Supplementary text for the article "Evolution of natural rock arches: A realistic small-scale experiment"

Jaroslav Řihošek[1*], Martin Slavík[1], Jiří Bruthans[1], Michal Filippi[2]

[1]Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic

[2]Institute of Geology of the Czech Academy of Sciences, Rozvojová 269, 165 00 Prague 6, Czech Republic

*Corresponding author: Tel.: +420 777786738

E-mail address: rihosekjaroslav@gmail.com

Video DR1 of physical model erosion

2019028_Video DR1.zip

JUSTIFICATION OF PURPOSE

A natural arch is defined as a rock exposure that has a hole completely through it formed by the natural, selective removal of rock, leaving a relatively intact frame (Wilbur, n.d.-a). Many rock arches are formed accidentally, when a combination of "microscopic" and "macroscopic" erosion mechanisms acts together with specific conditions such as the shape of the rock exposure, action of peculiar weathering processes, tectonic history, etc. These have been considered to be essential causes for the formation of natural arches (Vreeland, 1976; Barnes, 1987). Since various fractures in sandstone are commonly a clearly observable feature related to arches, many studies have dealt with the influence of fracturing and enhanced erosion in fracture zones in the creation of arch origins (Cruikshank and Aydin, 1994; Grab et al., 2011). However, no detailed mechanisms of arch formation have yet been given.

The present work was aimed on "perfectly shaped" rock arches that are formed in some sandstones and other granular rocks constituting materials in which the erosion is stress-controlled (see Bruthans et al. 2014; 2017, Filippi et al. 2018).

STUDY SITES AND MATERIAL CHARACTERISTICS

Physical modeling was conducted at the bottom of the Střeleč Quarry (Bohemian Cretaceous Basin), situated approximately 75 km NE of Prague, Czech Republic (50.493346N, 15.245163E). The quarry produces pure quartz sand for the glass industry. The friable sandstone and locked sand (SLS) was deposited during the upper Turonian and Coniacian in a shallow marine environment as coarse grained delta bodies (Uličný, 2001). Impressive features such as towers, arches, windows, etc. are developed in the wider area. The SLS is predominantly composed of fine to medium-grained angular quartz grains (95-99% quartz). The fine fraction content (particles smaller than 25 µm) is 1.4%, and is composed of well-ordered kaolinite (75%), quartz (24%), and illite (1%) (Bruthans et al., 2014). The SLS that was used for the modeling is characterized by an extreme contrast of tensile and compressive strengths. The uniaxial compressive strength is 2.7-3.2 MPa. Its tensile strength is 2-4 orders of magnitude lower than its compressive strength (Bruthans et al., 2014; Slavík et al., 2017). A high internal friction angle (74°) and low cohesion (6 kPa), both determined by the drained triaxial test (Bruthans et al., 2014), are associated with a partially interlocked fabric of angular grains (Dusseault and Morgenstern, 1979). The effectiveness of erosion of SLS depends on the stress level. SLS disintegrates in standing water and is eroded by rain if not loaded. On the contrary, if the same specimen is loaded by an external load or by weight of the overburden, which creates a compressive stress locking the internal structure, it resists both slacking, rain, and flowing water (Bruthans et al., 2014). Further experiments (Rihosek et al., 2016) have demonstrated that the SLS is an excellent material for an accelerated simulation of erosion because of the lack of any interstitial cement.

It is important to note that water erosion by watering can used as erosional agent of physical model presented in our work is just one of many erosion processes which are affected by stress. As demonstrated by Bruthans et al. (2014), stress is capable to orchestrate different erosion factors to carve similar shapes including arches (e.g. rain drop and flowing water erosion, slaking disintegration, removal of material due to salt and frost weathering, probably wind erosion).

Arches National Park is very rich in rock arches (over 2000 per 31 km^2), most of these having developed within the fin-like ridges of the Entrada Sandstone (Oberlander, 1977). Their presence is controlled by a joint system (Cruikshank and Aydin, 1994; Stevens and McCarrick, 1988). Landscape Arch is about 88 m long from base to base, and is considered to be one of the longest arches on Earth (Dixon, 2010). In the 1990's, several rockfall events of the arch occurred (Wilbur, n.d.-b).

