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Capturing/interpreting non-obvious slope controlling structures

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Abstract

Rock slope stability is, in many cases, controlled by throughgoing continuous planes, or fracture zones, within the rock mass. In many cases, these features are not obvious and are ignored during base level data collection. Failure to capture these features, or zonal swarms of parallel geologic structures, results in either conservatism in slope design, where experience dictates slope angles should be reduced, or in slopes that incorporate structural features that are likely to experience/control instability. Often, when such slope failures occur, the practitioner stretches to increasingly diverse failure modes incorporating rock bridges, step path failure, etc. when the failure is, in actuality, controlled by non-obvious, existing continuous structural features that were simply not defined or interpreted improperly. This failure to properly capture/interpret structural features continues even during slope failure delineation programs as the programs implemented are improperly configured, and the technical personnel assigned are unaware of the techniques necessary to properly quantify these features.

This paper illustrates some of the methods utilised, together with demonstrated examples of evaluating and interpreting such structural features, or swarms of features, and the impact on rock slope design.

Keywords: *structure, interpretation, narrow, non-obvious*

1 Introduction

Once upon a time, in the days of steam-powered computers, I was in awe of geologists and geotechnical engineers who could examine core and state, unequivocally, who observed geologic structures were of importance to design, and in many cases, even ascribe an orientation.

This certainty/infallibility was put to the test when it was noticed that many slope instabilities that could not be attributed to obvious visual controls were classed by these same engineers as 'rock mass failures', 'complex, multi-path failures', 'step path controlled along discontinuities', etc. It appeared that the gurus of the previous paragraph were not as infallible as I had thought.

Upon gaining sufficient experience to be put in charge of investigating major slope instabilities, I was able to target the structural features that were indicated by discontinuity mapping and slope monitoring. In most cases it was possible to isolate the particular structure, or structures, that was/were controlling the instability, without resorting to more exotic explanations. The icing on the cake was targeting, and proving through downhole displacement monitoring, slope instability occurring along a postulated, but hidden, plane derived as a function of slope displacement monitoring; a plane that did not coincide with known discontinuity networks. This was a narrow feature, being less than 60 cm in width, with little included gouge. The commonality of drillhole intercepts, coupled with the instability behaviour, reaction to remedial measures, and downhole displacement monitoring provided certainty in the structural interpretation. The rock mass, step path failure model, proposed by other workers for this area, was simply incorrect.

The burgeoning belief, on this engineer's part, that persistent structural planes were not adequately characterised during drilling was reinforced by an example shown in Figure 1. The structural feature cross-cutting the pit wall was targeted with drilling. Core drilling, as can be seen in the figure, did not indicate a major feature as any infill had been washed out. Only minor slickensides were apparent. Examination of the acoustic televiewer (ATV) log indicated a small structural zone of seemingly little significance. Yet, upon examination of multiple drillholes that were targeted to pierce the known plane, it became obvious that a potential slope controlling structural zone did, in fact exist. It was, however, narrow and essentially impossible to detect with a single faceted examination of the drillcore.

The question arose at that time as to how to better address/define such zones that they could be utilised in rock slope design. Efforts to answer this question resulted in the techniques described in this paper. They have been utilised and refined over the course of a substantial number of years in investigating existing instabilities for slope remediation and for design purposes.

