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The principle of rock bridges uncertainty

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Abstract

Rock engineering practice has long relied on rock bridge percentage as a measurable design parameter. Yet, this reliance rests on an assumption that a geometric property of a post-failure system can be meaningfully assigned to a pre-failure rock mass. This paper argues that it cannot. Observation is never theory-neutral, and the conceptual framework we bring to rock bridge characterisation shapes and distorts what we claim to measure. We introduce the principle of rock bridge uncertainty: the conditions required to identify and measure a rock bridge are the same conditions that confirm the rock mass has already failed or is in the process of failing. Through a series of mechanistic and geometric paradoxes, we demonstrate that rock bridges are not pre-existing features of the rock mass; they are products of the failure process itself. This distinction has direct consequences for failure forecasting methods, including the inverse velocity method, whose applicability to brittle failure is constrained by the very uncertainty that the principle describes. In place of deterministic rock bridge percentage, we propose the concept of rock bridge potential, a probabilistic characterisation of the strength of a fractured rock mass. The implications extend beyond technical methodology to engineering practice: by embracing uncertainty rather than ignoring it, we can make better-informed decisions about slope stability, excavation design, and risk management in fractured rock masses.

Keywords

Rock bridges, Uncertainty, Rock bridge potential, Failure mechanisms.

1 Introduction

Newton famously refused to speculate about the cause of gravity. *Hypotheses non fingo* (I frame no hypotheses), as he declared. His law of gravity does not refer to an underlying physical mechanism; it requires no unobservable quantities, only measurable ones. This is precisely why it worked. But Newton's discipline is harder to maintain than it appears. When attempting to understand rock mass behaviour, we often assume our process is equally straightforward: collect data, make observations, and synthesize an interpretation. This assumes we approach the rock mass without preconceptions. In reality, unless we have some a priori framework for what we expect to find, how do we decide which observations matter and which data to collect? Observation is never theory-neutral. We always bring

conceptual frameworks that guide what we look for and how we interpret what we find. Rock bridges exemplify this problem perfectly. Can we say, as Newton did, that the equations we use to characterize rock bridge strength require no unobservable quantities?

Consider Jennings (1970, 1971), who proposed Equations 1 and 2 to derive the shear strength parameters of a discontinuity equivalent to a set of co-planar rock bridges and joints (Figure 1). The equation contains a parameter, k, which must be measured.

$$c_{eq} = (1-k)c + kc_j \quad (1)$$

$$Tan\phi_{eq} = (1-k)Tan\phi + kTan\phi_j \quad (2)$$

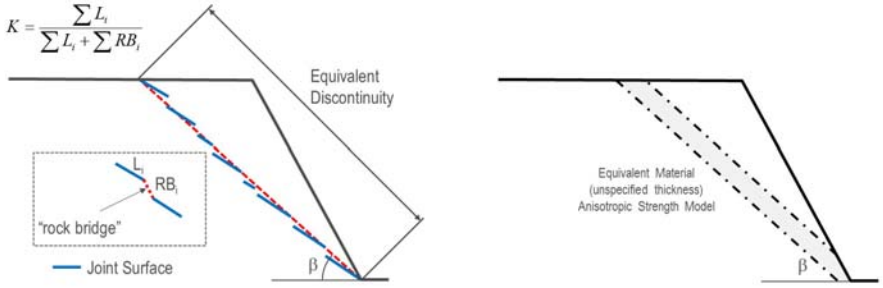


Fig. 1 Conventional representation of rock bridges according to Jennings (1970, 1971). Note that this approach is used to either specify the shear strength of a continuous (discrete) discontinuity surface or to define anisotropic rock mass properties in limit equilibrium and continuum modelling.

