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Integrating monitoring data into risk assessment and management for rock slopes

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Abstract

Large open pit and natural rock slope monitoring methods have become increasingly available and useful with advances in equipment, analysis techniques and data integration. The toolbox of remote and in situ instrumentation provides a wealth of opportunities to collect data and inform deformation-based analyses. As a result, observational design approaches are increasingly being adopted and are of benefit, as long as they are well integrated into risk assessments and the consequence of potential failures is well understood.

As monitoring data becomes increasingly available, we are able to consider the deformation capacity of slopes, particularly in post failure event back-analyses. The capacity for slope deformation prior to failure ranges from very small to very large strains, depending on the failure mechanism, which, in turn, depends on the geological and rock mass characteristics. Small strain deformations and failure modes must be identified early, so that the risk of failure can be assessed and mitigated if required. This relies on understanding the geological setting, and, in particular, the structural controls on the slope's stability. Case histories from several locations will be discussed within this framework.

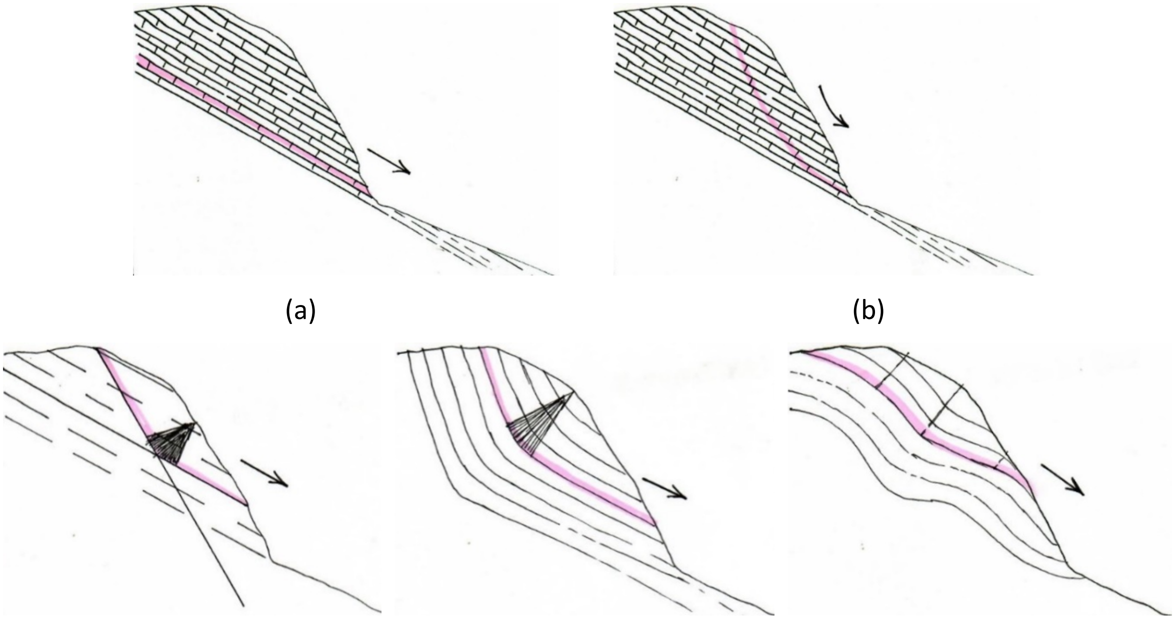
Keywords: *rock slope instability, remote sensing, deformation monitoring*

1 Introduction

Remotely sensed data is increasingly being applied to the assessment of slope stability for natural and excavated rock slopes, having the advantage of large spatial coverage from each sensor vantage point, and permitting the instrumentation team to install the equipment at a distance from the slope being monitored This is particularly useful if the slope is already showing signs of distress and access is limited by the slope geometry or there are concerns about instability. Remotely sensed data quality, quantity, and rate of acquisition have been increasing rapidly, as manufacturers develop new tools, and research and development results in enhanced ways to collect, clean, align, process and interpret data. The increasingly available stream of remotely sensed data provides an exceptional opportunity to better understand the progression and evolution of slope deformation rates and patterns as related to rock slope failure mechanisms and behaviour.

While this paper is being presented at a large open pit slope conference, the author will include discussion of monitoring and decision-making for large natural slopes, as the observations in both areas of engineering endeavour provide complementary information and understanding.