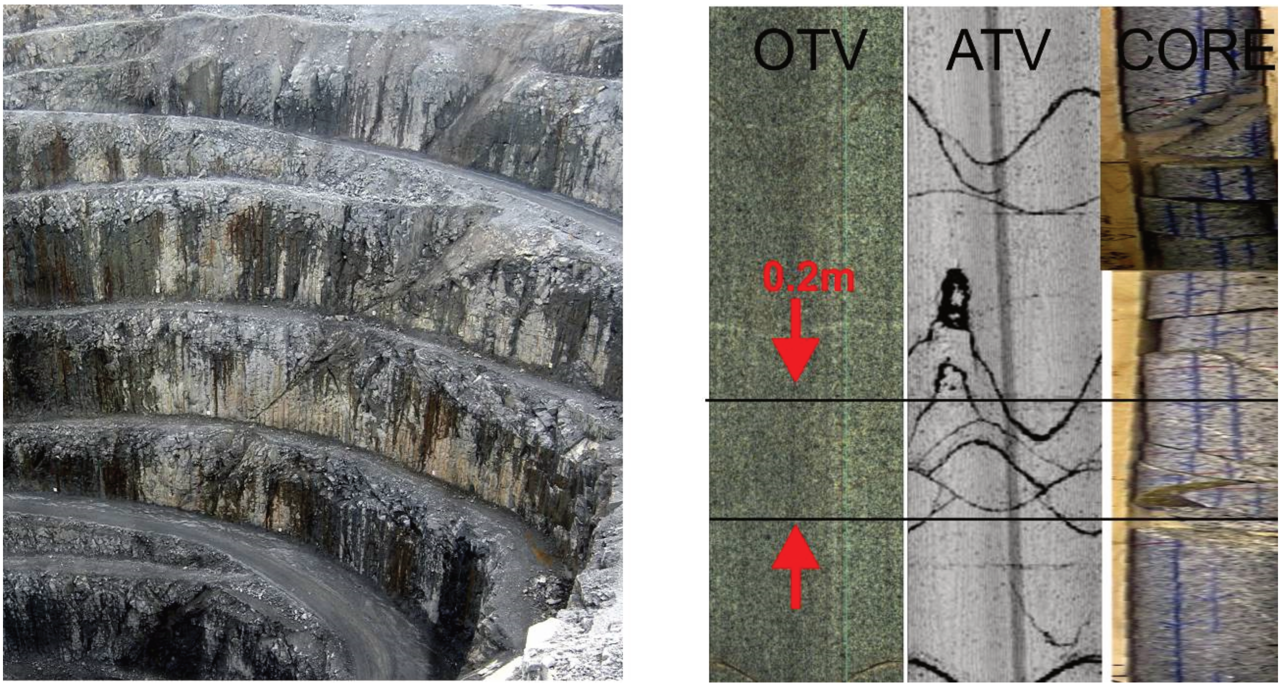

Figure 1 Observed geologic structure, slope, and drillhole

2 Detailed evaluation of drillcore and field data

Over the years, this engineer has observed oriented drillcore being logged with a specific orientation of an identified major structural plane being noted in the field. A structural orientation provided in such fashion, as has been confirmed innumerable times upon review, is generally in error as:

- When a structure (say a fault) is created, it results in disruption to the adjacent rock. If the rock incorporates localised weakness planes (bedding, foliation, etc.), these structures, too, are disrupted and sheared (Figure 2). In many cases, as has been observed, the structure is field determined to be parallel to these weak planes when, in actuality, this is far from the truth and it is in a different orientation altogether.
- Second, only intact structures are visible in the core. What one needs to determine is the orientation of all the discontinuities in the zone. In highly fractured zones the best estimate of the orientation will be obtained from ATV logging. Such analysis is best done with images of the drillcore depth matched to the ATV images. Simply picking a structural orientation that matches one's preconceived notions is not only generally wrong, but ignores the information necessary to determine the true major structure orientation. This is demonstrated in Figure 2. Note the intact discontinuities visible in the core photograph are foliation planes.
- Third, the thickness and intensity of a persistent structural zone is difficult to ascertain in the field from the core. Again, this is best done through coupled analysis of core photographs and the ATV images. As can be seen in Figure 3, no apparent fault orientation is readily observable.

For detailed structural interpretation, the orientations of all the available discontinuity sets shown on the stereonet should be considered.

- Finally, the observed structural observations must be combined and analysed between all available drillholes and surface observations. This is the only way possible to adequately link persistent, narrow, slope critical geologic structures from multiple data sources. Zones less than 10 cm in measured thickness have been demonstrated to be throughgoing planar structural features over a kilometre in length. Picking such a feature out from the core as a major structure is simply impossible, even for the best of us. Figure 4 illustrates this scenario, with the indicated drillhole intercepts traversing roughly 150 m across a structural feature. In all, surface mapping and drilling confirmed the structure being over 600 m in strike length.

