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Geotechnical design uncertainty and data collection

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Abstract

Rock mass characterisation, and subsequent engineering, is founded upon the data collected: data that reflects characteristics of the material that will be utilised for design. Thus, the varying geotechnical characteristics of rock fabric, major structure, lithology, alteration, and the plethora of other individual and combined parameters that are to be utilised for design of an excavation in rock must be carefully sampled by the field program, then appropriately reduced in order for it to be adequately represented by modelling.

At present, our modelling capabilities outstrip, in many instances, the data collected for design purposes. Collected data is hammered into a form, either by analytic approximations or empirical means, such that it can be included in relatively sophisticated models.

To speak of design reliability as a quantifiable term in such an environment is absurd. While the impact of the collected data can be quantified in terms of its impact on design uncertainty, if this data is unreliable to begin with or excludes critical information, then the resulting reliability bounds are meaningless as well.

This paper explores this concept in an attempt to illustrate some potential effects and to reinforce the absolute necessity of collecting accurate, verifiable data prior to attempting any statistically based stability assessments.

Keywords: *discontinuity, mapping, structure, interpretation, strength, uncertainty*

1 Introduction

Most, if not all, slope designs are deficient in some respect with regards to data collection and interpretation. This is primarily due to the practitioner's incomplete characterisation of the rock mass and its inherent design parameters/characteristics. These deficiencies affect the design uncertainty inherent to the engineering work. In the opinion of this author, many of these deficiencies, and their associated uncertainties, are never captured in evaluation of the design, resulting in excess risk, unknown risk, or excessive conservatism.

As such, a probabilistic design, or any design that attempts to incorporate some assessment of risk is invalid if the foundations of the design fail to incorporate the controlling design parameters and an accurate (or at least adequate) assessment of their range of uncertainty.

This document discusses some, but not all, of the parameters than can affect a slope design that may not be accurately quantified in data collection/reduction. Those discussed here include rock fabric, geologic major structure and rock strength, and even these only in part.

2 Rock fabric

The proper characterisation of rock fabric is essential to rock slope design in rock masses incorporating fabric discontinuities, or most rock masses. Such characterisation begins at the data collection stage (mapping) and propagates through the design through modelling. If data collection is inadequate or biased, either through the sampling procedures utilised or the assumptions made during mapping, this affects the design model/s. When such transpires, the design can be severely affected.

2.1 Fabric mischaracterisation

2.1.1 Discontinuity persistence

One technique that appears to be gaining in popularity for design purposes, as observed by this author, is to truncate the mapped discontinuity sample sets and only plot those greater than a minimum persistence on a stereonet; then use those orientation distributions for design purposes. The purpose of this exercise appears to be to isolate discontinuities with sufficient persistence to contribute to instability.

An example of this is shown in Figure 1. Here, the bench height was 10 m. Structures over 8 m in length were selected and plotted. As can be seen in Figure 1, this reduced the number of discontinuities plotted on the stereonet from 1,782 original population points to 106 points after truncation, or to roughly 6% of the original mapped values. This of course reduces the accuracy of the mean and variation of the discontinuity set distributions and fundamentally changes the population through the imparted bias.

What may be more critical than the orientation bias depicted is the length bias that is being imparted to the discontinuity orientations. The structures that are at high angles to the bench face are truncated by the bench height. Those that are at shallower angles to the face exhibit a greater length. This truncates and, in some cases, removes these sets from the orientation distribution while artificially enhancing the other discontinuity sets. As demonstrated in Figure 1, the discontinuity set that is sub-vertical on the face is essentially eliminated from the distribution.

Both the reduction in the data quantity and the shifts in set mean and variation, together with the potentially enormous bias on what discontinuity sets are visible on the stereonet, can have a substantial effect on design.

For this reason, the discontinuity persistence and distribution for the entire mapped dataset should be utilised in design. The referenced shortcut is likely to lead to errors and a baseline flaw in the data analysis. One should never truncate the distributions or selectively map specific structure orientations. It biases the entire design database.

Another common error in working with mapping discontinuity persistence is treating the raw measured persistence as an unbiased population sample. It is not. Truncation bias (the exclusion of structures that exceed the mapping face plane) has a substantial effect on the sample average. Only through correcting for this bias, perhaps through distribution free estimation techniques, can one obtain a better estimate of the mean persistence.

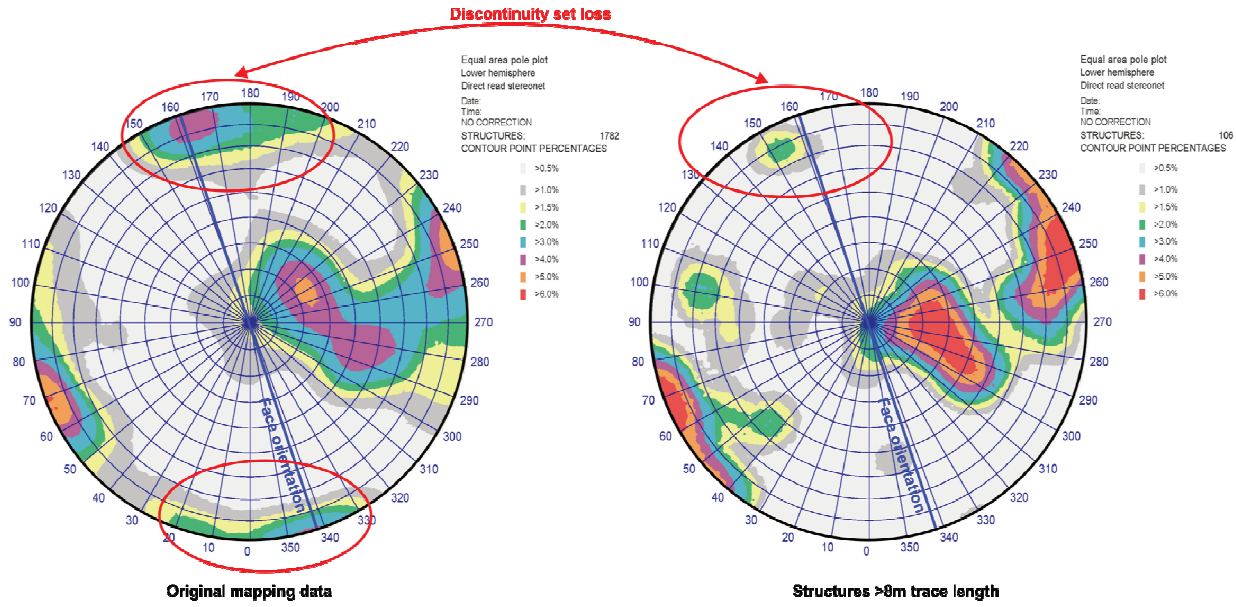

Figure 1 Orientation errors attributable to truncating the trace length population