Observation of large natural rock slope failures provides useful evidence about potential failure modes, including the influence of structure and the development of strain within the rock mass, leading to a variety of slope failure surface morphologies, as shown in Figure 1. These are based on observations of large natural slope failures as investigated and discussed by Stead & Walter (2015) and on the personal observations of the author.



(a) (b)

(c) (d) (e)

Figure 1 Observed failure mechanisms from large natural slope instabilities. Failure modes related to structures: (a) Planar translational slide; (b) Curved slide with rock mass failure; (c) Biplanar compound slide; (d) Curved compound slide; (e) Irregular compound slide (modified after Stead & Walter 2015, after Glastonbury & Fell 2000)

2 Monitoring large rock slopes

Several recent publications provide reviews of the applications of remote sensing techniques to assessing rock slope behaviour at a variety of scales of instability, including the comprehensive review by Lato (2021) for large natural slopes and by Eberhardt et al. (2020) for large open pit slopes. Workflows integrating traditional field and remote sensing technologies to consider natural rock slope instability are discussed by Hutchinson et al. (2015) and Abellán et al. (2014). DiFrancesco et al. (2021) and DiFrancesco (2021) emphasise the importance of data cleaning and critical evaluation of potential for errors in the data collected.

Digital models of rock slopes may be used to assess the geometry using point clouds or triangulated irregular networks (Hutchinson et al. 2022), the mineralogy using hyperspectral data, and the presence of water at surface using reflectivity data from some LiDAR data. Change in the slope geometry over time can be obtained from time sequential data acquisitions from radar monitoring (deformation is recorded as increasing phase difference in the datasets), point clouds (iterative closest point operations determine the offset between different point positions) derived from LiDAR (Figure 1), photogrammetry or total station measurements as discussed by Lim et al. (2005); Abellán et al. (2014); Hutchinson et al. (2015); Lato et al. (2015b); Bonneau et al. (2019a, 2019b); Hutchinson et al. (2022) and thermal data (sensing the difference in slope temperature in disturbed talus during and after rockfalls (Prescott et al. 2022; Schafer et al. 2022; Wellman et al. 2022). Interpretation of thermal data involves identification of changes in the image pixels and tracking the change in their position, which is similar to methods used to track block movement within debris flows.

In situ data is required to supplement the remotely sensed data and to provide essential information about the rock mass condition at different scales. At the bench scale or local slope surface scale, traditional field-mapping methods to collect information about weathering, and joint characteristics including roughness, aperture, alteration, persistence and spacing are required. At the larger slope scale, in-ground instrumentation is required to assess the depth and deformation characteristics of the slope instability detachment surface(s) (Hutchinson et al. 2022).

Numerous authors have demonstrated the effectiveness of integrating multiple remote-sensing techniques into assessment and monitoring programs (Sturzenegger et al. 2007; Brideau et al. 2011; Lato et al. 2015; Macciotta & Hendry 2021). The interpretation of the data is enhanced by having multiple vantage points, different data types, redundancy in case of data stream loss, and to verify detected changes. Generally, there are differences in the deformations recorded from different remote-sensing vantage points, depending on the direction of movement relative to the line of sight of each instrumentation. Critical assessment of the monitoring information is required, with comparison to measurements made manually or with other instruments when possible – particularly when working with complex natural settings (Abellán et al. 2009).

The massive amounts of data produced are unprecedented and are expected to become even larger as lower-cost networked sensors begin to be deployed (e.g. self-networking global positioning system units distributed across the ground surface). Significant effort is being expended to automate data processing to help with this problem and to give near real time data analysis (Kromer et al. 2015a, 2015b; Williams et al. 2018) and interpretation (DiFrancesco et al. 2020 & 2021; Farmakis et al. 2021). Attention must be paid to the models derived from remotely sensed data, using both manual and automated processes, because poor data quality can result in an inaccurate representation of the object's geometry and changes, and therefore incorrect interpretation of the deformation mechanism and progression toward failure. Change detection between datasets collected at long time intervals may include several epochs of failure which are represented as an apparent single failure.

A substantial amount of work has been done with terrestrial and aerial remote sensing and with satellite data. Utilising nearer-range point clouds, we are increasingly able to detect changes by comparing time sequential datasets and resolve individual rockfall events, as shown in Figure 2. When the data is well constrained and evaluated to be representative, it is advisable to collect and enter information into a database about rockfall source zone location, lithology and characteristics, shape and volume of the rockfall, rock mass structure, block fragmentation, impact positions and, in some circumstances with a detailed long-term record, velocity, critical displacement, conditioning and triggering events.

