The Bologna interpretation of rock bridges: what is real and what has the potential to be real?

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ABSTRACT: This paper presents a provocative discussion on the subject of rock bridges and, by extension, on the topic of rock mass strength. We believe that there cannot be innovation in rock engineering if we are not open to looking at problems from a different perspective, even though that means abandoning practices that are considered industry standards for better or worse. The Bologna Interpretation of rock bridges states that one can only know where a rock bridge is once one measures it. And to measure it, you need the rock mass to fail. This interpretation highlights the indeterministic nature of rock bridges: they become real only when we look at them. Before failure, there are no actual rock bridges, only potential rock bridges which exist everywhere at once.

Keywords: Rock Bridges, Bologna Interpretation, Rock Mass Strength.

1 INTRODUCTION

Rock bridges play a crucial role in supporting and maintaining the stability of slopes and underground excavations. However, there is currently a lack of understanding about accurately defining and consequently measuring rock bridges. Sixty years have passed since Terzaghi first looked at this problem in 1962. Since then, a combination of simple laboratory experiments and imperfect geometrical conceptualisation has confused the definition of rock bridges.

In the author's opinion, to solve the problem of rock bridges, we need first to address the issue of what is real and what has the potential to be real. We propose a novel and thought-provoking perspective on rock bridges that incorporates concepts and ideas from various disciplines, including philosophy and quantum mechanics.

The physicist Nils Bohr once stated that "*everything we call real is made of something we cannot real*". Similarly, rock bridges are intangible entities that collectively shape rock mass behaviour. For example, we know rock bridges must exist for the rock arch presented in Figure 1 to remain stable. However, there are limits to how much information we can gather about this rock mass that would confirm the extent and location of the rock bridges (e.g. compare photos from 2002 and 2022 in Figure 1). We conclude that before failure, rock bridges only exist as potential features throughout the rock mass. In the literature, rock bridge strength is considered independent of rock mass strength.

In reality, rock bridge strength is a manifestation of rock mass strength. This misinterpretation can lead to inaccuracies in understanding the stability and behaviour of rock masses and can result in improper design and assessment of rock engineering projects (Elmo et al., 2022a). For instance, the approach put forth by Jennings (1970, 1972) reflects a perspective that views rock bridges and rock bridge strength as equivalent continuum problems without proper consideration for damage processes. More importantly, Jennings (1970, 1972) ignored the comment made by Terzaghi (1962) concerning the impossibility of measuring rock bridges. They based their methodology on the imperfect 2D definition of rock bridges as the portion of intact rock separating intermittent joints. There is no doubt that rock bridges exist. However, the concept of intact rock bridges presented in the literature needs to be revised, starting with addressing one fundamental question: what are rock bridges?

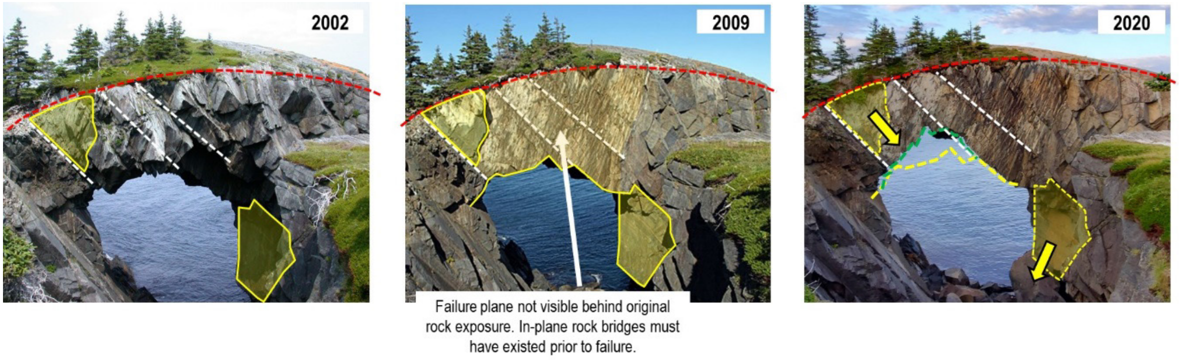

Figure 1. Evolution of Berry Head Arch (Newfoundland, Canada) from 2002 to 2020. Photos sourced from Google Images under a creative common license CC2.5.