A comparison of such raw persistence mapping means, by discontinuity set, with a distribution free assessment of the persistence is provided as Figure 2. While censoring bias may be minimised in the raw mean values by setting a censoring level during mapping, truncation has not been addressed. This results in errors being incorporated in the raw mean persistence value. It may be noted that mean mapping persistence can be in error by over 50% as compared to the distribution free estimate. This has real world consequences when designing a slope where discontinuity persistence is incorporated.

And just how were those discontinuities mapped? If photogrammetry is utilised (LiDAR scans can be problematic for discontinuity mapping) then was manual (on screen) mapping utilised or did a computer algorithm do the work? If it was a computer, then the data is likely to over-count the discontinuities by picking features that are not structures, undercount the structures if the selection threshold is set to high, and is almost certain to miss the structures with low relief. It is a compilation of irreconcilable errors.

As can be seen in Figure 3, the manually mapped data picks up on the tails of the discontinuity persistence distribution, or the portion of the distribution most critical for design purposes. Once again, we have unreliable data that will affect design. Note that the graph is shown as a demonstrative example. For those with greater interest in the topic, please consult Mathis & Elmouttie (2018).

Of course, the method used to image the surface, if photogrammetry is utilised for mapping, will surely have an effect. Several of the commonly used software programs that are not specifically designed for structural mapping impart mathematical relics to the mapped surface. The surface can be over-smoothed, rippled, or in other ways distorted (Figure 4). Such imparted distortions affect representation of the discontinuities that may be mapped. Compare this figure with an acceptable image (Figure 5) where sharp corners and surface relief are clearly observable. Such errors can result in large to very large errors not only in the orientation distribution but persistence and structural intensity distributions as well. Without removing the draped image and carefully examining the underlying digital terrain model (DTM), one may as well be mapping on bubble gum as the loss of sharp corners, edges, and even the image registration prevents accurate discontinuity mapping from being conducted on the inadequate model.

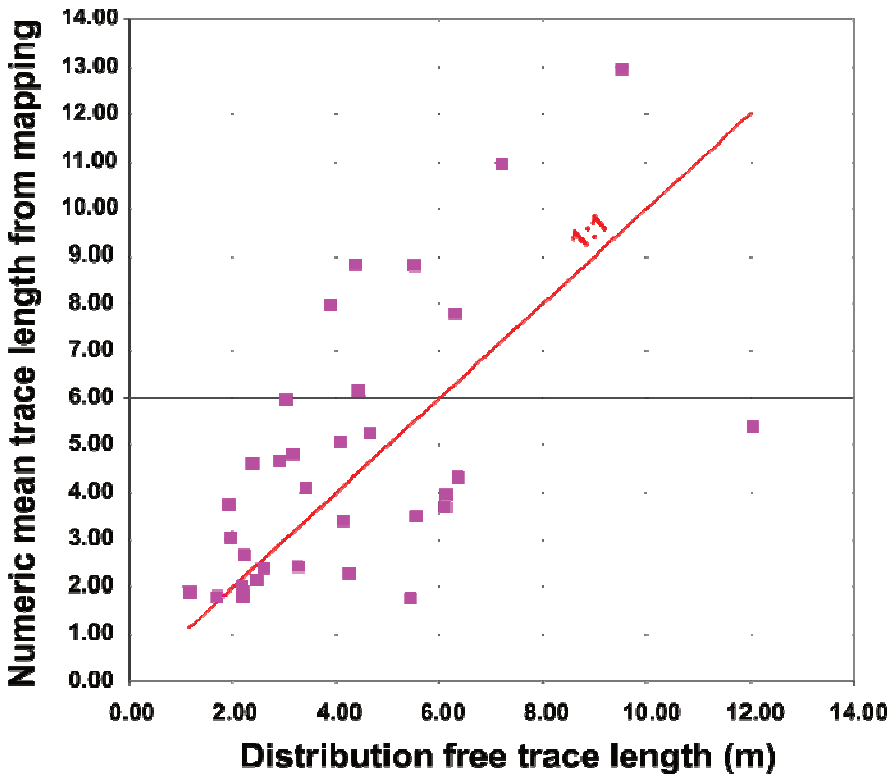

Figure 2 Persistence estimates: distribution free versus raw data (Mathis & Elmouttie 2018)

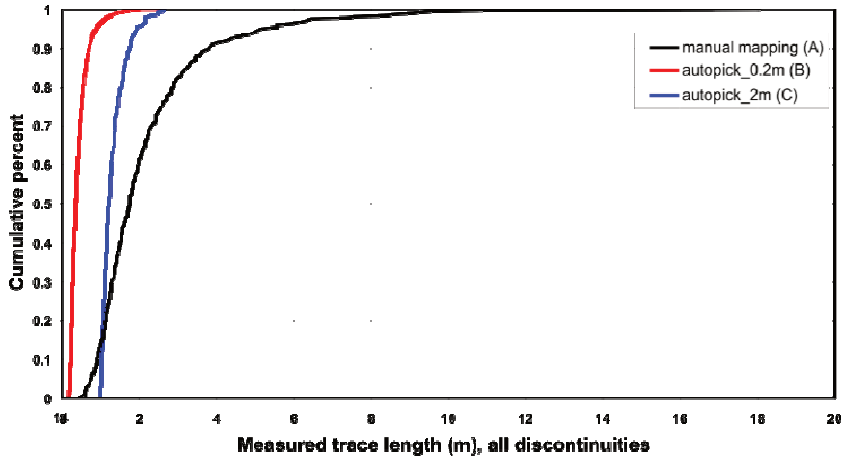

Figure 3 Influence of automated mapping algorithm on persistence (Mathis & Elmouttie 2018)