A well-organised database of objects identified from change detection supports evaluation of long-term evaluation of spatial and temporal trends, permitting a focus on the structural/lithological and geometry effects, as well as conditioning factors such as climate conditions, erosion and in the case of mining, blasting and mucking. If the database has a robust method of positioning events both spatially and temporally, it is possible to evaluate the rock mass conditions more fully when failures/excavations exposure structures located behind the original slope surface. Precursor events may be detected as well, but at this time, generally only in back-analysis (Figure 3). As more knowledge is gained about natural rock slope failure processes and conditioning factors, it is anticipated that we will move towards identifying the small volume precursor events as warnings of the subsequent larger rockfall event.

The interested reader is directed to the following papers for more detail about specific data processing techniques for working with remotely sensed point cloud data:

- Survey design for complex geometry: Lague et al. (2013); Lato et al. (2009 & 2010).
- Detection of rock mass structures and orientations: Slob et al. (2002); Jaboyedoff et al. (2007); Lato & Voge (2012); Voge et al. (2013); Riquelme et al. (2014).
- Analysis of joint persistence, joint spacing, block shape, supporting kinematic analysis: Buyer et al. (2020); Donati et al. (2021).
- Fusing point clouds with photographs: Assali et al. (2016).
- Detection of change to identify precursors to failure: Rosser et al. (2007); Jaboyedoff et al. (2007, 2009); Kromer et al. (2015b).
- Analysis of rockfall characteristics, including source zone characteristics, block shape and volume: Bonneau et al. (2019a, 2019c); DiFrancesco et al. (2021); Macciotta et al. (2020).

- Deposition zone characteristics: Bonneau et al. (2022).

