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What does nature know that engineers do not? Lessons from natural rock arches for rock mass classification and design

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Abstract

Natural rock arches have persisted over geomorphological timescales, encoding in their continued existence a form of knowledge about long-term rock mass behaviour that engineering practice has yet to fully articulate. This paper critically examines whether empirical tools developed for engineering contexts can explain what nature has already demonstrated. Applying the Q-system maximum unsupported span chart and RMR stand-up time diagram to a database of 100 arches from the Natural Arch and Bridge Society (NABS), we find that estimated Q values would require correction by up to two orders of magnitude to satisfy unsupported span criteria, while RMR-based predictions would demand ratings of 85-100 for rock masses that are observably fractured, blocky, and weathered. At the same time, many natural arches behave as slender beams supported by rock pillars, a failure mechanism that classification systems were never designed to recognize. The results suggest that engineering practice is simultaneously overconservative in its support recommendations and underconservative in its understanding of the actual failure mechanisms at play. The question this paper ultimately poses is a simple but uncomfortable one: what does nature know that engineers do not? In the end, all that we see or seem is but a rock bridge within a *rock bridge,* and therein lies the challenge. The stability of natural arches (i.e., natural rock bridges) is sustained by mechanisms that current design methods were never built to see, let alone quantify. The objective of this paper is to open a discussion on what it would take for rock engineering practice to finally account for what has been holding these structures standing all along.

Keywords

Rock bridge, Time-dependent damage, Rock mass stability, Fracture networks.

1 Introduction

Within the framework of fractured rock mass stability assessment, a critical challenge remains the accurate characterization of failure mechanisms and their connection to internal rock damage. The probability of failure depends on both pre-failure processes and triggering mechanisms that

cumulatively reduce rock mass strength (Volkwein et al. 2011). Stability is influenced by internal factors, such as excavation geometry, rock type, weathering, and degree of natural fracturing, as well as external triggers, including seismicity, natural geomorphological evolution, human activities, and climate-related effects (Corominas et al. 2014). Fracture systems control the geometry and kinematics of potentially unstable volumes, directly influencing the magnitude of potential instability events. The spatial distribution, orientation, persistence, and connectivity govern the size and shape of potentially unstable blocks (Elmo et al. 2018).

In fractured rock masses, stress concentrates at fracture tips, making rock bridges particularly susceptible to elevated tensile and shear stresses (Atkinson 2015). These rock bridges may undergo progressive failure not only due to stress concentrations arising from the geometric and mechanical configuration of the fracture network, but also due to degradation processes. Under environmental and mechanical loading (e.g., freeze-thaw cycles, creep, blasting, excavation, or seismic activity), rock bridges can progressively fail, driving the transition from stable to unstable conditions in both natural and engineered rock structures (Stead and Eberhardt 2013). The degradation of fracture cohesion can be described as a time-dependent fracture process acting along intact rock bridges on fracture surfaces (Kemeny 2003). Time-dependent damage involves the gradual deterioration of rock mechanical properties under stress levels below short-term strength, driven by mechanisms such as subcritical crack growth, delayed microcrack coalescence, rate-dependent deformation, and progressive damage accumulation. Despite their critical role, rock bridges cannot be directly observed or reliably characterized prior to failure, leading to significant uncertainty in stability assessments (Elmo 2023).

Current engineering practice responds to this uncertainty by relying on empirical methods that relate rock mass structure to mechanical behaviour and failure potential. These systems are widely adopted to support design decisions and to enable comparison of geological conditions across sites. Yet they share a fundamental limitation: they consider rock mass problems as inherently static. Rock mass quality indices are assigned at a moment in time, reflecting conditions as observed during site investigation or at the time of design. By reducing an evolving system to a single numerical index, our empirical methods implicitly treat the rock mass as a snapshot. This assumption is difficult to defend when the very mechanisms controlling failure are time-dependent, and when these systems were predominantly developed and validated in engineering contexts where stress evolution is driven by human activities such as excavation, drilling, and blasting.

This is precisely where nature offers a challenge to engineering practice. Natural rock arches have persisted over geological timescales, surviving sustained environmental loading, progressive damage, and the slow erosion of the rock mass around them. If current rock engineering design methods were applied to these structures, would they predict stability or prevent instability? Or would they fail to explain what nature has already demonstrated? Framed this way, natural rock arches become a benchmark against which the adequacy of our empirical tools can be critically examined. They encode, in their continued existence, a form of knowledge about long-term rock mass behaviour that engineering practice has yet to fully articulate.