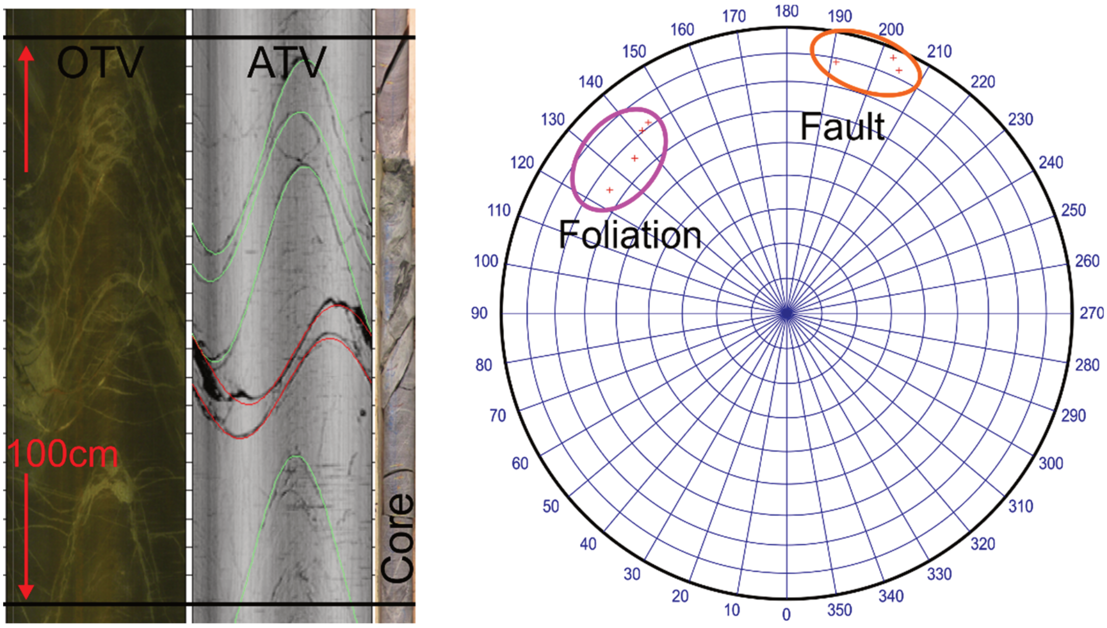

Figure 2 Disruption of foliation by faulting, in core and on polar stereonet

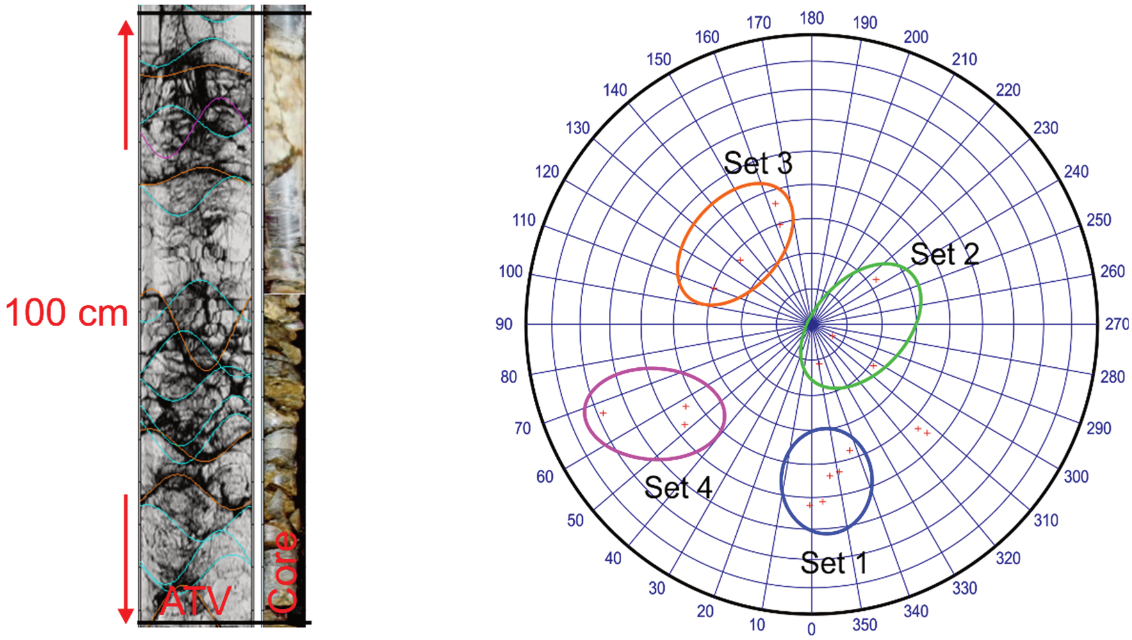

Figure 3 Fault zone with no discernible preferred orientation, in core and on polar stereonet

