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Structural Domaining for Engineering Projects

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ABSTRACT: Increasingly, geotechnical engineering analysis of project sites for major civil or mining projects are being based on analysis of database compilations and GIS summarizations of collected field program information, but without rigorous geological structural domaining having been undertaken to subdivide the project site into realistic geological entities.

This paper outlines the basics of Domain Characterization of a project area rockmass, recommending that assessment should always be two pronged – (i) domain scale, and – (ii) engineering structure scale; as rockmass characteristics are typically never the same at these two scale extremes. Geological simplification and coalescing of engineering characteristics and data into a sympathetic geological framework per area of a project site is what is missing today in innumerable projects. This paper attempts to set out methods and guidelines to help resolve this ongoing industry-wide problem.

1. INTRODUCTION

The concept of **Geological Domains** – each comprising a zone of consistent structural fabric and material properties, bounded by definable geological "interfaces" of structural importance, has been well entrenched in classic geological literature almost since the beginning of geological mapping. In fact, even the first geological map – William Smith's geological map of England ("The map that changed the world" – Winchester, 2002), is a domain interpretation, i.e. a simplification of reality to achieve a specific purpose. In Smith's case this was targeted for the canal builders, for communicating an interpretation of the spatial distribution of rock types across the UK, to aid their original construction.

Unfortunately, over the last few decades the insights gained by having a dedicated field geologist develop his or her own similarly useful structurally-based geological map of a project site (that incorporates usually the quite thorough understanding of the basic structural fabric of the site), has diminished almost inversely with the rise in utilization of modern sophisticated computer modelling approaches to achieve what has been thought the same end product. In the minerals industry, because of the financial ramifications of lack of proper geological conditioning of such computer-based maps, some of the geostatistics-based modelling approaches on which they have been based and the resource estimation derivations established from such maps also are coming under increased scrutiny.

Recent papers and discussions by Cowen, 2014, 2017 (echoing comments by Emery and Ortiz, 2004 and even earlier Stegman, 2001) lament the fact that rather than increased sophistication of modelling software packages reducing errors in resource estimation, the wider, but rather greater blind acceptance of these modern packages is appearing to be making things worse. These same parallels are common too in rock engineering, and not just in domaining, as pointed out by Carter, 2015. In order to properly conduct a geotechnical evaluation of a particular project site, one needs to reliably establish the distribution and variability of controlling parameters across the site, Martin and Tannant, 2004. There is always a need to prepare a reliable, structurally based geological map that is truly a domain map. However, in rock engineering, as in some areas of modern exploration geology this task is not being done as well as it should be, thus there is a need to go back to basics to resolve some of the problems discussed above.

That significant problems exist in rock engineering industry-wide in properly domaining engineering geological units across a project site is attested by many cases in project documentation where means and ranges of specific design parameters are tabulated based on much too wide spreads of base information. These types of problems are most commonly seen in analysis of laboratory test data where insufficient geological input has occurred in formulating the test work.

It is also common to see geologically inconsistent groups of pole concentrations on stereonet plots all being identified as specific joint sets – when in reality they might each constitute just a few poles of part of a girdle fabric – representing a folded structure. Evidence of multimodal peaks in laboratory data plots are a common giveaway that rock samples in the data sets are of mixed origin – with characteristically different rock units of one fabric being interspersed with another, leading to quite erroneous results. Consistency defines a Domain.

At any given project site, there may however be multiple geological domains, each with different engineering geological characteristics; and each comprising a unique set of definable and consistent rockmass conditions, bounded within definable contact margins. Such domain margins may be defined by relatively sharp bounding structures, which are commonly geological weaknesses (faults/shears etc.) or specific lithological contacts (ref. boundary type 1, and upper components of Figure 1).

The domain itself, within which conditions show consistency, could be an individual specific lithological unit or maybe a multifaceted rockmass, either of which would likely be jointed, but also could be layered, foliated or schistose. In some cases, the margins of the rockmass domain with these consistent conditions may be gradational (a "soft boundary" in resource estimation terminology) and therefore require an engineering decision on an optimal cut-off position (ref. boundary type 2, defined by consistent components in the lower part of Figure 1). Inevitably therefore, domain margins can be expected to be quite varied, but always the domain's internal conditions should remain consistent. The rockmass components for each domain however need to be checked for reasonable consistency in order to properly characterize the domain and its margins.