Before failure, the spatial distribution and geometry of rock bridges could, in principle, be described probabilistically, as there is no way to measure the number, size and location of the rock bridges. However, unlike Newton's gravitational constant, k is not an observable property of the pre-failure system; it is a post-failure interpretation retroactively imposed on a reality that no longer exists in its original state. By assuming a failure surface along which to measure k, we are, in effect, framing a hypothesis and then treating it as a measurement. Note that this approach neglects the tensile strength of rock bridges. This is not a matter of conservatism. The failure mechanism implicit in Equations 1 and 2 is one of pure shear, which excludes tensile resistance by assumption rather than by choice. This leads to the important question of whether the geometrical representation of rock bridges shown in Figure 1 is a faithful description of physical reality, or just a convenient construct that the literature has collectively normalized. We speak confidently about measuring the rock bridge percentage (the percentage of RBi relative to the total of RBi and Li) without questioning what rock bridges actually represent mechanically. The danger is circularity: we define rock bridges geometrically, design methods to measure them, and then treat the resulting numbers as physical evidence, without ever questioning whether the original geometric definition captures what actually governs failure.

This is not merely a practical limitation that better instrumentation might one day overcome. It is an epistemological constraint since identifying a rock bridge requires evidence of failure. This paper examines the implications of that constraint. It proposes a design framework for characterizing potential failure mechanisms that is consistent with what we can and cannot actually know about a rock mass before it fails.

2 Mechanistic uncertainty and geometric paradoxes

Consider the problem illustrated in Figure 2, which shows a block partially fractured through its half-section. If we were to complete the fracture by fully separating the block into two pieces, would we be proving that a rock bridge existed before failure, or merely witnessing the outcome of a failure mechanism? The distinction matters. The same block can be split by applying either a tensile or a shear force, and although the results appear identical, the failure surface would likely differ between the two cases. If the failure surface defines and measures the rock bridge, then the same pre-failure geometry yields different rock bridge measurements depending on how failure is induced. The rock bridge, in this view, is not a pre-existing geometric feature waiting to be measured, but a product of the failure process itself.

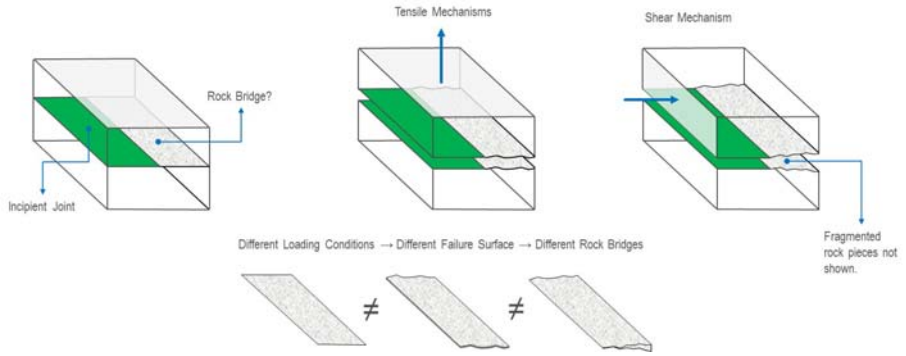


Fig. 2 A block partially fractured through half its cross-section. Completing the fracture by applying either a tensile or shear force produces the same result but different failure surfaces, raising the question of whether the rock bridge was a pre-existing geometric feature or a product of the failure mechanism itself.

This reframes the problem fundamentally. If rock bridges are a manifestation of a failure mechanism rather than an independently measurable property of the intact rock mass, then measuring them a priori is not merely difficult; it is conceptually incoherent. Equations 1 and 2 are used in a failure criterion that encodes an assumption about which failure mechanism occurred. It does not describe the rock mass before failure; rather, it presents a particular interpretation of the rock mass after failure and works backwards from there.

Consider the following three geometric tests of the assumptions current methods make about rock bridges.