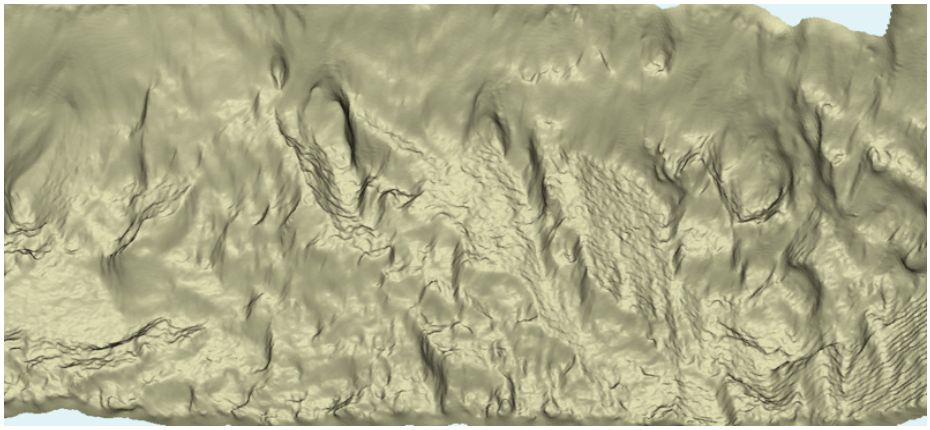

Figure 4 Photogrammetric digital terrain model without draped image with over-smoothing (Mathis & Elmouttie 2018)

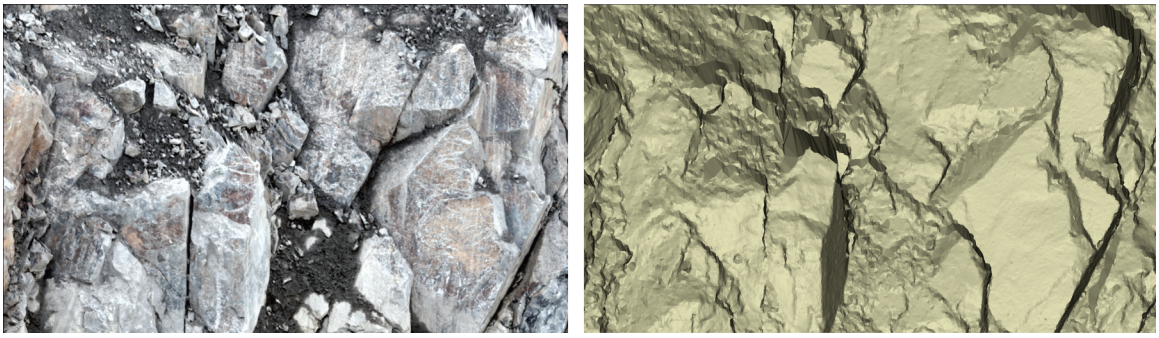

Figure 5 Acceptable draped image/digital terrain model (DTM) as compared to underlying DTM (Mathis 2020b)

So, the question now arises as to how the above has any impact on design. While being pervasive throughout any design work conducted, this is perhaps best illustrated through a simple figure (Figure 6). Here, it is shown how the assumption of infinite discontinuity persistence as compared to appropriately quantified discontinuity persistence quantification affects a bench face angle design. If this design were to be implemented, and the discrete fracture network (DFN) calculated bench geometry controlled the inter-ramp, for a 30 m high catch bench design (11 m catch bench width), the inter-ramp angle would be about 63°.

Compare that to the infinite discontinuity length's design inter-ramp angle, using the same bench height and width, of about 49°.

Bench face angle reliability was chosen at 80% for both of these examples.