2 WHAT ARE ROCK BRIDGES?

To measure something, we must first have a way to identify it and understand its properties. Without a clear definition of what we are measuring, it is difficult to determine the appropriate method or tools for measurement, and the resulting measurements may not be accurate or meaningful. Figure 2 illustrates the definition of rock bridges according to Elmo et al. (2018). This definition introduces the important constraints of block-forming potential and kinematic freedom. However, it remains incomplete since it is primarily based on the geometrical relationship between existing and intermittent fractures and, more importantly, the failure plane (rock bridge) is determined a priori. Similar to earlier definitions by Terzaghi (1962) and Jennings (1970, 1972), the definition of rock bridges illustrated in Figure 2 needs to account for network connectivity, degree of interlocking, and loading conditions and lacks a fundamental temporal dimension. Assuming several rock bridges exist that control the stability of a given structure, definitions of rock bridges commonly presented in the literature (e.g., Jennings, 1970, 1972; Call and Nicholas, 1978; Baczynski, 2000) assume the rock bridges would all fail at once.

Figure 3 below shows the location of a rockslide that occurred in December 2022 on the North-East face of the Snowpatch Spire (Bugaboo Group, British Columbia). Photograph evidence suggests that in-plane rock bridges existed that held relatively large sheeting structures in place. Failure can be attributed to progressive (time-dependent) damage, possibly related to significant daily and seasonal temperature variations, which has eventually caused these in-plane rock bridges to fail. The case presented in Figure 3 is analogue to the case illustrated in Figure 2(e). Still, it is impossible to i) accurately define the extent of rock bridges before failure and ii) recreate the failure sequence of all in-plane rock bridges that existed before failure.

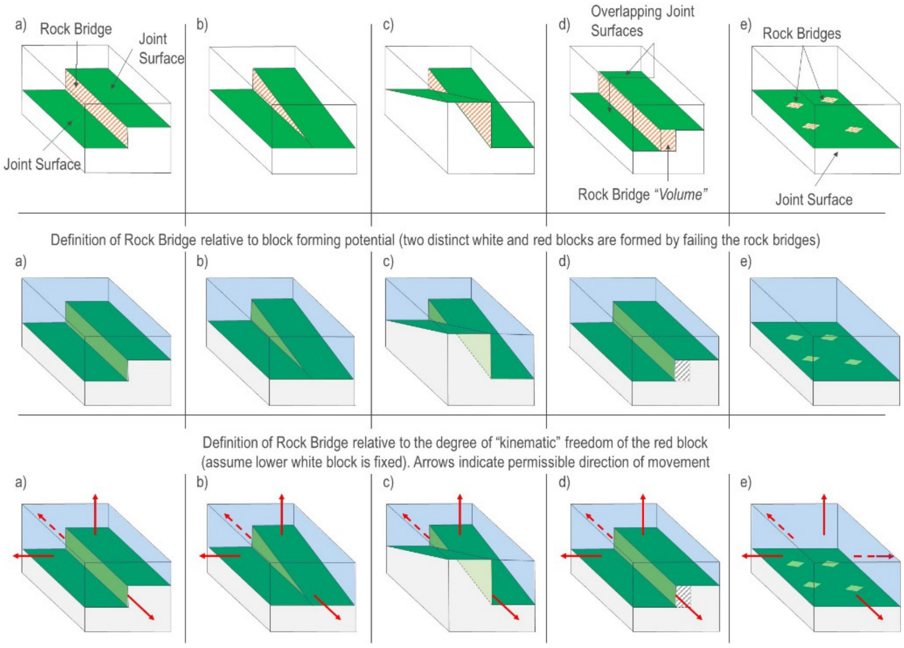

Figure 2. Definition of rock bridge relative to the block forming potential and block kinematics (modified from Elmo et al., 2018). The definition assumes the rock bridge location and extent are determined a priori, which is a limiting factor.

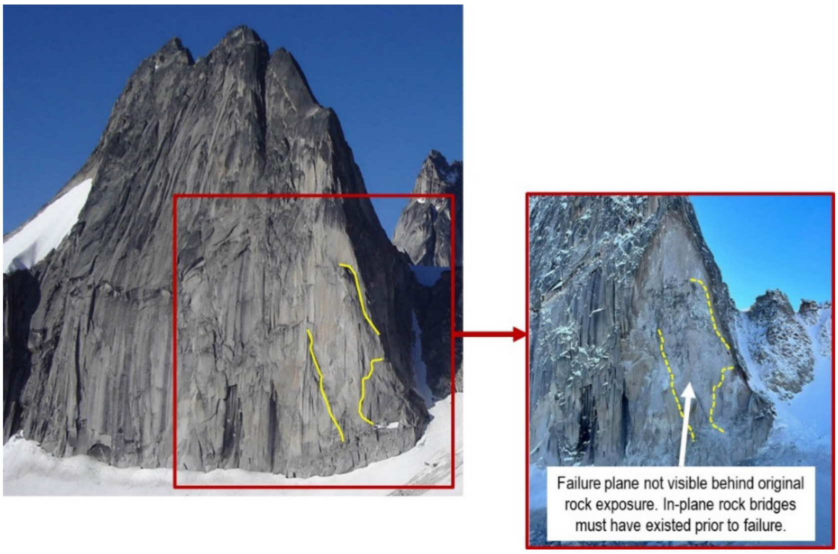

Figure 3. Photos showing the location of a rockslide that occurred in 2022 on the Snowpatch Spire (British Columbia). Images sourced from Google Images under a creative common license CC2.5.