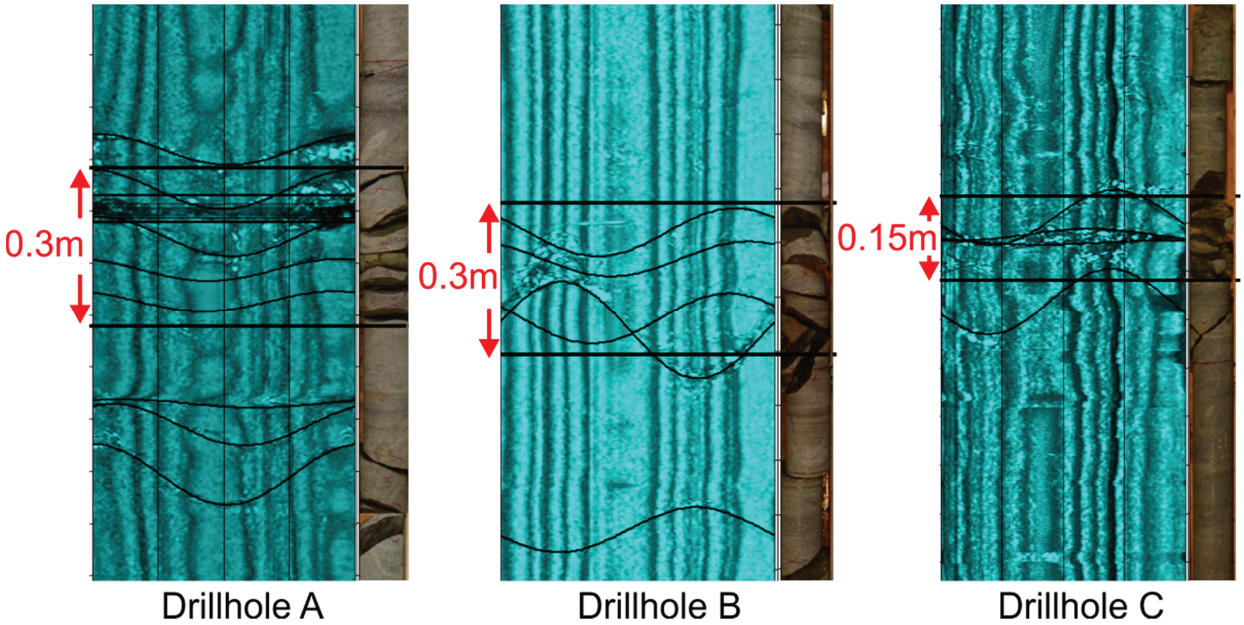

Figure 4 Narrow, persistent geologic structure as expressed in multiple drillholes

3 Methodology

The methodology developed by the author for the described structural interpretative technique is as follows.

3.1 Drillholes

Conduct ATV logging of drillholes whenever possible. Other core orientation methods simply do not provide the necessary data through the highly fractured rock within the fractured zone. As demonstrated in previous figures, the discontinuities adjacent to the zone of interest, in the more intact rock, may not parallel the fault structure and, as such, detailed structural orientations must be obtained from within the fractured zone. The downhole ATV logging should be conducted at maximum practical resolution by a trained user.

Images of the core should be inserted next to the ATV log in the data reduction software and these photos should be depth matched to the ATV logs.

Core should be logged with evidence of motion along the discontinuity surfaces being recorded. Gouge, rock flour, etc. may be found and should be noted. However, for thinner structures this is often washed out during the drilling process. Insert these observations as notes in the ATV data reduction software.

Identify the structural zones within the composite ATV/core/notes. These are from/to zones, with comments as to why they were chosen, if desired. Do not ignore 'broken zones' or swarms of parallel discontinuities. These can often be a portion of a continuous feature that is simply difficult to identify in a specific location (Figure 5).

For each identified drillhole structural zone, evaluate the discontinuities on a stereonet. These will typically cluster in one to three sets. At times, the fault set is clear. At other times the controlling features on the core/ATV images conflict with what the net demonstrates. If not sure, record the individual set orientations for the major discontinuity sets within the zone. They are generally helpful during interpretation by providing potential alternative orientations. If they are incorrect, they are simply background noise that disappears during structural interpretation. Record the depth, apparent thickness, and mean orientation for each zone and then ascribe spatial coordinates. As noted, there may be one to three, or more, orientations with the same apparent thickness and spatial location.