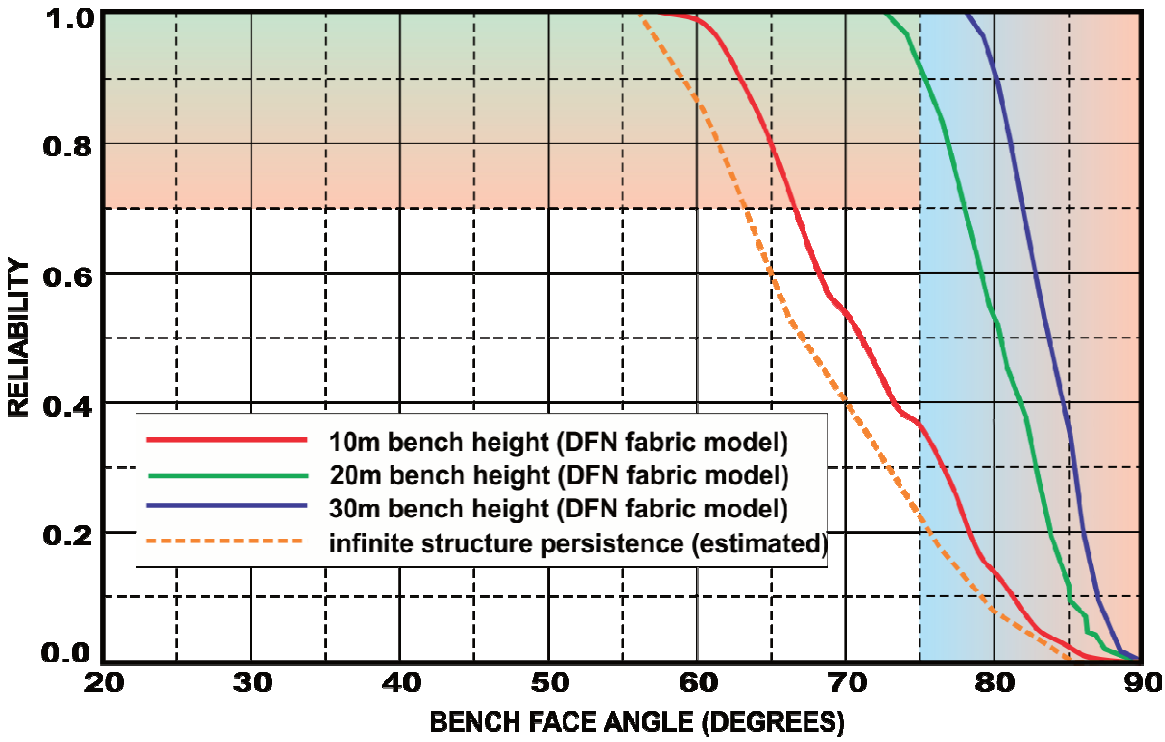

Figure 6 Effect of bench height and discontinuity persistence on bench design (Mathis 2014)

By analytic extension, it is obvious that any variation, or error, in the discontinuity persistence, discontinuity intensity, and the orientation distributions themselves will result in some error in the design and its associated reliability.

Yet, such factors are rarely, if ever, incorporated or discussed as to the effect on design reliability, even though they can have substantial impact on the design. This is especially of concern when one ascribes a risk level to the design without incorporating such obvious uncertainties as described above.

2.1.2 Discontinuity orientation

Oriented core drilling is often assumed by practitioners as providing accurate data with regards to slope design.

It does not.

First, even if drilling could accurately sample each and every discontinuity encountered, the surface sample size is very small, regardless of the diameter of the core. This concept can be illustrated with a 63 mm diameter core (area of 0.003 m^2) piercing a 5 m diameter discontinuity (area of 19.6 m^2), or about 0.015% of the discontinuity's area. This sample size effect increases the dispersion of the orientation data.

Second, the methodology employed in obtaining the structure orientations from a drillhole can render the data near useless. Barrel orientation techniques can result in the core being rotated in the barrel (Figure 7), resulting in discontinuity orientation error. What is depicted in the graph are actual measured rotational errors between runs. The theoretical distribution is that error that could be attributed to mismarking the scribe line (logger error) as compared to the tool errors. As shown, the errors can be quite large.

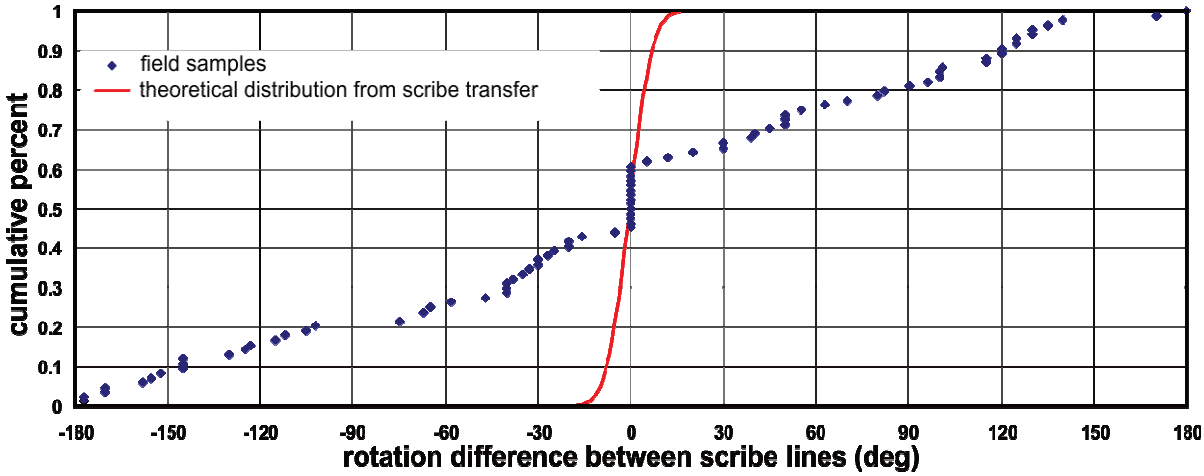

Figure 7 Cumulative measured barrel rotation between drill runs

Downhole oriented structures from acoustic televiewer (ATV) logging, with discontinuities verified on depth matched core photos, were compared to the same drillholes logged with a barrel orientation technique. As depicted in Figure 8, only about 13% of the structures encountered in the drillhole, on average, could be logged using the barrel orientation technique. This will have ramifications on estimates of structure intensity, orientation distribution means, dispersion, etc. And that is if no barrel rotation occurs between runs.

On top of all these errors are the errors associated with logging, where the logger determines which structures are a 'natural' discontinuity versus a mechanical core break. This is not as much of a problem with ATV logging, but a similar problem arises in that loggers often ignore cross core breaks even on ATV logs. As can be seen in Figure 9, the representation of alpha/beta angles from barrel-oriented core, as determined from multiple actual drillholes in varying orientations, does not begin to approach what one would expect.

One response to the above, heard on several sites, is that they applied the Terzaghi correction to the data and that eliminated the above issues.

