađena 1976.*

Figure 7 *The town's park-garden*
Slika 7. *Gradski perivoj*

3 Lithological structure and geotechnical characteristics of the tuff sediments
Litološki sastav i geotehničke značajke naslaga sedre

Over the limestone lower chalk are laying tuff beds on which the town Jajce was built. In these tuff beds the Pliva has cut a river bed that ends with an 18 m high waterfall into the river Vrbas. Tuff is sweet water calcium-carbonate sediment that is extremely porous, formed from algae and moss that assimilate CO_2 from the water. By reducing CO_2 from calcium-carbonate $Ca(HCO_3)2$, the calcite $CaCO_3$ forms a calcite shell around and in that way different shapes of tuff are produced. For the growth of algae and moss, that enable the production of tuff, specific morphologic, geologic, biologic and hydrologic prerequisites are required. Water needs to be clean without chemical or biological pollutions. Its temperature may vary from 10 °C to 23,4 °C, with alkalinity 3,6-2,7, hardness 10,2, pH 7,1-7,5, with favorable light conditions, and its speed needs to be from 0,5 to 3,5 m/s. Any change of these conditions slows down or completely stops the development of tuff. Sewage and chemical pollution speeds up the retardation and destruction of tuff. In geological past, the climate and hydrological changes were frequent resulting in changed conditions of creation and destruction of tuff. The result of creation and destruction of tuff are differences in geotechnical characteristics and the tuff is found as:

- Compact petrified rock, partially caught with cracks and faults, often filled with tuff sand. In hard tuff beds, pores of smaller dimensions are found (diameter 1-30 mm) and bigger empty spaces – caverns with a diameter up to 2-3 m. Caverns can be partially or completely filled with tuff sands. In caverns limestone gravel and sand can be found, the proof of special hydrological occasions, like large water waves with limestone boulder transportation from greater distances. Under such conditions hard tuff is destructed and detritus is created.
- Fine grain bounded, weakly bounded and unbounded tuff is mixed within tuff beds. Their geotechnical characteristics are extremely different because bounded fine grain tuff and homogenous textures have the characteristics of hard stone, but unbounded tuff is presents detritus extremely prone to erosion. Half bounded tuff was created by consolidation of tuff detritus, but did not go through a phase of petrification and these tuff beds are prone to erosion.

4 Analysis of possible consolidating interventions
Analiza mogućih sanacijskih zahvata

Because of specific geological structure and morphological and hydrological characteristics of the terrain, bedding and the waterfall of the Pliva river were exposed to erosion and degradation of the waterfalls several times during the past. The first position of the Pliva waterfall was directly at the mound with Vrbas and today it is about 200 m upstream. Its first technical consolidation was conducted almost 100 years ago, but part of the waterfall along with the concrete spillway crown was degraded by the year 1947. The next technical interventions on the waterfall and river bed were conducted during 1958. Due to long and intensive precipitation during 1995 and 1996 two large water waves occurred that intensively eroded tuff beds along the river bed and waterfall. The river banks were under-dug and demolished and on the right bank large landslides occurred. Previously conducted interventions did not secure the stability of the waterfall and the concrete constructions distorted natural looks and the beauty of the waterfall.

Therefore, we explored the possibility of using injection as a method of stabilizing tuff beds in a wider region of the waterfall which should enable tuff detritus to behave as hard tuff. The whole region was additionally toughened by filling the caverns with bonding agents. As a research area the Pliva waterfall was chosen because of extremely non homogenous composition of the tuff beds. Success in using suspensions based on Portland cement is questionable due to bad ratio of pore dimensions to dimensions of particles of cement with standard grading and the penetration ability of micro-cement is definitely greater. Before the injection with micro-cement the penetration was tested in a laboratory on the samples of 0,72 m^3. Injecting under pressure of 4 bar was conducted with mixtures based on Portland cement PC-45, micro-cement of fineness 40μm and micro-cement of fineness 20 μm. In all the used mixtures 2 % of plasticizer was added, and water to cement ratios were 3,0; 1,5; and 1,0. For the sample injected with Portland cement PC-45 hardened to unbounded part of injected sample ratio was 0; 0,68 for micro-cement of fineness 40 μm and 1,0 for micro-cement of fineness 20 μm.

By ultrasound speed testing on samples of naturally hardened tuff vpsr(n) and samples of tuff detritus that were injected with micro-cement of fineness 20 μm vpsr(g), the ratio of average speed values of primer waves was vpsr(n)/vpsr(g) =0,5. These ultrasound waves' speed ratio shows that tuff sand and dust by injecting with micro-cement of adequate fineness are gaining better geotechnical characteristics than naturally hardened tuff.