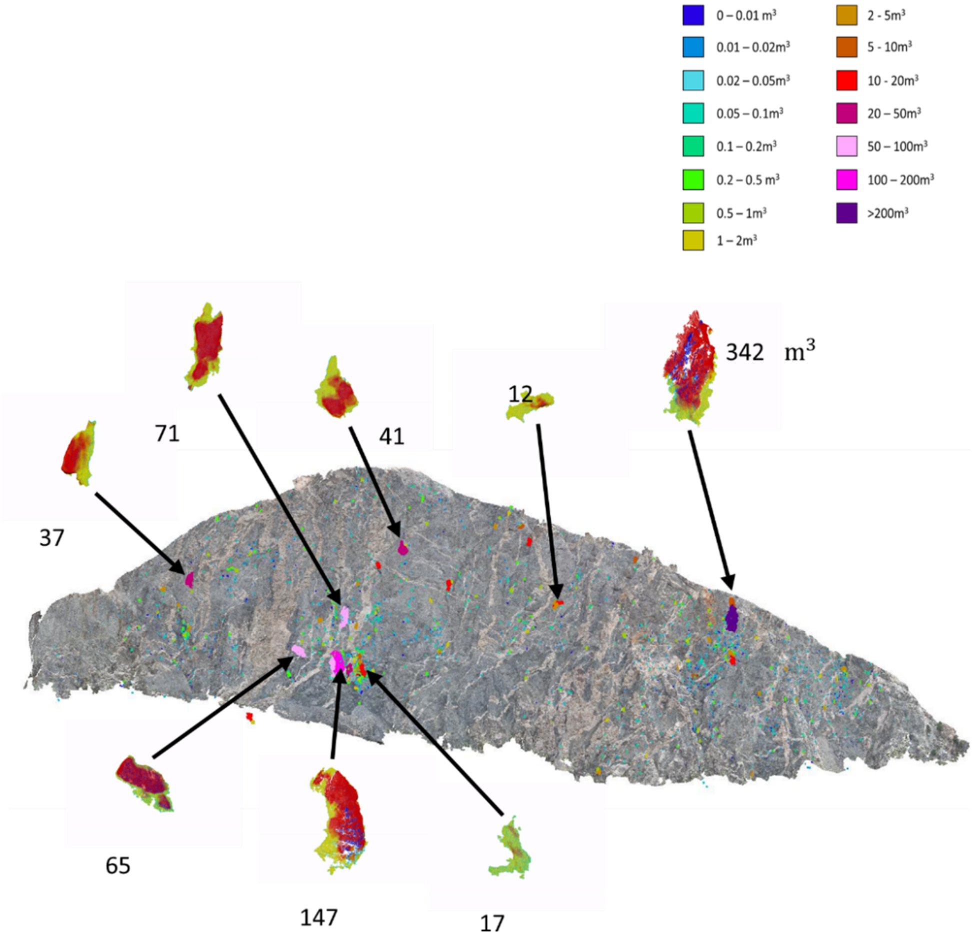


Figure 2 Rockfall inventory based on changes detected between time-sequential LiDAR scans for a 300 m high natural rock slope, superimposed on a photogrammetric model. Scan data was collected over four years with time between scans ranging from three to 10 months. Data processed by R Burns

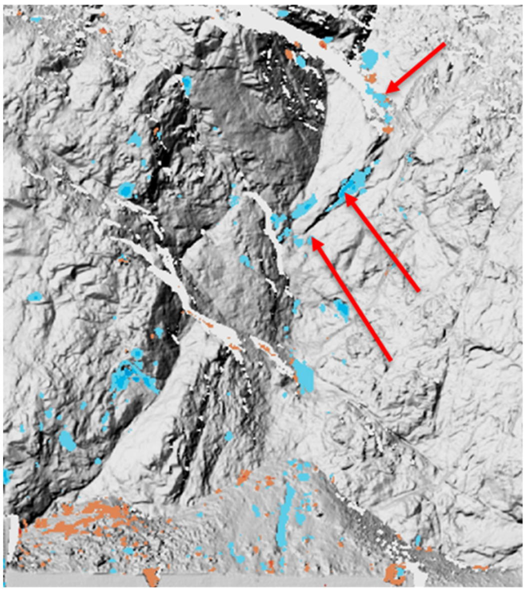


Figure 3 Back-analysis of a 100+ m^3 rockfall. Arrows show locations of precursor smaller-volume events distributed at the edge of the larger-volume rockfall event. Blue indicates loss of volume, and orange indicates accumulation of volume. Data processed by A Graham

3 Managing rock slope instability risk

As longer-term and more continuous data records become available for natural slope analyses, the challenge is to determine when failure is likely to occur. Theoretically, the failing mass may display several cycles of increasing and decreasing deformation rates, identified as progressive and regressive behaviour (Zavodni & Broadbent 1978), as shown in Figure 4. Records from open pit mining slope observations, where more continuous datasets are available, often show several cycles of progression and regression, and may progress for a short period of time before brittle failure at small amounts of cumulative deformation or may undergo multiple cycles leading to substantial deformation over time.

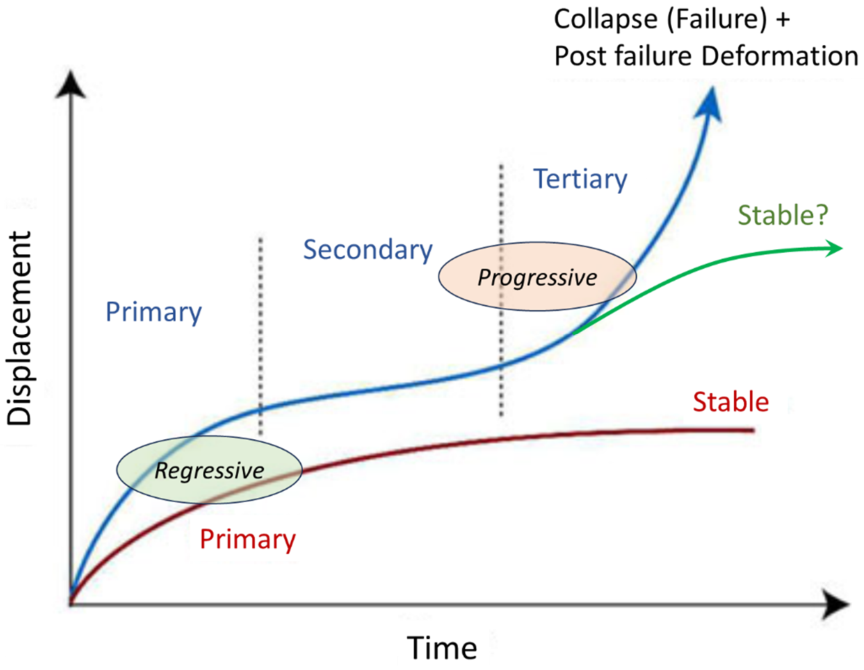


Figure 4 Slope deformation patterns over time, demonstrating different stages of creep. Velocity ratios are used to determine the significance of rate change: deceleration is termed regressive deformation, while acceleration is termed progressive deformation. Tertiary creep may lead to failure, or may turn regressive for several to numerous cycles, depending on the total slope deformation capacity