Ultimately, the questions driving this work are simple but uncomfortable ones: what does nature know that engineers do not? Yet accepting that natural structures operate outside the constraints of design codes and prescribed safety margins raises a second, more pragmatic question. When a natural arch, stable in the sense of standing but unverified in the sense of safe, becomes a tourist attraction and individuals are permitted to walk under or above it, how should its condition be assessed?

This paper investigates rock arches as natural laboratories that provide insight into the mechanical behaviour and stability of rock masses.By applying unsupported span and stand-up empirical approaches to these natural structures, we critically examine whether tools developed for engineering contexts can capture the rock mass conditions that govern process-driven, time-dependent stability. The analysis raises fundamental questions about the interpretation of empirical methods in natural settings and about how numerical model input parameters should be developed to support stability assessments across both short and long timescales.

2 Natural Arches: Stable or Surviving Structures?

The analysis draws upon one of the most comprehensive inventories of natural rock arches, compiled by the Natural Arch and Bridge Society (NABS), an all-volunteer non-profit organization founded in

1988 in Utah and dedicated to the study and preservation of natural arches worldwide. A natural arch is a rock exposure with a hole that passes completely through it, formed by the natural, selective removal of rock while maintaining a relatively intact frame. The feature must be composed of exposed rock surrounded by air, and the opening must be a true through-hole in a topological sense (NABS 2026).Beyond maintaining an extensive database, NABS has developed a standardized descriptive framework that provides a consistent language for systematically classifying and examining natural arches. The classification identifies key attributes that describe arches in terms of their environmental context, morphology, dimensions, geological setting, genetic mechanisms, and evolutionary stage.

The natural arches in the NABS database are documented according to their existence at the time of observation. This aspect opens a broader discussion on how the concept of stability should be interpreted for such structures. Stability, in an engineering sense, implies a quantifiable margin of safety, yet no factor of safety can be directly assigned to these natural structures through observation alone. What can be stated with confidence is that a standing arch, by definition, has not failed. Therefore, from an engineering perspective, its factor of safety is greater than 1. Whether it is marginally above unity or considerably so remains unknown. This distinction matters because a structure hovering near the threshold of failure and one with substantial reserve capacity may appear identical to an observer yet carry fundamentally different implications for what their apparent stability tells us about long-term rock mass behaviour.

We could argue that the NABS database captures "survival" rather than safety. Furthermore, the documented population may also reflect a degree of survivorship bias, as short-lived arches may fail before being recorded. Consequently, the apparent stability of surviving arches does not indicate whether they are close to or far from failure. This is a subtle but important difference to keep in mind when interpreting the analysis that follows. Indeed, in the context of underground excavation design, the terms stable and safe are not simply synonymous with the absence of failure; they carry the implicit assumption that the factor of safety is considerably greater than 1, reflecting both regulatory requirements and the engineering judgment embedded in our design methods. Transposing that expectation onto natural arches, where such an assumption cannot be verified, risks conflating "structural survival" with engineered safety. These two conditions may overlap, but are not equivalent.

2.1 Database

The database considered in the current study comprises 100 arches for which span measurements were available. These structures are distributed across a wide range of geographic regions and environmental conditions, including coastal settings, where marine processes play a dominant role, as well as inland environments encompassing deserts, mountainous terrains, and other non-coastal landscapes (Figure 1). Reported arch spans vary widely, ranging from 1 m to 103 m. Sedimentary lithologies are the dominant host rock (78 arches), primarily sandstone and limestone formations. Igneous rocks account for 16 arches, commonly associated with basaltic and other volcanic lithologies. The remaining 6 arches occur in metamorphic rocks such as slate, schist, and marble. Only 2 arches in the database are known to have collapsed over the years.