PROGRESS OF DENUDATION

Using the frontal view, denudation of the top of the model's fin at seven different points was measured (Figure 1A in main article). It was revealed that during the initial stage, cross-sections I, II, and VII adjacent to the arch eroded, on average, at the rate of 3.2 to 6.3 mm per erosional step; and then the erosion rate surrounding the arch decreased to ~0.5 mm per erosional step, on average (Figure 1B in main article). In the mature stage (erosional step 40-85), cross-sections IV and V at the arch lintel showed the lowest erosion of 0.1, resp. 0.6 mm per erosional step, on average; while in the senile stage (erosional step 85-93), they eroded at the highest rate 4.8-4.9 mm per erosional step, on average. The erosion rate at cross-section VI showed a rapid erosional rate during the initial stage (4.4 mm per erosional step); subsequently the rate decreases to 0.6. resp. 1 mm per erosional step. In the case of III, the initial erosion rate was 2.5 mm per erosional step, and then it remained more-or-less constant, with a speed of 0.9-1 mm per erosional step. It can be seen from Figure 1A in main article that while both cross-sections III and VI were outlined onto abutments at erosional step 0, their location in relation to the arch changed during the development of the arch because the

line of sight wasn't aligned with the incision. The mean denudation per erosional step of the corresponding stage on cross-sections I-VII is illustrated on Figure 1B in main article.

For the sake of analysis of the arch's lintel erosion in its cross section at the center of the arch, the 3D photogrammetric model for each tenth erosional step was created. Area (Ai) and circumference (Ci) was measured on cross section of arch's lintel to calculate Relative area (RAi), Relative circumference (RCi), and Mean radial recession (MRRi), in corresponding erosional step i. The following formulae were used:

$$RA_i = A_i/A_0, (1)$$

where A_i is the area in the step i and A_0 is the area in the initial stage,

$$RCi = C_i/C_0, (2)$$

where C_i is the circumference in the step i, and C_0 is the circumference in the initial stage, and

$$MRR_i = (A_i - A_{i-1})/C_{i-1}, (3)$$

where A_i is the area in the step i, A_{i-1} is the area in the preceding step, and C_{i-1} is circumference in the preceding step.

ARCHES ON INCLINED DISCONTINUITIES

Development of a rock arch on an inclined discontinuity was studied on a small-scale physical model in the Střeleč Quarry (Figure 1). The setup of the experiment was analogous as in case of physical model for the arch developing on a horizontal incision. The lateral compression decreases erosion of the lintel which serves as a buttress of the rock face while the erosion along the inclined incision removes material not supporting the structure (Figure 2). Such arches commonly develop on an inclined discontinuity associated with vertical cliff face (Figure 3).

Figure 1 Initial step of physical model of arch on an inclined discontinuity.

Figure 2 Final step of physical model of arch on an inclined discontinuity.

Figure 3 Arch developed on an inclined discontinuity. An example from Czech Paradise − Duhová brána (Rainbow gate) in Protected landscape area Bohemian Paradise.

ADDITIONAL DISCUSSION TO ARCH FORMATION RATES

It is usual that arch evolution in many places around the World normally occurs over thousands of years or more.

Our experiment on SLS and a natural example of the La Dame Blanche (The White Lady) Arch in the vicinity of Dieulefit, France (http://www.naturalarches.org/blog/rapid-evolution-of-an-arch/), shows that the process can also be very fast. The La Dame Blanche Arch consisted of a

crumbly clay-like rock and evolved from youth through maturity to collapse in the course of just a few years. The arch was first observed in 2009 as a small opening in a fin of the rock, and culminated as a thin bridge in 2014 with a span of approximately 6 m. The arch collapsed in 2015.

The evolution of smaller rapidly-developing arches is dominated by granular disintegration or the flaking of scales, so we have to be cautious extrapolating the results presented prior herein to larger natural arches and bridges built of firm sandstone, with significant amounts of fracturing. In such arches, the stress may exceed strength limits. The physical erosional model can then be adopted assuming some simple structural delimitations: a roughly steady rate of erosion, and relatively negligible size of the eroded elements. Caution must be taken when applying an erosional agent in order to reflect the theorized intensity and distribution of erosion under natural conditions.

NOTE ON THE SUITABILITY OF LOCKED SAND AS AN ANALOGUE TO DEVELOPMENT OF ARCHES IN CEMENTED SANDSTONE

Sandstone arches are dominantly developed in cemented sandstones, less commonly in locked sands. However, exposed surface of cemented sandstone is usually affected by weathering which effectively decreases cement bonding between individual grains. Framework-supported sandstone with cementation will be transformed on its surface to non-cohesive locked-sand during weathering. This superficial zone is commonly just a few mm thick. Navajo sandstone and some other rock types on Colorado Plateau (USA) showed decrease of tensile strength on weathered surfaces by several orders of magnitude to values typical for locked sand (Bruthans et al., 2014).