As noted earlier in this paper, slope deformation interpretation generally considers both the velocity of slope movement and changes in the velocity ratio. Assessment of the potential for failure depends on defining response limits considering precedent experience to give best estimates of expected rock behaviour. Precedent experience may be with similar large natural slope instabilities or previous push backs in open pits where different walls are likely to have different tolerable limits. Careful monitoring and interpretation of deformation rates and changes are required to establish limits for response. In an open pit these may include changes to operations, including remote equipment operation within potential spatial limits of failure or impact, operation only in daylight hours when evidence of acceleration to failure may be observed in the pit (rockfalls, wall ravelling) by a full-time geotechnical inspector, among other responses. With increased velocity/progressive deformation, areas of the pit may place and communicate the need for barricades identifying exclusion zones where no work is to be completed, leading, in the extreme, to full pit evacuation of personnel. The trigger action response plans (TARPs) used to manage these responses rely on reasonable velocity thresholds to signal the need to change between TARP levels which are generally based on precedent experience. In the case of large natural slopes, management of the hazard in response to deformation-monitoring data includes different levels of scrutiny of the instrumentation data, emergency response team notification and action, and public notification and evacuation warning. One example of a TARP related to public safety, from the Aknes rockslide in Norway, is shown in Figure 5 (after work by Blikra 2008; Kristensen et al. 2020).