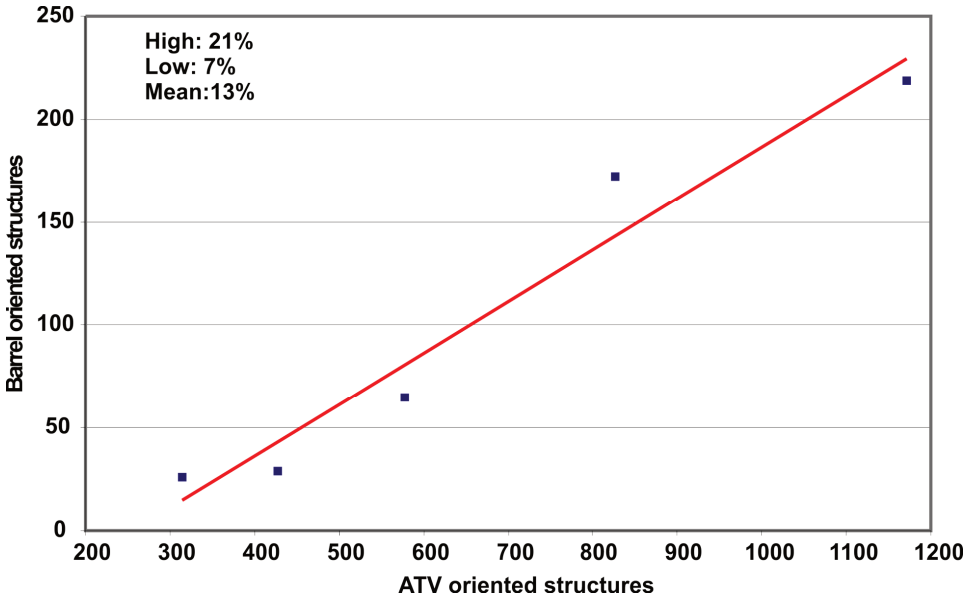

Figure 8 Acoustic televiewer (ATV) versus barrel orientation discontinuity count

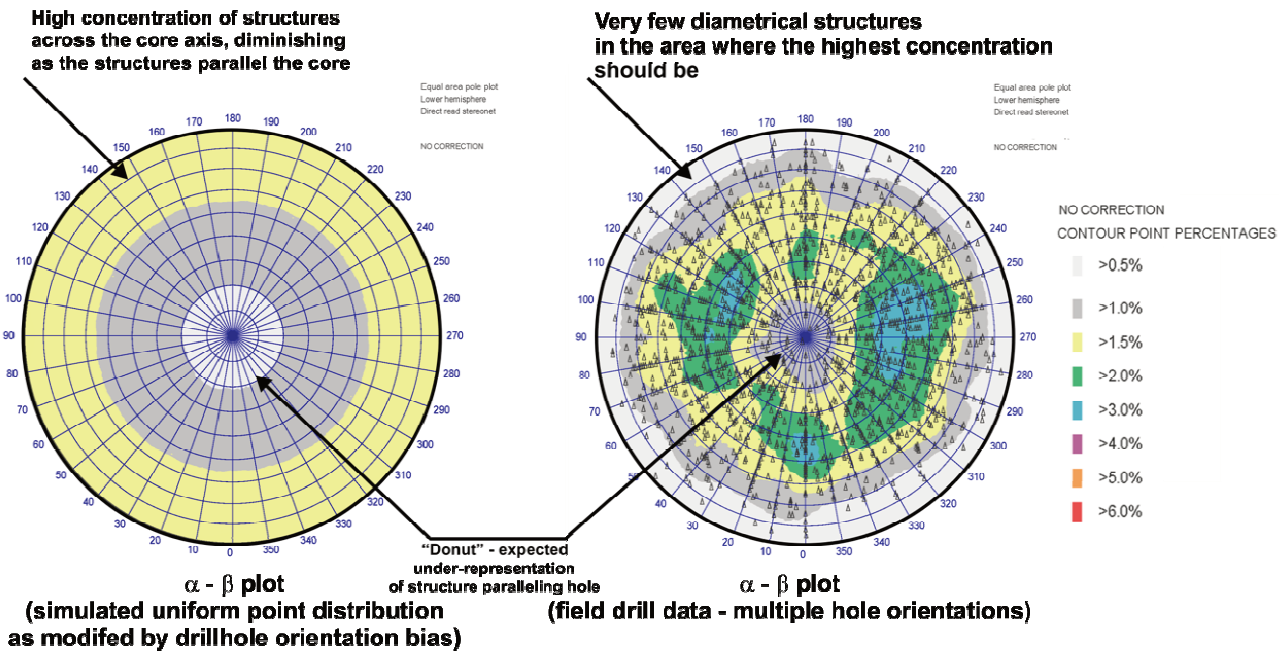

Figure 9 Logger error in determining natural versus mechanical discontinuities, multiple drillholes

The Terazaghi correction is a very simplistic correction that was proposed to reduce the orientation bias from line sampling, whether it be drillholes or scanlines. It is not, nor was ever intended to be, applicable to the previously described physical core orientation errors. It does not correct such errors.

One of the flaws of the Terzaghi orientation correction is that it leaves a wide band (roughly 30° to the mapping line) where no correction to orientation is conducted due to the influence of the sine correction factor becoming too large.

The method is also fundamentally flawed in that it fails to incorporate the persistence distribution of the discontinuities and the orientation distribution themselves, as demonstrated in Figure 10. Thus, the Terzaghi weighting factor not only over-represents the bias at shallow angles to the mapping line but fails to incorporate the orientation distribution as well as the discontinuity persistence. For those interested, the theoretical roots of the equations shown in Figure 10 may be found in Mathis (1988).

While it can be argued that it may be difficult to incorporate the set persistence and the orientation distribution into drillhole data orientation correction, it is not impossible, especially if local mapping data is available.

Alternatively, one can combine data from drillholes in directions chosen to minimise the drillhole orientation bias and then combine the data from these drillholes. While not perfect, it provides a practical solution to the problem which avoids utilising the Terzaghi correction.