The interaction of lithology and fabric and geological age of the units within each domain will in turn control their material properties. A domain would thus be expected to be defined by consistent lithological, structural and rockmass material properties (ref. left diagrams in Figure 1). At the domain scale, one might thus define three divisions that need characterization –

(i) ***lithology***:- defining intact rocktypes, plus weathering, and alteration, which in turn controls – m_i, UCS_i, E_i;

(ii) ***structure***:- defined in terms of surfaces and infills of all structural features, fabrics and at all scales of discontinuities, which in turn will control – *JRC, Jr, Ja*, *JCond*, of individual elements of the fabric, from small scale foliation to large scale (domain bounded) faulting; … and …

(iii) **rockmass material properties**: as characterized by GSI/Q/RMR – i.e. the full classifications, plus individual discrete components and backup lab parameters.

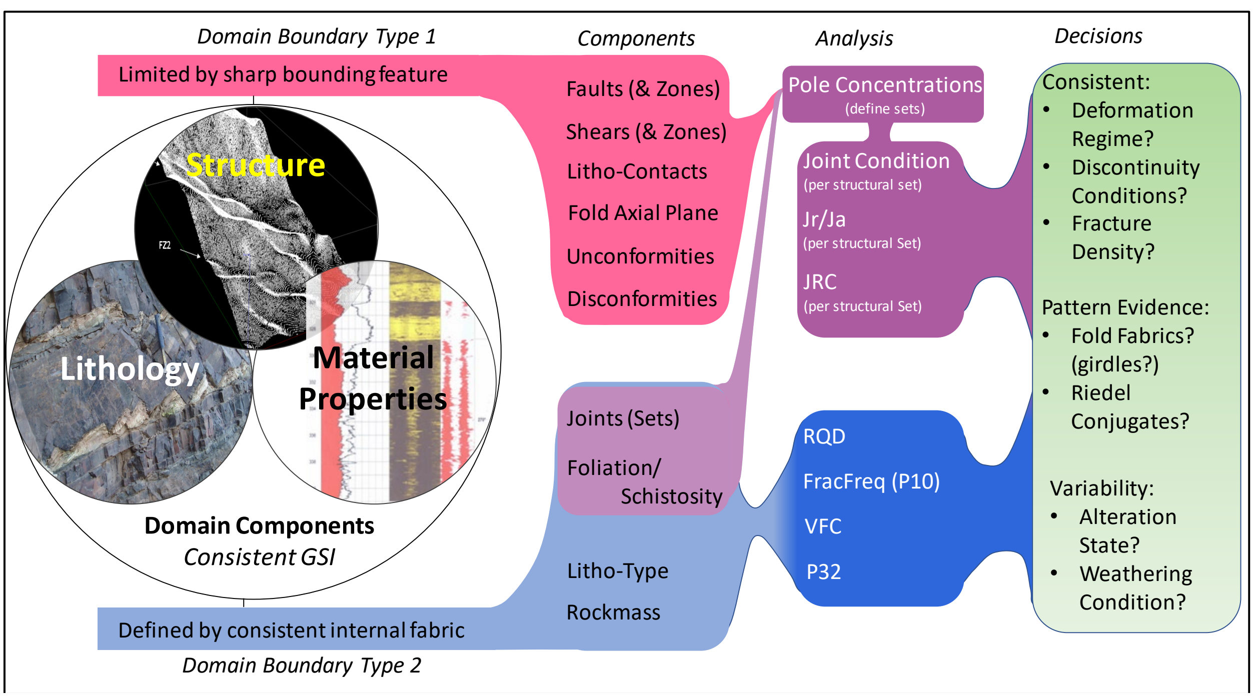

Figure 1: Workflow for defining the Prevailing Domain Geological Components (Lithology= lithostratigraphy; Structure = internal fabric and Material Properties = intact and rockmass), and then analysis of the Components requiring definition for unambiguous *GSI* classification of a Structural Domain

Typically, for projects extending over wide areal extents multiple domains commonly exist. Nevertheless, one can often define regions where even though different domains are identifiable within it (each with different lithology and structure, i.e., rockmass conditions), there will usually be consistency in the local stress and groundwater conditions. Such zones might thus be considered **Geological Regimes** (Table 1), and both these regimes and the internal domains may each then be scale-controlled, depending not just on project size, but also on uniformity of stress state and groundwater conditions. There may also be situations where stress state and groundwater conditions need to be more specifically defined for each domain.