The case studies presented in Figure 1 and Figure 3 confirm that a different approach is required to explain the nature of rock bridges. We propose using an analogy with the principle of complementarity of quantum mechanics, which states that particles can exhibit both wave-like and particle-like properties, but not simultaneously. This principle was formulated by Niels Bohr, one of the pioneers of quantum mechanics, to explain the behaviour of subatomic particles and the seemingly contradictory results of various experiments on them.

Pre-failure, knowledge of the rock bridge's location and size, and the rock bridge's strength are complementary to each other, meaning that they cannot be measured simultaneously. This is because the act of measuring one property necessarily disturbs the other. If we know a rock bridge's shape and size, we can determine its strength. But to know a rock bridge's shape and size, we need to break it, i.e. overcome its strength. This is the principle behind forensic geology tests carried out by Shang et al. (2017), demonstrating that it is impossible to validate assumptions about rock bridges' size without performing destructive testing. Forensic geology confirms Terzaghi's (1962) hypothesis about the impossibility of accurately measuring rock bridge strength before failure.

Nonetheless, rock engineering literature continues to accept the idea proposed by Jennings (1970, 1972) and incorrectly treats rock bridges as measurable gaps between intermittent joints. This led to the conviction that it is possible and correct to measure a rock bridge percentage and then use it as input to determine an equivalent rock mass cohesion. Indeed, we challenge engineers and researchers to identify and measure the rock bridges responsible for the stability of the structure shown in Figure 1, Figure 3 and Figure 4 (below) using the conventional rock bridge analysis.

We argue that the problems can only be studied using simulations that explicitly model process rock mass damage in combination with a sensitivity analysis. It is not a matter of determining an elusive rock bridge percentage and associated rock bridge's strength but instead trying to understand the critical parameters controlling the stability of the rock structures under consideration.

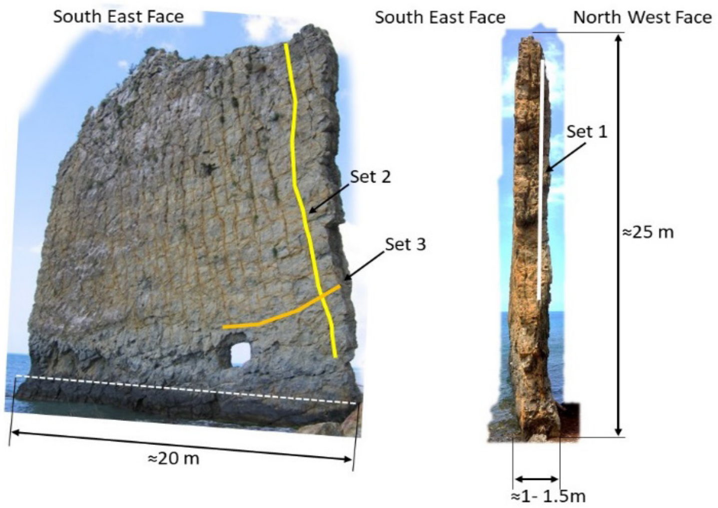

Figure 4. Parus Rock. Data from GoogleMaps and photos shared under a creative common license CC2.5, by Dukachev (2005).

3 THE BOLOGNA INTERPRETATION OF ROCK BRIDGES

In the author's opinion, the rock engineering community needs to foster a culture that supports and encourages experimentation and the promotion of new ideas, even when those appear to conflict with commonly accepted empirical approaches. Creating an environment encouraging cross-disciplinary interpretations is vital, as these can lead to new perspectives and discoveries. This paradigm forms the foundation for suggesting a unique and contemplative method for studying rock bridges. For instance, Elmo et al. (2022b) reinterpreted an analogy proposed by Prof. Al.-Kalili to explain quantum entanglement as a proxy to explain rock bridges and rock mass behaviour: "*as the coin spins, one cannot tell whether the coin is tail or head. Only when the coin stops the result (head or tail) is revealed*". Like a spinning coin, the state of rock bridges within a stable rock mass is uncertain until failure occurs. Only then can rock bridges be observed and measured. This view is known as the Bologna interpretation of rock bridges (Elmo et al., 2022b).

The Bologna Interpretation does not negate the existence of rock bridges; on the contrary, it agrees with observations made by Hencher et al. (2012) and Bolla and Paronuzzi (2020), which showed that rock bridges could only be observed and their extent measured post-failure. The exact appearance, intensity, and location of rock bridges remain unknown. Still, their existence can be assumed, and their impact on the strength of a rock mass can be evaluated through a potential analogy.