1. If we removed all the joints from the slope problem illustrated in Figure 3a, would the rock bridges still exist? When rock bridges are defined as the intact rock material between the endpoints of existing joints, their existence is conditional; they exist only relative to the joints that bound them. Remove the joints, and the rock bridges appear to disappear with them. Did the rock bridges truly disappear, or did they grow to the point where they exist everywhere at once in the now-intact rock mass?
2. Conversely, consider equivalent slope problems sharing the same rock bridge percentage but very different geometries (Figure 3b). According to Jennings's equations, the equivalent cohesion is identical whether the failure surface contains one, two or even fifteen rock bridges. Any attempt to scale cohesion to the specific length of individual gaps implicitly assumes a universal scaling law for rock strength (an assumption recent work has called into question; see Bewick and Elmo 2025) and complete knowledge of the failure surface geometry before failure. The consequences of this become clear when examined numerically. For a slope of height (H) of 30.5m with a failure plane inclined at 33 degrees, a problem with 10,000 rock bridges would consist of a series of 5.6mm joints separated by gaps of just 1μm (10^{-3} mm). To the naked eye, this would be indistinguishable from a single continuous joint surface. And yet Jennings's equations would assign it the same equivalent cohesion as a slope with a single rock bridge spanning the entire failure surface.
3. Now consider an intact rock slope, without joints, loaded by a surcharge along the crest (Figure 4). As loading increases, new cracks will eventually appear and propagate. Those cracks play the role of the joints in Figure 1, and the intact intervals between them are, by definition, rock bridges. Using Jennings's framework, we have created rock bridges. And yet we could not have known their locations without predicting exactly where the new cracks would form. This paradox reveals that we cannot treat rock bridges as a property of the rock mass in its current state. They are a property of a future failure state that does not yet exist.

These geometrical paradoxes further highlight the challenge of defining rock bridges relative to a failure surface that has yet to form, and they are central to the concept of rock bridge potential introduced in Section 4.

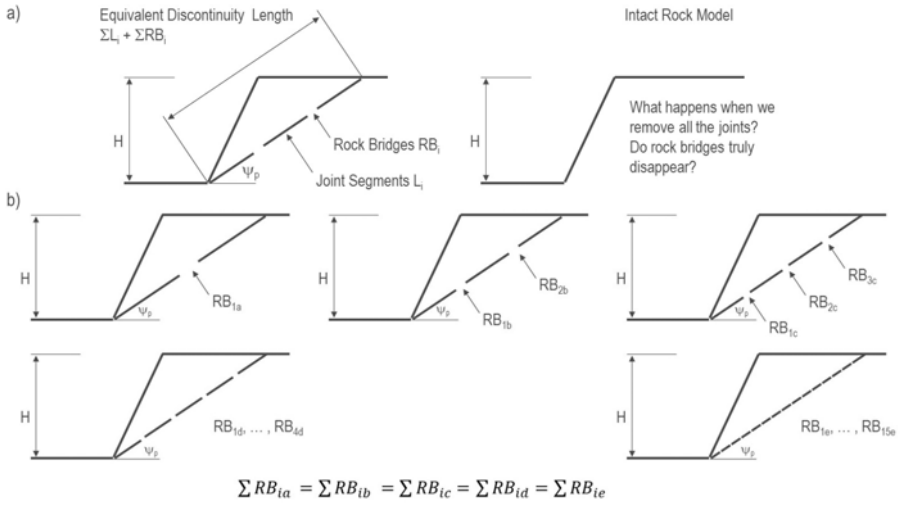


Fig. 3 Illustration of the geometric paradoxes arising from the classical approach to rock bridge characterization in rock engineering design. (a) Do rock bridges truly disappear if we remove the joints? (b) How can 5 different slope geometries be assigned the same equivalent cohesion as defined in Equation 1?

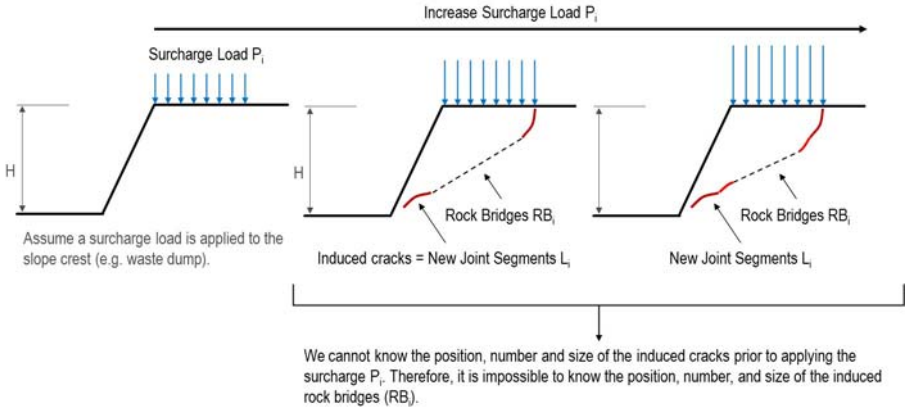


Fig. 4 Illustration of how an initially intact rock mass develops new cracks under increasing load. These cracks define rock bridges retrospectively. Their locations could not have been known without predicting exactly where fractures would form, confirming that rock bridges are a property of a future failure state, not of the current rock mass.