3.2 Surface mapping

Complete and detailed surface mapping is required for this portion of the pre-interpretative work. Normally, this engineer photogrammetrically maps most of the discontinuities greater than 0.15–0.5 m trace length that are visible on the excavated face or on outcrop. These structures are then weeded based on structural criteria and persistence. Discontinuities with evidence of motion are selected together with discontinuities that exceed a minimum trace length threshold (normally between 4–6 m). Of course, these structural features are ascribed spatial locations and orientations, together with the noted persistence.

As for drillholes, such structures may not be identifiable on surface mapping (especially photogrammetric or scans) as a single feature. Instead, they are often found as swarms that can be traced across the face or outcrops. Also, as for drillholes, sorting by discontinuity set prior to spatial plotting increases the ease of determining such locations (Figure 6).

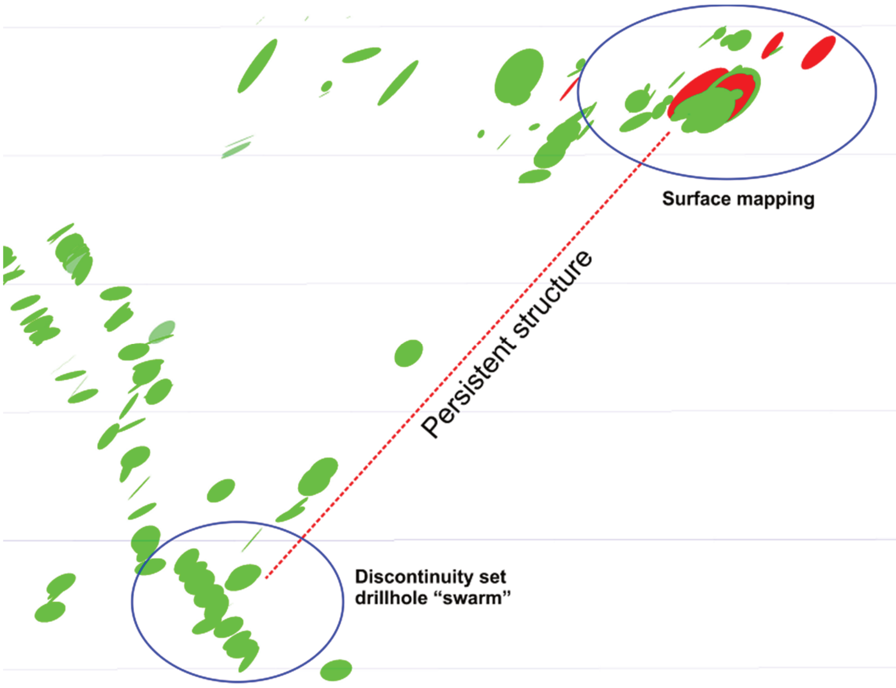

Figure 5 Drillhole discontinuity swarm indicative of major structure (sectional view)