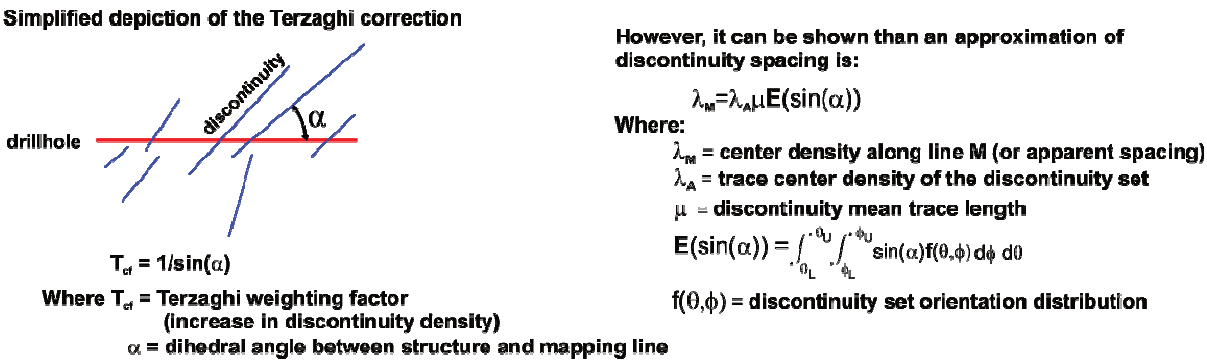

Figure 10 Fundamental theoretical errors in the Terzaghi correction formulations

2.1.3 Fabric impact on overall slopes

It has often been encountered on site where personnel state that the errors associated with fabric data collection have no impact on the operation as they are only worried about the inter-ramp and overall slope and fabric has no impact on those slope design parameters.

Nothing could be further from the truth.

As was demonstrated above, for a bench controlled inter-ramp angle for a specific example, the design inter-ramp angle would be 63° if the discontinuity persistence was correctly estimated and incorporated in bench design versus 48° for an infinite persistence case. In this example, local bench geometry, as determined utilising local rock fabric models (DFN) impacts, and in this case controls, the inter-ramp slope angle.

Second, rock fabric is critical to, and must be properly modelled, if one is incorporating DFN in inter-ramp and overall slope design. This modelling must accurately reflect the assumptions incorporated in the data collection process as well as model how the discontinuities may manifest in the slope.

For example, examine the two slope scenarios provided in Figure 11, where an overall slope incorporating a ramp and two inter-ramp sections is depicted. The first (left) assumes a homogenous distribution of discontinuities (rock fabric). The second (right) incorporates the increased discontinuity development in a fracture zone within the slope. Note the substantial differences in the evaluated stability, here depicted as SRF (strength reduction factor), between the two scenarios. The SRF is often assumed to be equivalent to the Factor of Safety.

Data collection, and reduction, is only part of the issue. Accurate incorporation of the carefully collected and reduced discontinuity data can have a profound effect on slope design, and its uncertainty, as well. All affect the uncertainty attached to the slope design.

2.2 Major structure mischaracterisation

Major geologic structures, or through cutting geologic structures on a slope scale, are likely among the most under investigated and, from a stability perspective, misunderstood items in terms of slope design.

For many years, a 'major structure model' was simply whatever the geologist had on the shelf. This generally consisted of regional and ore control faults but little else. This author recalls one instance where a 15 cm wide fault zone, healed with quartz, was characterised as a major structure as it 'contained ore'. Yet, when asked about the 1 m gouge zone in a different orientation about 10 m away from the 'major fault', was told that it wasn't considered a major structure as 'those are all over and don't control the ore'.

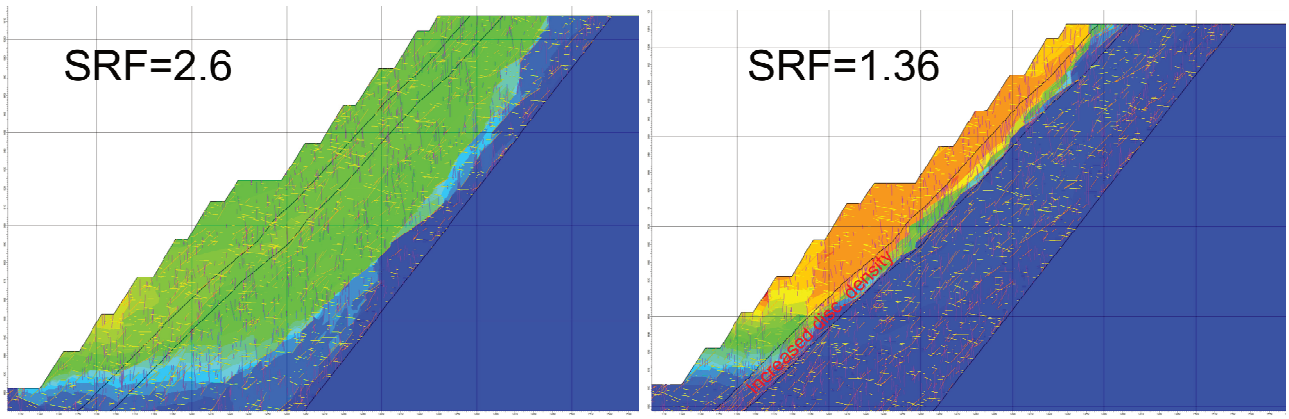

Figure 11 Implementation of varying discontinuity domains in slope design (Mathis & Elmouttie 2018)

That has changed to a certain extent, but not as much as one would think. Major slopes still exist without a geotechnical drillhole or major geologic structure model for stability purposes.

Determining the location, orientation, and characteristics of major structure in the vicinity of a design rock slope is not as simplistic as it may seem. From review of other's work for slope designs, it appears that sectional analysis of structures exhibiting gouge or major motion is still in vogue.

Unfortunately, that is insufficient.

Many throughgoing geologic structures that have the potential to control a rock slope are not obvious. They may be narrow, persistent structures with substantial strike length; or they may be zones 5–10 m in width that, while accommodating substantial movement in the past and developing very persistent internal parallel discontinuities, never developed any gouge; or they can be anywhere in between. An example of a very narrow, but slope controlling geologic structure, in drillcore is found as Figure 12.

It is difficult, if not impossible, to look at a broken zone in a piece of core and determine the orientation of the major structure. In fact, it requires substantial analysis. An example can be seen in Figure 13.