3 The principle of rock bridge uncertainty

Once the position and size of a rock bridge are known, this knowledge manifests in measurable deformation, indicating that the rock mass has already begun to respond to loading. But by that point, it may be too late to accommodate the deformation in design. This creates a fundamental dilemma. Designing against failure requires anticipating the deformations we wish to prevent, which means knowing where the rock bridges are and how large they are. This is precisely the information that becomes available only after failure processes are already underway.

We term this the principle of rock bridge uncertainty: the conditions required to identify and measure a rock bridge are the same conditions that confirm the rock mass has already failed or is in the process of failing.

The principle has a direct analogue in quantum mechanics, where the act of measurement disturbs the system being measured. Here, the disturbance is irreversible, since once the rock mass has failed, the pre-failure configuration cannot be recovered; it can only be inferred. And it is that inference, dressed in the language of measurement, that current methods present as a design parameter. The practical consequence is that any design approach based on a deterministic value of rock bridge percentage is, at best, an assumption about which failure mechanism will occur and where. At worst, it is a false precision that ignores the very uncertainty it should quantify and may lead to non-conservative strength estimates (Elmo 2023). Acknowledging this does not make the engineering problem unsolvable,but it reframes what a solution can legitimately claim.

The principle of rock bridge uncertainty is clearly expressed in the application of the inverse velocity method to brittle failure. As discussed by Beingessner (2026), the past two decades have seen

significant advances in slope monitoring technology, accompanied by a growing reliance on phenomenological approaches to failure forecasting. However, the inapplicability of the inverse velocity method to certain brittle failure cases, such as the Libby Dam in Montana (Rose and Hungr, 2007), illustrates the risk of overreliance on monitoring data. Slope monitoring technologies are capable of detecting brittle failure precursors, but only when the underlying failure mechanism is sufficiently understood, and it is precisely that understanding which current approaches to rock bridge characterisation fail to provide. In fractured rock masses, rock bridges must rupture to create the very failure surface that the inverse velocity method assumes exists from the outset. Indeed, in Fukuzono's (1985) experiments, a failure surface exists from the outset; therefore, the method presupposes what the rock mass has not yet produced.

Progressive rock bridge degradation occurs through brittle fracturing and the coalescence of discontinuities, generating episodic acceleration that reflects discrete bridge failures, periods of apparent stability that mask internal crack propagation, and sudden transitions when critical connectivity thresholds are exceeded. Field observations confirm that inverse velocity trends become interpretable only after sufficient bridges have failed, approximating a through-going failure surface. Before this transition, inverse velocity patterns are erratic (Beingessner 2026). This is a direct expression of the pre-failure uncertainty we have described. The method becomes readable precisely when the rock bridge problem has already resolved itself. This reframes inverse velocity analysis not as a prediction tool but as a state-dependent indicator whose validity depends on how far along the failure surface has progressed. Paradoxically, while the method cannot predict failure timing during the rock bridge rupture phase, monitoring inverse velocity patterns can serve as an indirect indicator of approaching criticality, specifically, of the transition from failure surface creation to acceleration along established discontinuities. A rigorous application, therefore, requires identifying when sufficient failure has occurred to enable viable failure mechanisms and integrating connectivity metrics with traditional displacement monitoring to better constrain uncertainty in rock-bridge-controlled systems.

4 Rock bridge potential as a mechanistic correct alternative to the rock bridge percentage

The arguments developed in the preceding sections converge on a single conclusion: rock bridges cannot be treated as measurable geometric features of a pre-failure rock mass. But if rock bridges cannot be measured, how should they be characterized? We propose that the answer lies in reframing the problem entirely, from one of measurement to one of potential. The distinction is not merely semantic. A measurable quantity describes something that exists in a determinate state prior to observation. A potential describes the capacity of a system to produce a particular outcome under particular conditions. Rock bridges, we argue, belong to the second category. They do not exist as fixed geometric entities waiting to be measured; they emerge as the rock mass transitions from a stable to a failed state. Before that transition, we can speak only of the potential for rock bridges to develop along a future failure surface that does not yet exist.