Using this experience a new experiment was performed with changed sample dimensions, types of micro-cement and the injection pressure on samples of different length [5]. The aim of the second experiment was to check the results from the previous experiments and to find out the penetration length of injection mixtures for 4 different types of cement. This data gave us the distance between injection points for tuff according to the used type of cement.

The following types of Portland cements were used for experiments:

- PC-45, mark A
- micro-cement, blaine (surface Area) 650 m^2/kg, mark B
- micro-cement, blaine 900 m^2/kg, mark C
- micro-cement, blaine 1200 m^2/kg, mark D.

Into the steel pipes with a diameter 100 mm and a length of 0,5; 1,0; 1,2; 1,5 and 1,8 m, tuff sand and dust has been poured, compressed every 20 cm with a hammer on to a 94 mm wide cob. This way compression of sand and dust was almost like in nature.

The water to cement ratio was 1,0 for all types of cement used. After mixing the water and cement in given ratios for 2 min, a plasticizer in amount of 2 % of the cement weight was added and mixed for 1 min. So prepared injection mixture was pressed into the steel pipes with perforated basing containing compressed tuff detritus. Injection was conducted under pressure of 6 bars and stopped after the injecting mass showed up on the perforated end or after 40 min of injecting. After 28 days, pipes were opened, the length of bonded samples was measured and the speed of ultrasound waves was measured. Results of this experiment are shown in Figure 8.

The experiments showed that injecting the tuff with injection mixture based on Portland cement PC-45 is not possible, because the injection mixture had almost no penetration in tuff detritus. There is a possibility of using the consolidation injection for tuff detritus using micro-cement of different fineness, or different blaine. Hereby the range of injection depends on fineness of the cement and varies from 0,53 to 1,62 m. When blaine values rise the primer speeds of ultrasound waves rise as well and thereby the values of dynamic modulus of elasticity. The distance between

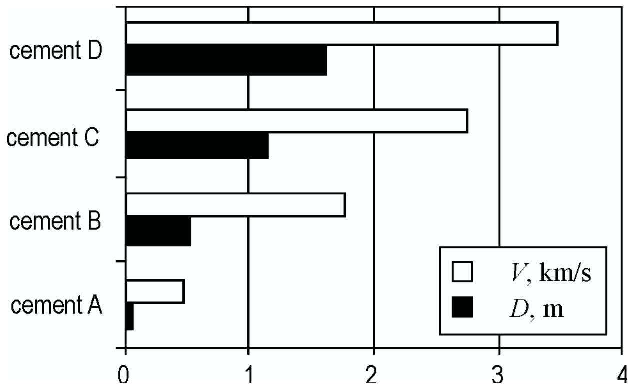

Figure 8 *Length of bonded samples D and speed of ultrasound waves V*
Slika 8. *Duljina očvrslih uzoraka D i brzina V ultrazvučnih valova*

injection points can be up to 3,0 m if micro-cement of greatest fineness is used for injection mixtures. In that case the best lithofication of tuff detritus is produced, that is the best resistance to erosion. The price of micro-cement increases as the fineness of the cement increases so the distance between injection points should also be determined by taking into account economical criteria.

Due to heterogeneity of the tuff beds in the region of waterfall the variability of particles the crack and cavern porosity change. There are mostly tuff beds with tuff sand and dust porosity, and much less the lithofied tuff with crack porosity. Caverns take about 6 % of volume of tuff beds. Caverns and larger cracks can be injected with mixtures on the base of cheaper cement PC-45, and the use of micro-cement should be limited just on the tuff sand and dust. Ref. [3] is showing the injecting process on testing ground and the first results of testing the control injection points. Used was a method of graduate approach that enabled evaluation of injection success by measuring the dry contents of the injection mixture in the primary and secondary injection points, and control drillings enabled checking the reduction of porosity and improvement of geotechnical characteristics of tuff.

Sum consumption of the dry mixture in the first rows of secondary injection is 3 times lower than the primary injections, and dry mixture consumption in the second row is 6 times lower than in the first row. Success indicator of consolidation injection in tuff sands and dust is not always correct. Additional control drillings showed that injection mixture based on micro-cement did not always reach the set distance of 3 m [5]. This fact was verified with cross-hole testing of seismic wave speed before and after the injection [5]. Investigations showed that there were zones in tuff sands where seismic wave speed did not change even after injecting. Those were the zones injected with mixtures based on cement with fineness 40 μm. These facts match the experiment results shown in Figure 8.

Samples of injected tuff detritus have the looks of naturally hardened tuff with homogenous texture (Figure 9). Besides the shown geotechnical aspects, the use of micro-cement has also an important visual advantage that usually has great natural values.

Stabilization of waterfalls with concrete constructions usually degrades natural values. As shown in chapter 2, wider area of the Pliva waterfall has great cultural and historical values and every technical intervention has to be in accordance with these values.