NOTE ON THE ORIGIN OF WELL-DEVELOPED ARCHES

Part of arches clearly originated by random failures of material with lesser importance of stress control on erosion (e.g. Natural Bridge in Bryce Canyon National Park). However well-developed arches (elegant, with smooth surface and nicely curved over most of its span) are probably all the result of strong control of stress on erosion. Stress is the only factor that we are aware of, which physically interconnects all grains or building blocks in a larger scale (Bruthans et

al. 2014) in a rock body into a single system - landform. Instant feedback of the stress field in the

landform onto its shape makes stress the only factor capable of organizing the erosion to carve non-

random shapes.

REFERENCES CITED

Barnes, F.A., 1987. Canyon Country Arches and Bridges: Moab, Utah, Canyon County Publishers,
    416 p.

Bruthans, J., Soukup, J., Vaculikova, J., Filippi, M., Schweigstillova, J., Mayo, A.L., Masin, D.,
    Kletetschka, G., and Rihosek, J., 2014, Sandstone landforms shaped by negative feedback
    between stress and erosion: Nature Geoscience, v. 7, p. 597–601.

Bruthans, J., Filippi, M., Schweigstillová, J., and Řihošek, J., 2017, Quantitative study of a rapidly
    weathering overhang developed in an artificially wetted sandstone cliff: Earth Surface
    Processes and Landforms, v. 42, p. 711–723.

Cruikshank, K.M., and Aydin, A., 1994, Role of fracture localization in arch formation, Arches
    National Park, Utah: Geological Society of America Bulletin, v. 106, no. 7, p. 879–891.

Dixon, J.C., 2010, Canyonlands and Arches: Windows on landscapes in the American southwest, *in*
    Migoń, P. ed., Geomorphological Landscapes of the World: London, Springer Science, p. 39-
    47.

Dusseault, M.B., Morgenstern, N.R., 1979, Locked sands: Quarterly Journal of Engineering
    Geology, v. 12, p. 117–132.

Filippi, M., Bruthans, J., Řihošek, J., Slavík, M., Adamovič, J., and Mašín, D., 2018, Arcades:
    Products of stress-controlled and discontinuity-related weathering: Earth-Science Reviews, v.
    180, p. 159–184.

Grab, S.W., Goudie, A.S., Viles, H.A., and Webb, N., 2011, Sandstone geomorphology of the
    Golden Gate Highlands National Park, South Africa, in a global context: Koedoe, v. 53, no. 1,
    14 pages., doi: 10.4102/koedoe.v53i1.985.

Rihosek, J., Bruthans, J., Masin, D., Filippi, M., Carling, G.T., and Schweigstillova, J., 2016, Gravity-induced stress as a factor reducing decay of sandstone monuments in Petra, Jordan: Journal of Cultural Heritage, v. 19, p. 415–425.

Oberlander, T.M., 1977, Origin of segmented cliffs in massive sandstones of southeastern Utah, *in* Doehring D.O., ed., Geomorphology in arid regions, Proceedings of 8th Annual Geomorphological Symposium: Binghamton, State University of New York Publications in Geomorphology, p. 79–114.

Slavík, M., Bruthans, J., Filippi, M., Schweigstillová, J., Falteisek, L., and Řihošek, J., 2017, Biologically-initiated rock crust on sandstone: Mechanical and hydraulic properties and resistance to erosion: Geomorphology, v. 278, p. 298–313.

Stevens, D.J., and McCarrick, J.E., 1988, The arches of Arches National Park, a comprehensive study: Moab, Utah: Salt Lake City, Utah, Mainstay Publishing, 169 p.

Uličný, D., 2001, Depositional system and sequence stratigraphy of coarse-grained deltas in shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic: Sedimentology, v. 48, p. 599–628.

Vreeland, R.H., 1976, Nature's Bridges and Arches, Volume 1 – General Information: Westminster, California, self-published, 64 p.

Wilbur, J.H., n.d.-a, Natural Arch Information: Frequently Asked Questions: http://www.naturalarches.org/archinfo/faq.htm (accessed May 2018).

Wilbur, J.H., n.d.-b, Landscape Arch: http://www.naturalarches.org/big9-1.htm (accessed May 2018).