This interpretation (referred to as the Bologna Interpretation in Elmo 2023) draws an instructive analogy from quantum mechanics. A spinning coin has no definable face until it stops; the outcome (heads or tails) is not hidden from us but genuinely undetermined until the spin resolves. In the same way, a stable rock mass contains no definable rock bridges. It contains the potential for rock bridges to form and break simultaneously with the initiation and propagation of rock mass failure. To insist on measuring rock bridges before failure is to insist on reading the face of a coin that has not yet stopped spinning.

This concept is referred to as the rock bridge potential (Figure 5). Elmo (2023) provides several quantitative examples of rock bridge potential. Rather than seeking a deterministic rock bridge percentage value, the rock bridge potential characterises the strength capacity of a fractured rock mass through a combination of parameters: intact rock strength, loading conditions (both magnitude and direction), the connectivity of the existing discontinuity network, and the degree of block interlocking within the rock mass (Elmo 2023). Each of these governs not only whether rock bridges will form, but where, how many, and of what size. Quantifying rock bridge potential in practice requires the explicit modelling of intact rock fracturing, simulating the initiation, propagation, and coalescence of cracks within a represented discontinuity network, rather than prescribing failure surface geometry in advance.

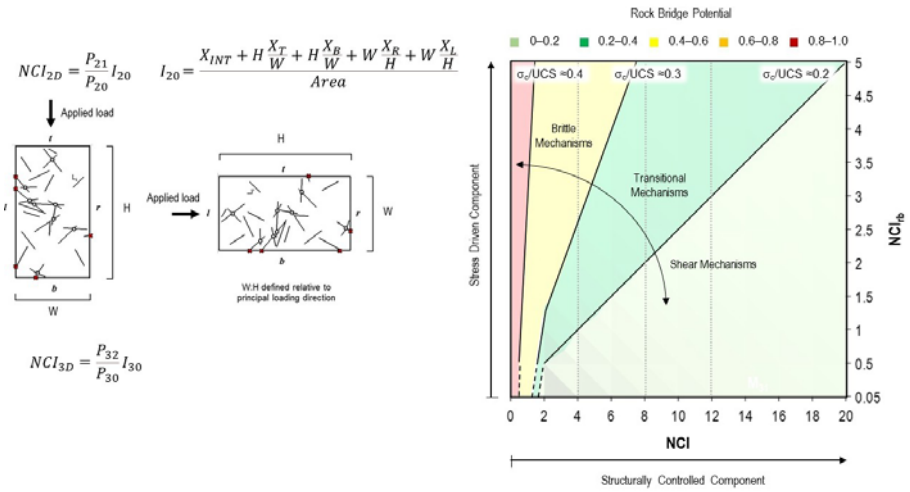


Fig. 5 Concept of rock bridge potential and formulae for 2D and 3D analysis, modified from Elmo 2023 and Bewick and Elmo (2025). NCI represents a measure of natural fracture connectivity prior to failure. NCI_{rb} is a measure of the net connectivity associated with the formation of new cracks.

5 Conclusions

Before we can ask how to measure rock bridges, we must first ask whether the measurement we are attempting is coherent. The principle of rock bridge uncertainty presented in this paper says it is not. The conditions that allow us to identify and measure a rock bridge are the same conditions that tell us the rock mass has already failed. This does not mean the engineering problem is unsolvable. It means that the solution must be reframed. The question is not what the rock bridge percentage is along a potential failure surface, but what the probability is that a kinematically viable failure surface will develop under anticipated loading conditions. Answering that question requires models that explicitly represent the discontinuity network and simulate intact rock fracturing, so that rock bridges emerge and fail as they do in reality, rather than being prescribed as fixed geometric inputs. This is not a higher standard of modelling sophistication, but the minimum condition for consistency with what rock bridges actually represent.

Jennings' framework represented a necessary and valuable step in the development of rock engineering, but continuing to rely on it while ignoring its fundamental limitations is no longer defensible. This is not a question of practical convenience versus model complexity. It is a matter of professional ethics. We owe it to the discipline and to those who depend on our designs to work with frameworks that acknowledge what we can and cannot know.

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