Stabilization of waterfall area can be conducted even with the jet grouting method. This method enables stabilization of the ground regardless of the volume of the particles, because the ground structure is destructed with highly pressurized fluid flow and earth particles are mixed with cement suspension and after bonding this mixture forms different geometrical shapes of earth with improved geotechnical characteristics. Hydrological flow destroys the ground in the diameter of 2,5 m, depending on the ground type, conduction and used fluid. For not so highly compressed tuff sand and dust the diameter of 1,5 m can be used.

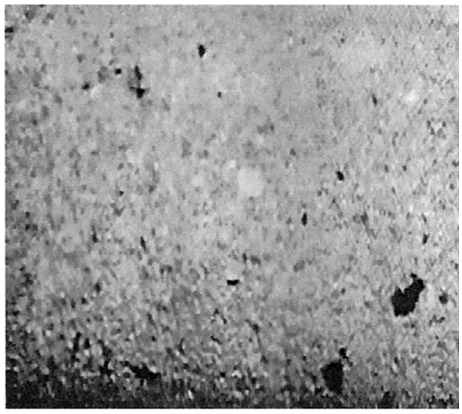

Figure 9 *Looks of tuff sand and dust injected with micro-cement*
Slika 9. *Izgled mikrocementom injektiranog sedrenog praha i pijeska*

Hardness of the ground after jet grouting depends on type and volume of cement and ground and it increases with the diameter of the ground particles and cement volume and is within next values:

- Dust 5-10 N/mm²
- Sand 10-25 N/mm²
- Gravel < 25 N/mm².

For tuff sand and dust jet grouting with one-fluid-direct injecting can be used, which for uses flow of cement suspension destruction and bonding of the ground. This technique is used for materials that closely represent the composition and granulation of tuff sand and dust. The body of injected mass that was dug resembled hard tuff with homogenous texture (Figure 10).

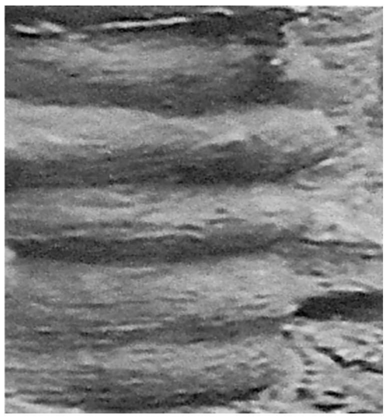

Figure 10 *Ground after jet grouting*
Slika 10. *Tlo injektirano mlaznim postupkom*

Comparing the samples injected with micro-cement to the samples after jet grouting it is easy to see that jet grouting leaves larger amount of pure cement. In extremely heterogeneous tuff sediments, though, jet grouting is questionable in regions with caverns and hard tuff.

Caverns filled with hard materials, because of their placement, give the whole region an additional dose of security in the region of the waterfall, which is hard to achieve with jet grouting.

Jet grouting method has the advantage of achieving greater toughness in shorter time. The main advantages of injecting with micro-cement are achievement of the almost natural look of tuff, a possibility to completely fill the caverns and cracks with bonding material and the possibility of conducting the works near the waterfalls.

A special disadvantage of jet grouting is the possibility of damaging waterfalls while conducting the works near the waterfall and the possibility of damaging to natural skeleton of tuff because of the highly pressurized fluid flow. Conducting the works with jet grouting under given circumstances needs additional investigation, can endanger the waterfall stability and probably needs some technological adjustments.

5 Conclusion
Zaključak

The technical usability of methods for waterfall stabilization on tuff deposits depends on natural, urban, architectural and historical values of the town area. These are also the reasons why concrete and reinforced concrete constructions should be avoided, and stabilization of tuff detritus with bonds that give natural looks of naturally toughened tuff should be preferred. The possible choices are extremely rare, especially because of extremely heterogeneous lithological and geotechnical characteristics of the tuff beds.

As possible technical solutions for waterfall protection from erosion the preferred ones are:

1 Injecting the beds with adequate suspensions based on micro-cement
2 Jet Grouting.

Before in situ experimental injecting based on micro-cement an experimental the laboratory investigation on the samples of 0,72 m^3 volume was conducted. The results showed that injecting the tuff sand and dust based on micro-cement is possible. Second experiment was conducted in pipes with different length and the results proved the first experiment, but also determined the reach of injection of Portland cement PC-45 and three types of micro-cement. Distance between the injection points can be up to 3,0 m, if the injection mixture is made based on cement of best fineness. Jet grouting as an alternative to injecting with micro-cement has some advantages, especially due to greater hardness of treated ground and shorter execution time. Its success is questionable in caverns and hard tuff region. A special disadvantage of jet grouting is a possible endangering of the waterfalls structure and possible damage to natural skeleton of tuff because of a highly pressurized fluid flow.

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