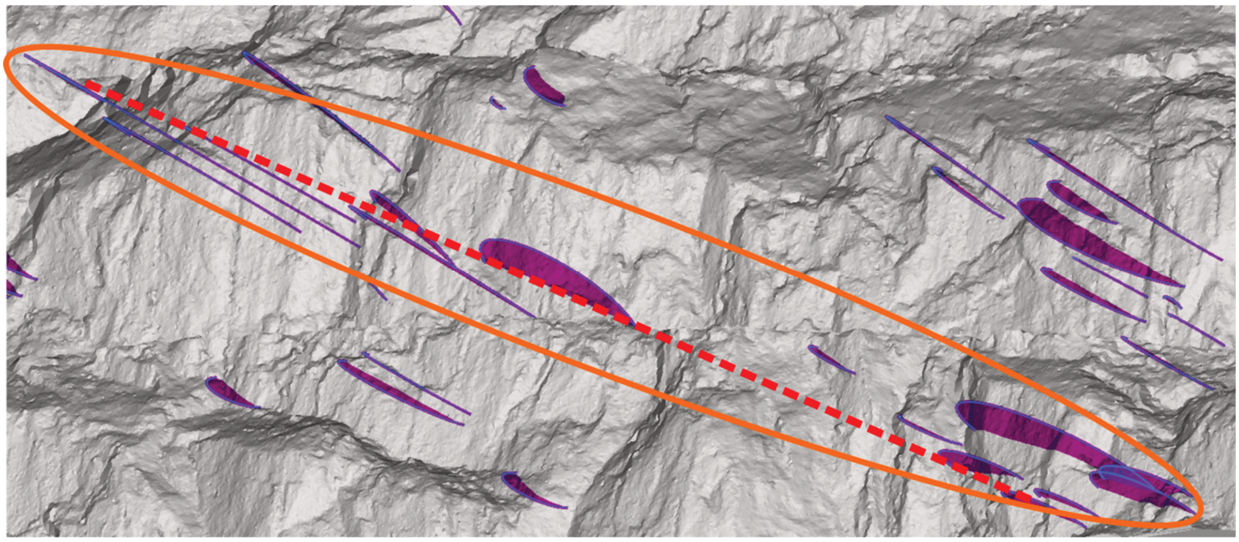

Figure 6 Wall mapping showing discontinuity swarm indicative of major structure

3.3 Global structure interpretation

Global structural interpretation is simplistic as long as one pays attention to detail.

Once the discontinuities describing major structures are sorted by sets and plotted spatially, together with the minor discontinuities describing swarms, visual assessment is normally all that is necessary to 'connect the dots'. The accuracy, or completeness, of such a composite collection of individual structures is enhanced by identifying and examining the characteristics ascribed to the individual features. A surface is then fit to these features. In many cases the orientation of this mathematically fit structural surface will be quite similar to the mean of the discontinuity set.

The interpreted structural feature is then examined as to where it passes through drillhole and outcrop. In some cases, the structural feature is incompletely persistent and simply is not found in local areas of the interpreted plane. In other cases, examination of the core/outcrop results in the discovery of the structural plane which is then added to the dataset.

4 Practical examples

Non-obvious persistent geologic structures have been demonstrated to control rock slopes.

Example 1, depicted in Figure 7, is a persistent geologic structure of around 0.3 m thickness, including the tectonic damage zone adjacent to the structural plane. In reality, the persistent plane is likely around 1–3 cm in thickness and extends over half a kilometre in strike length. This feature is very similar to the structural zone depicted in Figure 4 as ATV/core images.

There is always some uncertainty as to what shear strengths to assign to such a feature. However, the structural feature is generally throughgoing and must be incorporated in the slope design. In this case, the design inter-ramp slope was over 100 m in height. Any slope failure along this interpreted structure would certainly impact the pit ramp system.

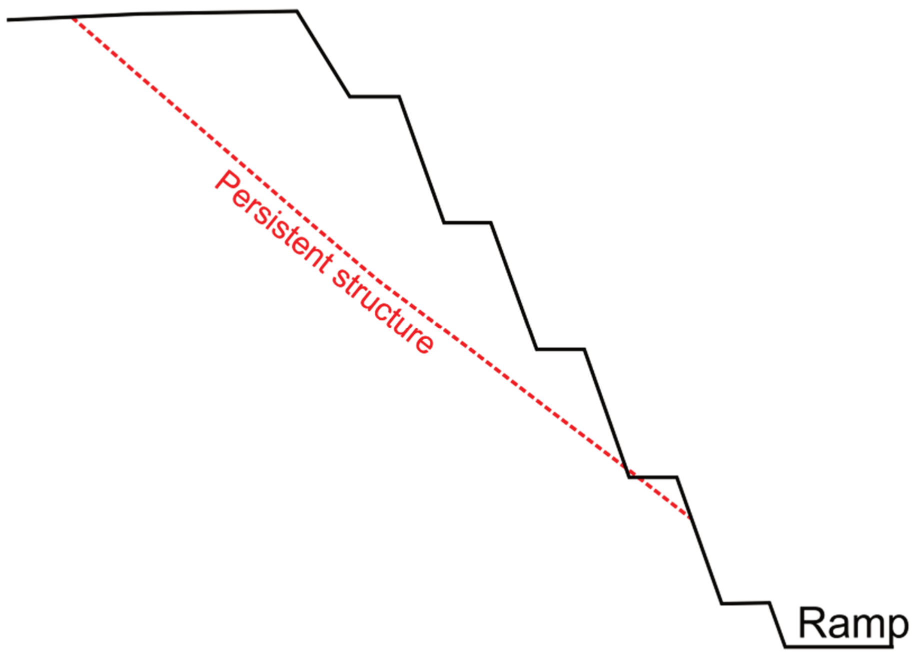

Figure 7 Persistent, narrow feature controlling slope inter-ramp design

Example 2 (Figure 8) depicts a persistent, non-daylighting interpreted geologic structure behind an existing inter-ramp. This slope, around 100 m in height, failed and spilled onto the ramp. A subsequent analysis was conducted numerically assuming that the instability was rock mass controlled. Numerous exercises were undertaken to adjust the numerical model such that the failure characteristics matched those indicated by the model.