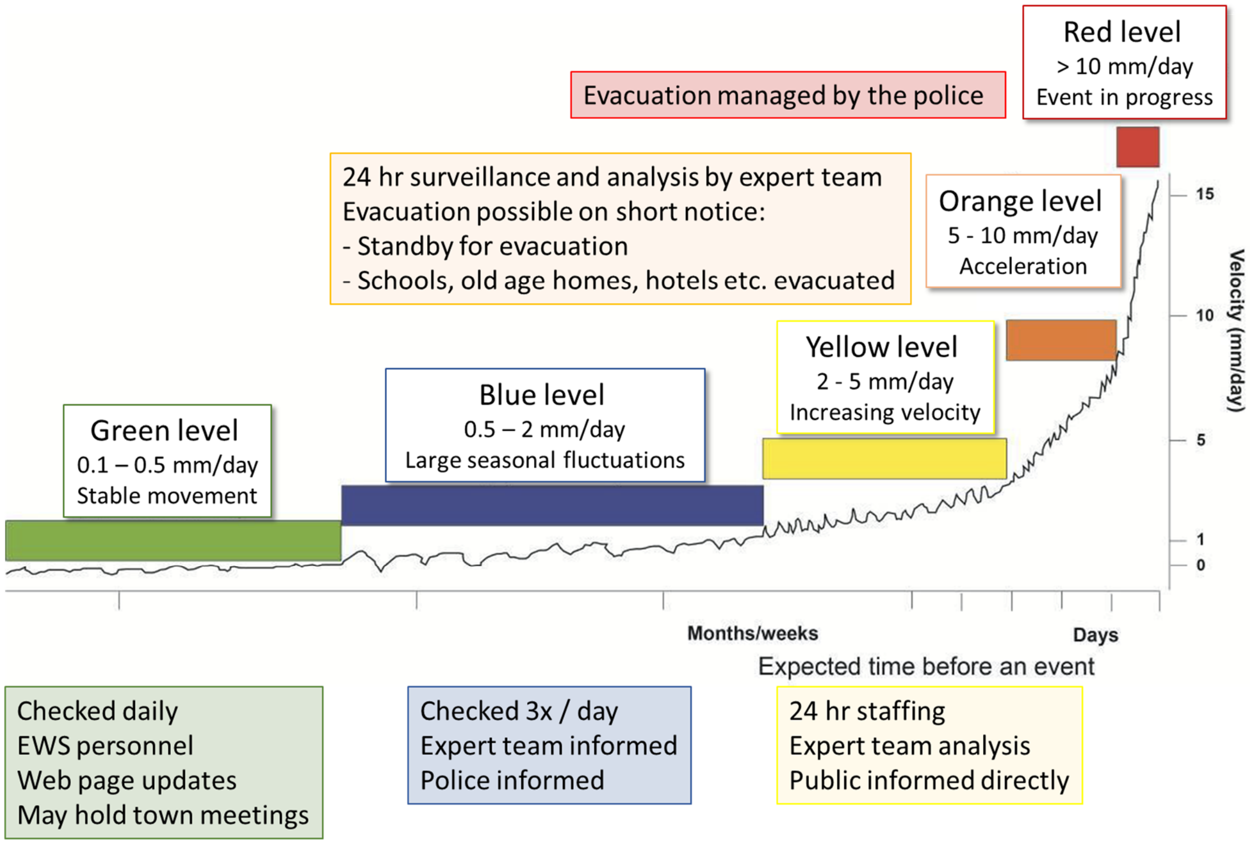


Figure 5 Slope deformation velocity thresholds triggering different responses, ranging from regular monitoring as managed by emergency warning system (EWS) personnel, through multiple levels to evacuation managed by the police at the red level. Members of the public with reduced mobility/ability to respond quickly to evacuation notices are evacuated at the orange level

In the case of the Aknes slide, confidence in the threshold velocities was gained over several years after the instrumentation program was implemented, and relied on observations and assessment of seasonal response.

The definition of critical velocity thresholds to trigger different responses is the most challenging component of the evaluation of potential for failure for a large rock slope. Some slopes (e.g. the Leo slope at Bingham Canyon Mine), failed at approximately 7% slope strain (defined by the cumulative deformation prior to failure) relative to the slope height, as shown by Robotham (2021). In this case, one flank of the mass involved in the failure was bounded by a fault, providing a continuous and weak lateral release plane for the slide, as modelled by Ergun et al. (2022).

Considering this case, it is proposed that a deformation capacity threshold be considered for cases which may fail in a brittle manner after limited deformation. This would supplement the established process based on velocity and acceleration/deceleration, which inherently assumes that the slope may undergo multiple cycles of progression/regression. Relating this to the simplified sketches in Figure 1, slope instabilities where there is at least one large structure on which deformation can occur have more potential for brittle instability with limited pre-failure deformation (Figure 1a). Slopes with larger deformation capacity are hypothesised to be subject to progressive failure through the rock mass (Figure 1b) or geometry-induced strain accumulation prior to development of failing slope geometry.

4 Conclusion

The development and adoption of remote sensing monitoring equipment, as well as advances in in-ground instrumentation able to provide a real time data feed are changing the way monitoring programs are being designed and how the data is used to manage stability and risk.

The widespread deployment of photogrammetric, LiDAR and InSAR methods (Lim et al. 2005; Abellán et al. 2014; Hutchinson et al. 2015; Lato et al. 2015b; Bonneau et al. 2019b; Moretto et al. 2021) to assess slopes can be attributed to several advantages of these techniques, including the increasing ease of collecting and interpreting the data, the relatively large and continuous areal extent of the data collected permitting a broader view of the geological setting and structural measurements, and the ability to collect this data from safe vantage points located at a distance from the slope. These methods also produce a representation of the slope geometry each time the data is acquired, providing the equivalent of an 'as-built' model.

Continued work is required to relate the geological setting to potential failure modes in order to guide risk-management methods based on deformation thresholds. A key component of slope stability assessment is understanding of the location of shear surface(s), and therefore the installation of in-ground instrumentation. The plethora of relatively easily accessible remotely sensed data providing spatially extensive coverage is transformative for slope monitoring but must be coupled with subsurface information to assess the nature and progression of the failure.

In his discussion of the observational method, Peck (1969) noted that failure to anticipate unfavourable conditions is one of the most serious issues with the method. By not anticipating all possible failure modes, the design team is not prepared for all foreseeable deviations of the real conditions from those assumed in the design. As a result, the team won't have assessed appropriate courses of action for all scenarios.

> *'If the engineer suddenly realises that the observations show the job to be heading for trouble against which he has no defence, he must reach crucial decisions under the pressures of the moment. If he is very unlucky, he may find that there is no adequate solution at all.'* Peck (1969)

Peck also cautioned against the use of the observational method for brittle failure. He noted that 'the presence of brittle elements in a resisting mass may, if not appreciated, lead to failure in spite of the use of the observational method.'

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