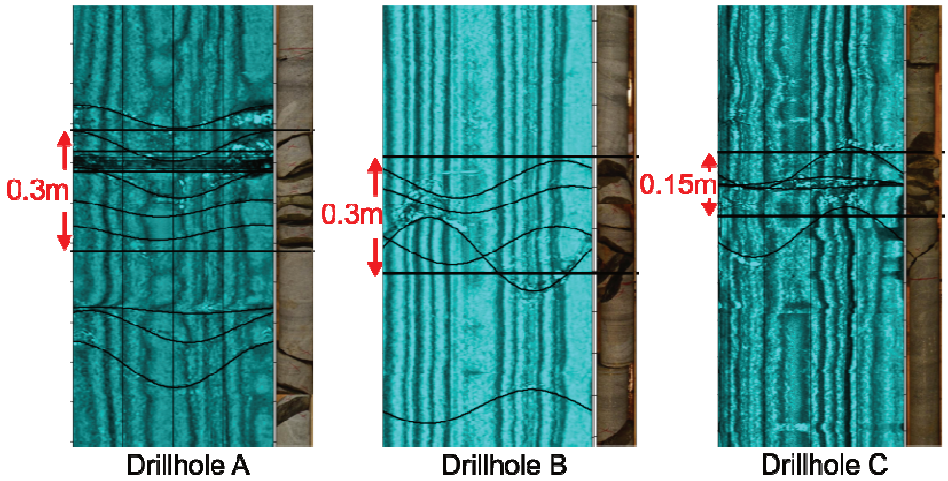

Figure 12 Narrow, slope controlling geologic structure (Mathis 2020a)

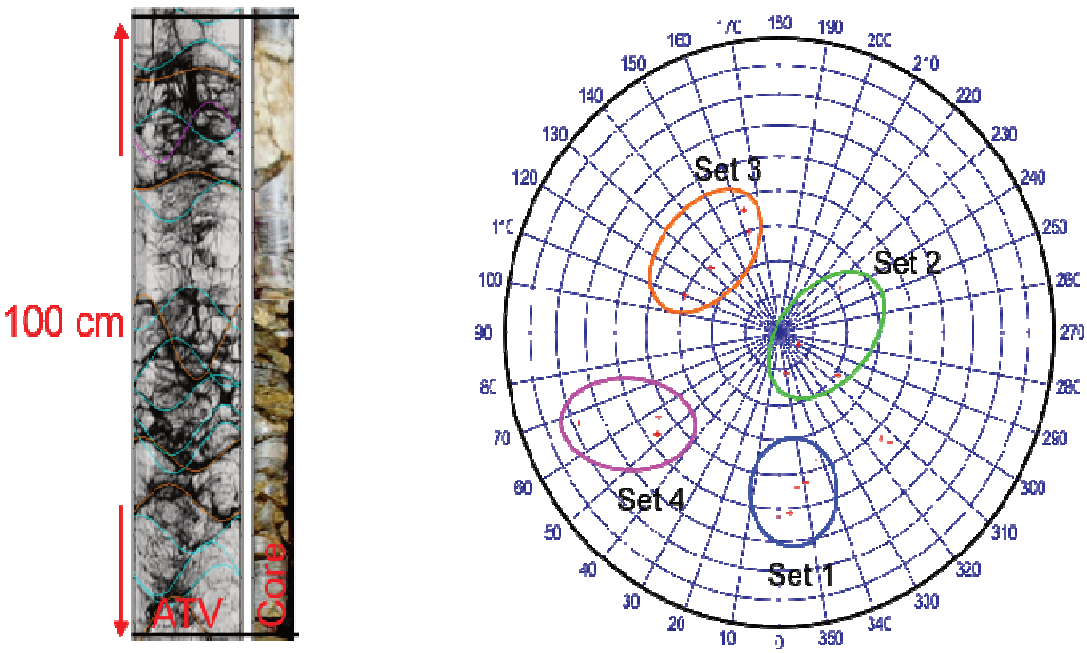

Figure 13 Discontinuity sets within a fault zone: which one is the fault orientation? (Mathis 2020a)

Only by carefully examining the drillcore from multiple drillholes, and the included potential structural zone orientations, located spatially, together with any surface mapping, can one begin to piece together the complex picture of slope controlling major geologic structures.

A methodology has been developed by the author for the interpretation of major structures and is found in Mathis (2020a). This reference expands on the brief description in the foregoing paragraph.

By failing to expend the necessary time, effort, and resources on defining the potential major structures controlling a rock slope, the design is certainly not verifiable nor can design uncertainty be quantified.

2.3 Strength mischaracterisation

2.3.1 Point load testing

Point load testing is quite popular for field data collection as it provides an estimate of rock strength. One may question its popularity as it is expensive, time consuming, destructive, and requires a large number of samples in order to approximate a single uniaxial test. It is argued that the method is 'accurate', yet the method is simply an index test which indirectly estimates rock compressive strength through tensile failure of the tested sample. Secondly, the reduced Is_{50} value is adjusted by a multiplier in order to estimate the compressive strength. This multiplier is commonly assumed to be 24 but can range between values as low as 8 and as high as 35. The penetration of the platens on softer rock renders the results inherently variable, and generally inaccurate in such a material.

The effect of the multiplier (I_{S50}) on point load estimated compressive strengths can be seen in Figure 14. Note in Figure 14 that the field calibrated multiplier for the specific example in question was determined to be about 16. This was arrived at by conducting carefully controlled point load testing in a relatively homogenous rock. A laboratory testing program was designed to mirror the samples tested in the field. While such efforts have certainly been conducted by other professionals in the field, it does not appear to be commonplace, at least based on the author's experience. Yet, as can be seen, the point load estimates can easily shift 25–50% based upon the applied multiplier, having a substantial effect not only on the intact rock strength estimate, and the calculated rock mass rating, but on the rock mass strength estimate as well.

Point load data and the associated data reduction process are, in the experience of the author, often suspect. For several field programs, point load gauge pressure readings have been provided with no corresponding piston area. This renders the data meaningless. In one case, technicians were, and had been, conducting point load tests for some time, yet did not know, and could not obtain, the piston area such that the gauge pressure readings could be converted to sample imparted load. Of what value was the collected data? In several other cases, the test platens were worn so flat on top that the sample was essentially being crushed between flat plates, pumps had leaky cylinders resulting in pressure bleed-down between pump strokes, and incorrect and at times faulty pressure gauges were observed being utilised. What effect did these have on the results? Were they reported in the presented data?