Subsequent investigation indicated that a persistent structure was found, as shown, underlying the slope. This feature was not incorporated in the original analysis, rendering it invalid.

Note that in the aforementioned cases it was not necessary to reach for complex failure geometries, or rock bridge interactions, to obtain a reasonable geometry for potential slope displacement. In fact, the slopes were controlled by geologic structures that existed in the rock mass but were simply difficult to define. Detailed geologic and geotechnical interpretation of the available information, supplemented by additional investigation once targets were defined, resulted in a much more risk realistic assessment of the local slope's stability.

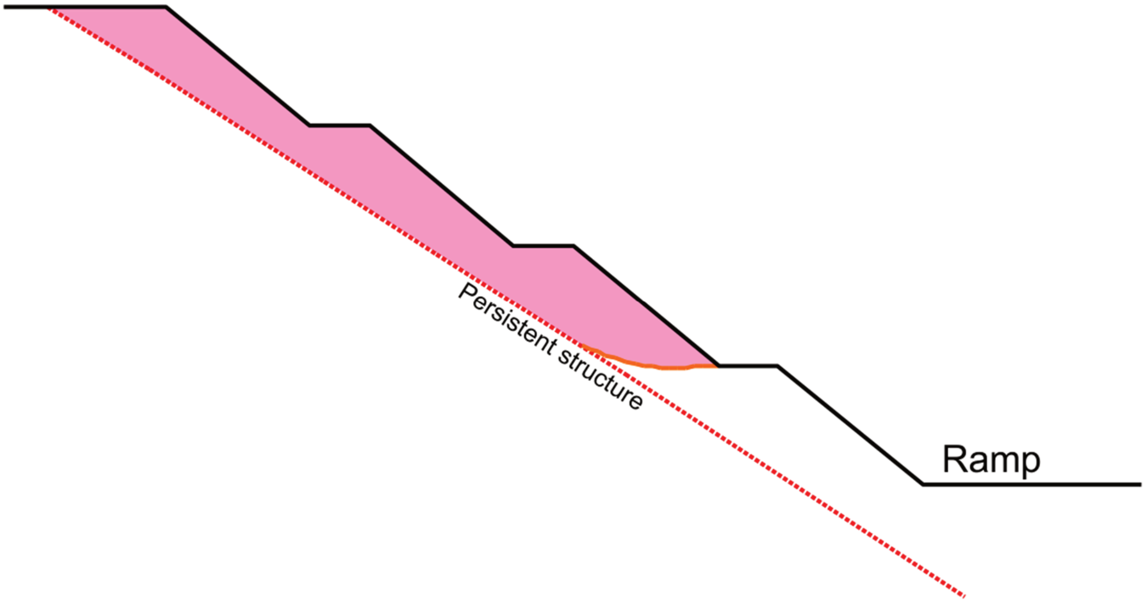

Figure 8 Undetected geologic structure underlying slope instability

5 Conclusion

The information provided within this article is a simplistic overview of the work than can and should be conducted, in the opinion of this engineer, for any geologic structural interpretation purposed for slope stability analysis.

Many data collection campaigns, at least as observed by this engineer, fail to collect the requisite information to even begin an analysis such as this. The work requires a basic understanding of what structures may be of importance and how they may manifest in core and outcrop. Only then can adequate interpretation be conducted.

Further, such structural data collection and interpretative work requires a rigorous framework. While intuition is appreciated, it should build on information that is collected and not be the foundation for data collection or analysis.

A complete, and detailed, understanding of the local discontinuity sets and structural domains is, of course, necessary for this interpretative work to be undertaken.

Of course, the personnel assigned to such a task, whether it be logging, logging interpretation (including ATV structural picks), downhole and surface structural zone picks, and subsequent interpretation must be experienced in all aspects of the work.