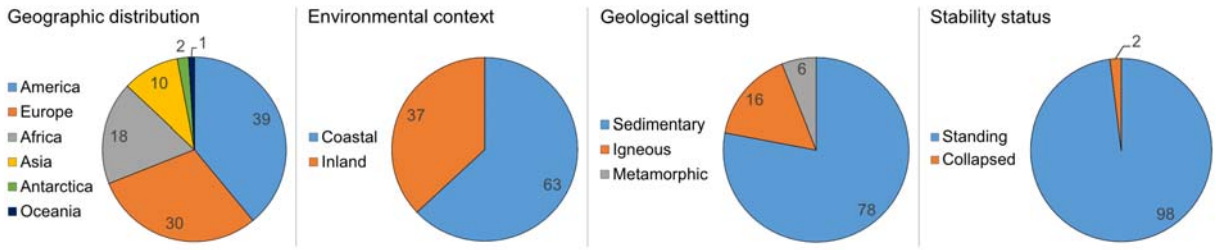


Fig.1Summary of the natural arch database, including geographic distribution, environmental context, geological setting, and stability status.

3 Empirical Maximum Unsupported Span and Stand-Up Time

The preceding discussion has established that empirical classification systems were developed within an engineering paradigm that is potentially misaligned with the conditions governing the stability of natural rock arches. The analysis that follows directly tests this proposition. By applying two of the most widely used empirical tools to the subset of100 natural arches from the NABS database, it becomes possible to move beyond conceptual critique and examine, quantitatively, how far current

methods are from explaining what nature has already demonstrated. This is not an exercise in finding fault with tools that have served engineering practice well in their intended domain. Rather, it is an attempt to expose the boundaries of their applicability and to identify precisely where and why they break down when confronted with structures whose stability is a function of geological time rather than engineered through design.

3.1 Q-System Analysis

The Q-system (Barton et al. 1974) is adopted in this study as the primary framework for rock mass characterization. While RMR (Bieniawski 1989) and GSI (Hoek et al. 1995) remain widely used in practice, the Q-system is unique in offering a comprehensive empirical chart that directly links rock mass quality to stability assessments and support recommendations. This makes it particularly well-suited to this investigation, where the goal is not merely to assign a quality index but to evaluate whether the classification output can meaningfully inform stability judgments for structures governed by long-term, time-dependent processes. The Q-system rating is calculated according to:

$$\mathrm{Q} = \frac{RQD}{J_n}\frac{J_r}{J_a}\frac{J_w}{SRF} \tag{1}$$

Where *RQD* is the Rock Quality Designation index (Deere et al. 1967),J_n,J_r,J_a denote the joint set, roughness, and alteration numbers, respectively. J_w is the water reduction factor, and SRF is the stress reduction factor.

The maximum unsupported span is determined for ESRs of 1, 1.6, and 3 using Equation 2 below.

$$Max.Unsupported\ Span = 2\ \mathrm{ESR}\ Q^{0.4} \tag{2}$$

The stress reduction factor (SRF) could be reasonably estimated in the range of 2.5-5, reflecting near-surface, low-stress conditions and the possible presence of weakness zones. Assigning a value to the joint water reduction factor (J_w) is less straightforward. Natural arches are rarely subject to sustained water inflow in the engineering sense, which would suggest a value of 1. However, water plays a fundamentally different role in coastal arches, where it acts as a long-term agent of erosion, scouring, and chemical alteration. This distinction exposes a conceptual limitation of classification systems in general when applied outside engineering contexts. Assigning a value to J_w for natural arches, therefore, requires engineering judgment that goes beyond the parameter's original intent and serves as an early illustration of the broader interpretive challenges that arise when empirical classification systems are applied to natural structures. For the purpose of this paper, we have assumed a J_w of 1 for inland arches and 0.5 for coastal arches, acknowledging their periodic or permanent exposure to water and the associated effects of wave action, tidal fluctuation, and salt-driven chemical weathering. These assignments represent a pragmatic interpretation of the parameter's original intent rather than a strict application of the Q-system rating criteria.

The RQD, J_n, J_r, and J_a parameters were estimated from qualitative interpretation of available field images, without direct field measurements. This approach introduces inherent uncertainty, and variations in the calculated Q values are to be expected; more detailed characterization will be pursued in future work. At this stage, however, the precision of individual parameter estimates is secondary to the broader observation the data reveal. The natural arches in the NABS database are assumed to be stable. For arch spans greater than 10 m, their estimated Q values would need to be corrected by up to two orders of magnitude to satisfy the criterion for the maximum unsupported span shown in Figure 2. This is not a minor calibration issue, and it suggests that something beyond what the classification captures is keeping these arches standing. That gap is precisely what this paper sets out to examine.