Table 1. Definitions

DEFINITION	CONSISTENCY	
REGIME	Across Multiple Domains	Stress & Groundwater
DOMAIN	Lithology	Material Characteristics
	Structure	Discontinuity Geometry
		Surface Characteristics

2. IMPORTANCE OF DESIGN DOMAINS

2.1. Why Domains

Geotechnical analyses cannot represent the exact reality of areal variability of true rockmass conditions in engineering calculations. Accordingly, simplification of actual rockmass and boundary conditions is always necessary, but ultimately this simplification must be accurate enough to test assumptions for finalization of decisions on representativeness of design parameters.

The geotechnical engineer ultimately decides which rockmass properties are required as input into the analyses and to what accuracy the data must be defined. However, at different stages of a project these requirements may not be feasible to be met for a given domain data set. These limitations need to be better understood by both geotechnical engineers undertaking designs and by geologists collecting data. Generally, key input parameters will be measured, while lesser parameters may be calculated and/or estimated. Because of natural geological variability there is always a limit to the volume of rock that can be represented by one set of parameters for any specific analysis. A domain thus needs to be defined to represent a volume of rock with a specific set of rockmass design parameters that is appropriate to not just the scale of geological variability evident across the project site, but also with respect to the scale of engineering structure under consideration.

Major engineering structures (e.g., dams, tunnels, open pits, underground mines etc.) frequently are sited across multiple geological domains. In consequence, no one *GSI*, *RMR* or *Q* value will likely be sufficiently diagnostic of site conditions to be representative enough for design purposes. Defining appropriate ranges and collecting sufficient data to be truly representative in classification assessments should therefore be the focus for engineering structure site characterization.

Such characterization obviously should start with careful "domaining" of the region around (and including) the project site, so that unique, unambiguous zoning is achieved of the entire area of engineering importance. Care, however, must be taken in this domaining process to not overly complicate design by creating too many domain divisions. Obversely, too simplistic a domaining approach is also not sensible.

Throughout this process, it is important to stress that there is always a need to synthesize and simplify complex geology, but without losing the essence of variability in diagnostic conditions. For example, depending on the scale of sedimentary layering present in a rockmass, distinction might be made, for instance, between one rockmass area and another, based on the distribution of alternating lithological units (viz sandstone/shale variations) within each area, with one location perhaps being characterized as a composite unit (lumping together the complete bedded sequence). In another area, perhaps each bed would be thick enough and different enough to be individually characterized. Equally, appropriate delineation is needed of complex metamorphic or igneous terrains, so that appropriate domaining envelopes can be delineated.

Stegman, 2001, although writing about lack of accuracy in resource estimates due to inadequacies of domain envelope definition, made several observations germane to setting both exploration and geotechnical domaining envelope requirements - viz

(1) first and foremost - domains should be defined by a geologists' understanding of the geology and structure, not just drawn on the basis of computer modelling;
(2) domains must consider correct structural fabric and structural boundary controls;
(3) domain boundaries must be drawn at locations of realistic change – they must not be too broad, as this results in smearing of parameters across the domain, nor should they be too tight, as this produces models that assume a greater spatial continuity of specific parameters than may actually exist;
… ... and last but not least;
(4) domains must adopt consistent definition of along strike limits; conditioned by bounding drill hole data intersections at the limits of each domain envelope.

2.2. *Design Process*

Civil or mining excavation and construction projects develop through a workflow that entails project-specific data collection and then use of the data as input into the design (Figure 2). Geological data is required to describe properties of the rockmass in which excavation is to be undertaken and can also influence decisions that rely on rockmass strength or stability, both of which, particularly when structurally controlled, most likely will be direction dependent (Stead and Wolter, 2015).

It is best practice nowadays for geological interpretations to be presented to the design engineer in 3-D computer geological models, through which sections can be cut. Such models are already interpretations and simplifications – a fact affecting accuracy that is not always appreciated by the engineers using the modelled data. To avoid misconceptions and errors in design analyses based on misunderstandings of what is and is not reality in such models, there must be better communication of likely certainty and accuracy limits passed through to the engineers with delivery of such models, Campbell et al, 2015. The fault ranking scale proposed in Carter, 2018 provides a useful approach for indicating to the designer which fault has more or less certainty in its interpretation. Always, in generating geological models, (even simple geological sections), it is important to make it clear what is fact and what is inferred, as those interpretations cannot replicate reality. Therefore they must always be understood to represent simplifications of actual geological conditions. This is not to say that modern geological modelling software creates models that are inaccurate, nor unrepresentative, but rather that they present a "best estimate" of what may be considered the most representative geological features and domains existing within the area of interest.