The so-called rock mass potential (Elmo et al., 2022b) depends on a combination of the following parameters:

- Intact rock strength.
- Loading conditions (magnitude and direction).
- Rock mass connectivity.
- Rock mass interlocking.

During the failure process, the rock mass potential is transformed into kinematically controlled mechanisms, including elastic deformation and plastic yielding, resulting in the fragmentation of intact rock and the sliding and rotation of blocks. Elmo et al. (2020) introduced a new indicator of rock mass connectivity (NCI, network connectivity index) that combines information about fracture size (fracture intensity), fracture intersections, and the number of fractures per area or volume (fracture density). The definition of NCI for 2D and 3D problems is provided in Equation 1, assuming equidimensional sampling area and volumes. P_{21} represents the areal fracture intensity (ratio of the sum of fracture length to sampling area), P_{20} is the fracture density (number of fractures per sampling area), and I_{20} is the intersection density (number of intersections per sampling area). In Eqn. (1), P_{32} represents the volumetric fracture intensity (ratio of the sum of fracture area to sampling volume), P_{30} is the volumetric fracture density (number of fractures per sampling volume), and I_{30} is the volumetric intersection density (number of intersections per sampling volume.

$$NCI_{2D} = \frac{P_{21}}{P_{20}} I_{20} \quad \text{and} \quad NCI_{3D} = \frac{P_{32}}{P_{30}} I_{30} \tag{1}$$

It is possible to take advantage of numerical simulations of fracturing processes to define a rock bridge potential defined as the ratio of induced fracturing (NCI_{rb}) to the summation of natural (NCI) and induced fracturing (NCI_{rb}).

$$Rock\ Bridge\ Potential = \frac{NCI_{\mathrm{rb}}}{NCI + NCI_{\mathrm{rb}}} \tag{2}$$

The rock bridge potential describes whether stress-induced phenomena primarily control rock mass behaviour (e.g., spalling) or vice versa failure occurs due to structurally controlled mechanisms or as a combination of both (Figure 5).

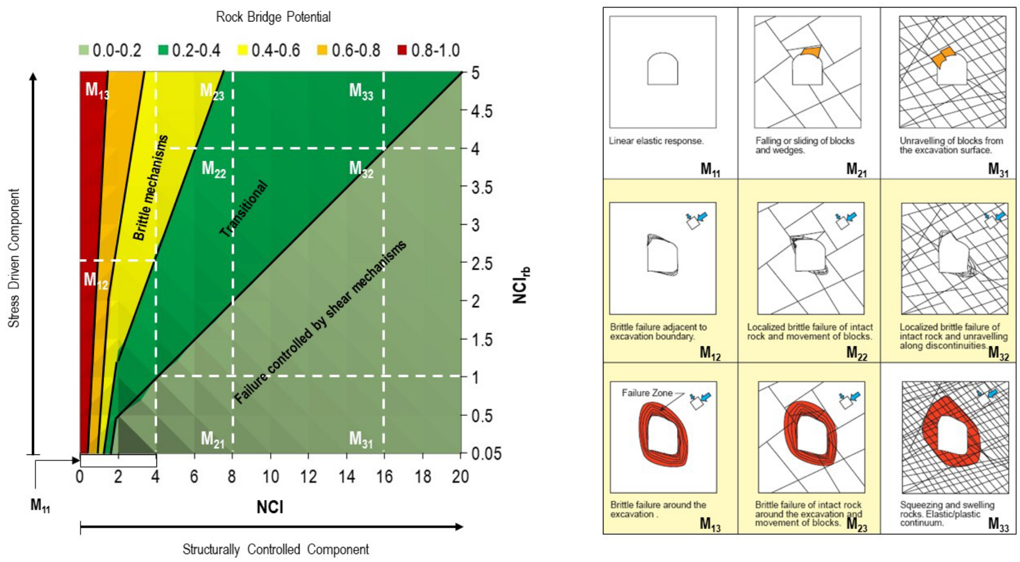

Figure 5. Relationship between rock bridge potential and the rock mass behaviour matrix by Kaiser (2019).

4 CONCLUSIONS

This paper discussed the problem of rock bridges. We have proposed a new interpretation (Bologna Interpretation) that highlights the challenge posed by uncertainties related to the knowledge of the intensity and the location of rock bridges before failure. Because rock bridges would only come into existence upon failure, it becomes impossible to truly calibrate and (validate) the results of a continuum-based forward analysis because of the impossibility of accurately determining a key input parameter for equivalent rock mass strength (rock bridge intensity). To truly simulate the impact of rock bridges, the design process should focus on the numerical modelling of fractured rock masses using discrete element models and fracture mechanics principles.

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