This limitation is compounded by a more fundamental issue, as virtually all empirical classification systems do not explicitly incorporate failure mechanisms. With the partial exception of spalling and squeezing conditions, which can be indirectly reflected in the SRF parameter of the Q-system, classification systems such as RMR (Bieniawski 1989) and GSI (Hoek et al. 1995) offer no framework for distinguishing between modes of failure. Yet many natural arches bear a striking geometric resemblance to relatively slender beams supported at both ends by “rock pillars”, a configuration in which the governing failure mechanism is flexural, driven by bending stresses and tensile failure at the arch crown or haunches. This is fundamentally a beam problem, and beam mechanics lie outside the

conceptual domain of classification systems. Applying the Q-system to a natural arch is therefore not merely a matter of parameter uncertainty; it is a category error. The tool is being asked to assess a failure mechanism it was never designed to recognize, which helps explain why the calculated Q values are so systematically inconsistent with observed stability.

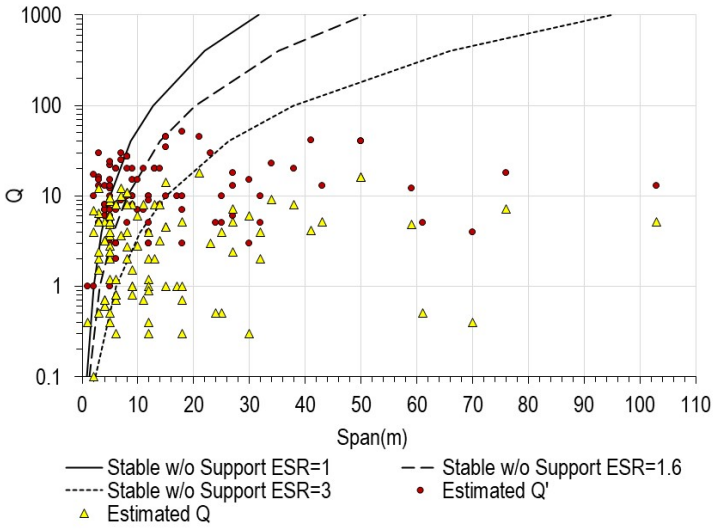


Fig. 2 Estimated Q and Q' values for the arches considered in the study, and curves corresponding to Equation 2 with ESR values of 1, 1.6, and 3, respectively, to represent different stability conditions (permanent to temporary excavations).

3.2 RMR Analysis

A similar contradiction emerges when the stability of natural arches is examined through the lens of RMR. Stand-up time charts (Bieniawski 1989), which relate unsupported span to rock mass quality, would require RMR ratings of 85-100 to justify the longevity of the arches in the NABS database. These ratings correspond to exceptionally competent, massive, and essentially unweathered rock masses. Field evidence, however, suggests otherwise. Most arches in the NABS database exhibit rock masses that are intensely fractured, blocky, and variably weathered, conditions that would consistently yield RMR values well below 85, as illustrated by the representative examples shown in the right panel of Figure 3. This is not a marginal discrepancy. Once again, the empirical tools available to engineers would struggle to predict, let alone retrospectively justify, the stability of natural arches.

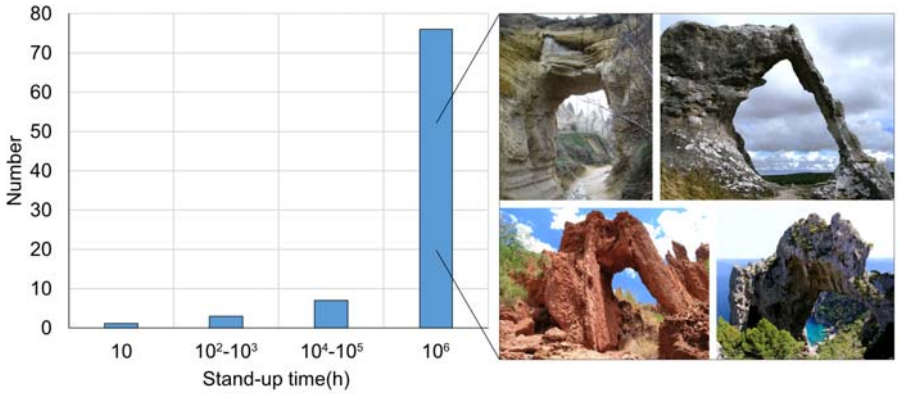


Fig. 3Distribution of stand-up time classes inferred from RMR for unsupported conditions. Representative examples of the actual rock mass conditions associated with very good quality ratings are shown on the right (photos from NABS 2026 and online).