Additionally, the technician often sorts through the samples to obtain one 'suitable for testing'. While the sample in Figure 15 was obviously not tested, it is the sole 'testable' sample within the box. As such, in the experience of the author, it is at risk for being tested as a 'representative' intact rock specimen. How would this be representative of the fault gouge surrounding this lone piece of silicified, intact rock? The occasional requirement that samples must be sawed to length, and taken at specific intervals, essentially demands that such a sample be tested.

If point load test results are utilised in any way in slope design, it runs the risk of contaminating the database. In most cases it would be better, and cheaper, to utilise spatially distributed uniaxial testing (of carefully selected samples) for determination of compressive strengths for rock mass rating calculations.

While point load testing results can be utilised as a proxy for laboratory compression testing, great care must be taken when doing so as the material specific I_{S50} (Figure 14) can have profound impact on the results.

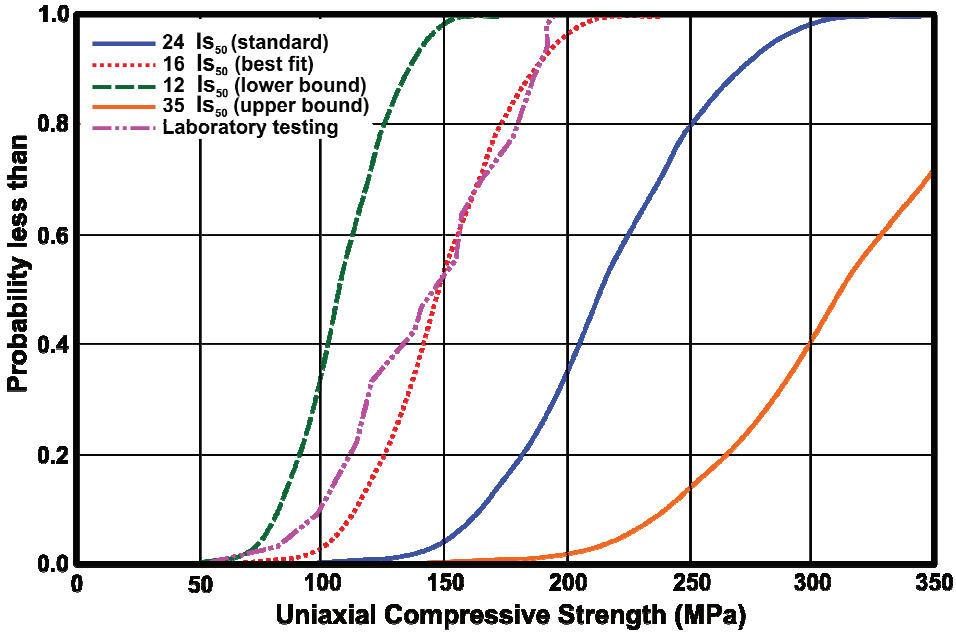

Figure 14 Comparison of I_{S50} multipliers for a selected population of samples

Figure 15 Intact rock sample in fault gouge. Is this a representative strength sample?

2.3.2 Discontinuity direct shear testing

Discontinuity direct shear is generally conducted to determine shear strengths for a variety of design issues: bench, inter-ramp, and overall slope designs.

The testing specification ASTM D5607−08 (2008) requires that shear testing be conducted on the sample from the lowest to the highest normal load. As the sample is reset and then sheared again at a higher normal, surface degradation occurs. The result is sample crushing (Figure 16). As such, when utilising this specific ASTM specification, it is likely, especially in more fragile rocks, to bias the results; at times severely.

A solution is to cycle the normal loads randomly through the test range. This provides a true 'peak' value for a variety of normal loads. Shear travel is continued until such time as the residual shear strength is attained. For HQ core, this may be as high as 10–17 mm of displacement. One can expect an argument with the lab at this point, but the results may be worth the dispute. Alternatively, one can increase the number of samples tested and only conduct shearing at one or two normal loads.

Some labs also have an artificial stop on travel and limit the shear travel to 5–8 mm of displacement. This is occasionally insufficient to attain residual shear strength values.

Finally, one should always examine the shear samples post testing, either as photographs or physically. Results have had to be discarded based upon such examination as there were indications of sample tilting, digging into, and scraping on, the potting compound, etc.

The above lead to uncertainty in the data and design; something not captured in a standard evaluation.

Just how much can this affect the design? In one case, a variation in over 6° on the peak friction angle is recalled as being incurred by such testing effects. Whether that is significant or not is up to the design engineer. Whether it should be captured in the uncertainty of the design is not.

Figure 16 Direct shear sample crushing

3 Conclusion

This article could likely have been extended for many more pages. It could have covered additional topics as well as examined those presented in much greater detail. The purpose of the article, which is to raise awareness among practitioners, would be defeated by such a treatment.

Based on experience, and many years practicing in the field, engineers do not like being told they may be collecting, reducing, or incorporating data in their designs incorrectly; especially if it is contrary to how they were trained or to their corporate guidance. If the changes impact either the client's or the design engineer's costs or income stream, it will have a similar effect.

However, after having reviewed a fair number of designs, reports, and many, many articles over the course of a 40-year career in the industry, it is fairly easy to state with certainty that perceived errors discussed in this article are ubiquitously incorporated in most self-same designs, reports, and articles.

If one conducts or reviews a slope design, one should understand the data collected: the methodology, the flaws, etc. The designer should then attempt to either address the uncertainties by better/additional data collection or by incorporating the inherent uncertainty in design.

The general rubric under which this article was submitted was geotechnical design uncertainty. The hidden uncertainties described in this paper are often unknowingly incorporated in design; and not accounted for. Such uncertainties should not be ignored. To do so would be remiss; at whatever level of review.

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