4 Discussion and Conclusions

As discussed in this paper, the tools available to engineers were designed to build structures, not to evaluate those that nature has already built and time has already tested. Applying them uncritically risks either false reassurance or unnecessary intervention. A more honest approach would acknowledge that the stability of natural arches demands a different kind of analysis grounded in an understanding of the specific failure mechanisms at play, attentive to the time-dependent processes that common rock engineering design methods cannot capture, and able to recognize that the absence of failure is not, by itself, evidence of safety. The contradiction between observed stability and

classification-based predictions invites a deeper question: why can nature engineer structures that our methods would deem to require support? Three interconnected reasons emerge from this analysis:

i. The role of rock bridges cannot be captured by representing the rock mass as a single number; stability in structures like natural arches is governed by the specific geometric and mechanical configuration of fractures, the integrity of load-bearing rock bridges, and the three-dimensional architecture of the structure itself. These are properties of a particular place and a particular structure, which require explicit structural analysis and modelling, not index-based generalization.
ii. While conservative design is a legitimate and necessary principle in engineering, conservatism applied through tools that misrepresent the failure mechanism is not true conservatism. Instead, it is simply an error in a cautious direction. The empirical methods are not designed to capture time-dependent processes, nor are they calibrated to recognize the failure modes that govern arch stability. The result is a practice that is simultaneously overconservative in its support recommendations and underconservative in its understanding of the actual mechanisms at play. Nature, by contrast, has no design code, but it has time, and through time it has selected only the structures whose geometry, rock bridge configuration, and load-bearing architecture were adequate to survive. That is a form of structural optimization that our current methods are not equipped to replicate or even fully recognize. In this sense, approaches based on the block theory (Goodman 1995) may provide an appropriate conceptual framework, considering the potential time-dependent development of unstable key blocks through progressive fracturing and erosion over time.
iii. The dominant paradigm in rock engineering, applying GSI in combination with the Hoek-Brown failure criterion, leads to representing the rock mass as an equivalent continuum, effectively smearing the discrete, structured nature of the rock mass into homogeneous plastic behaviour. As Barton (2025) has argued, this approach systematically exaggerates plastic deformation and impacts the representation of the true mechanical response of jointed rock masses, particularly in conditions such as natural arches where block interaction and interlocking are the primary sources of strength.

References

Atkinson B K (2015) Fracture Mechanics of Rock. Elsevier.

Barton N R, Lien R, and Lunde J (1974) Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, 6:189–239.

Barton N (2025) Reflections on Unrealistic Continuum Modelling; NB&A: Oslo, Norway, 30p.

Bieniawski ZT (1989) Engineering Rock Mass Classification.Wiley, New York.

Corominas J, van Westen C et al. (2014) Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment, 73:209–263.

Deere D U, Merritt A H, and Coon R F (1969) Engineering classification of in-situ rock. Air Force Weapons Laboratory, Albuquerque, NM.

Elmo D, Donati D, and Stead D (2018) Challenges in the characterisation of intact rock bridges in rock slopes. Engineering Geology, 245:81–96.

Elmo D (2023) The Bologna Interpretation of Rock Bridges. Geosciences, 13(2), 33.

Goodman R E (1995) Block theory and its application. Geotechnique, 45(3), 383–423.

Hoek ET, Kaiser PK, and Bawden WF (1995) Support of Underground Excavations in Hard Rock. A.A. Balkema, Rotterdam, The Netherlands.

Kemeny J (2003) The time-dependent reduction of sliding cohesion due to rock bridges along discontinuities: A fracture mechanics approach. Rock Mechanics and Rock Engineering, 36:27–38.

NABS,https://www.naturalarches.org/. Accessed at 01.30.2026

Stead D and Eberhardt E (2013) Understanding the mechanics of large landslides. Italian Journal of Engineering Geology and Environment, 6:85–112.

Volkwein A, Schellenberg K et al. (2011) Rockfall characterisation and structural protection - A review. Natural Hazards and Earth System Sciences, 11(9):2617–2651.