Another issue of importance that needs discussion with the designer, and must be done way in advance of starting on generating such models, is scale of detail needed for design. A regional geological map is of little to zero use for providing detailed information for the design of some small but vulnerable project component. For geological models to be useful to the design engineer, the scale, location and described geological features need to appropriate for the proposed detail of required engineering analysis. Clear communication with the design engineer is required not only to determine scale and extent of the required modelling to cover the project site, but also clarity is needed of the level of granularity of geological domaining needing to be incorporated into the model so that the level of geological detail is appropriate for the design needs. Usually this process is iterative, with further refinement of a preliminary model often required, with additional data collection also needed on occasion.

For the engineer, the engineering design approach strategy is dependent on what is understood from the communication of the geology model and its domains. This iterative process of data collection prior to design and continuing through construction or mining must also extend into the operating phase to monitor rockmass response and further calibrate the original design-based models of the entire "engineering structure - geological environment" system interaction.

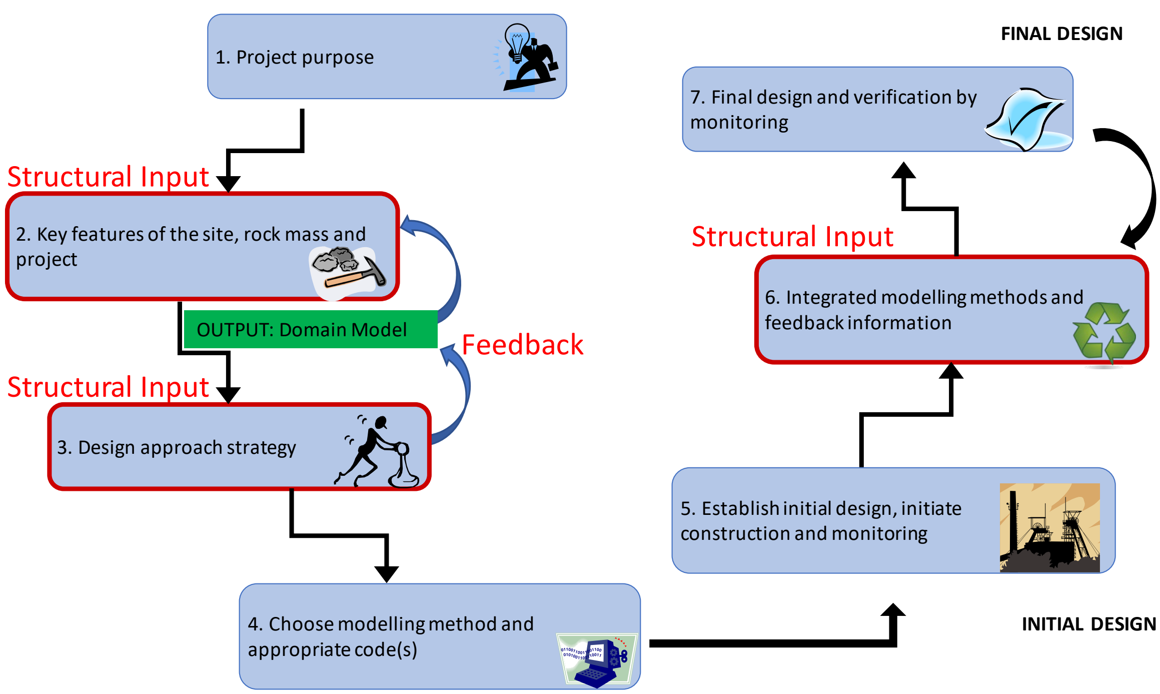

Figure 2: Typical civil or mining construction project workflow, showing where structural geology domain input is likely required to inform the design strategy. Modified after Hudson and Feng, 2007.

Sometimes during construction or into operations, monitoring may highlight deficiencies in earlier understanding which may necessitate updates to the designs or remedial measures even. Usually monitoring provides additional data that in most cases confirms the expected rock-structure interaction response compared with the original design data. However, in some cases unexpected behaviour occurs, that hopefully is monitorable and not too adverse, but certainly warrants further evaluation, sometimes with collection of additional data, and updating of domain extents and domain material properties. In such situations, the geologists involved in the original domaining can often achieve faster understanding of unexpected monitoring feedback (Figure 2), allowing rapid modification of original geological model inputs, thereby facilitating design verification checks. Hopefully in such cases the monitoring has caught the unexpected before failure occurs – as per Case 3 in Figure 2 of Carter, 2018.

2.3. *Domain Scaling*

For a typical project site, the scales of domains that need definition not only change with the scale of the engineering structure under construction, but also change with the scale of the controlling parameter being considered in the design process.

To understand controlling rockmass strength as it applies for a typical blocky rockmass in which or on which most engineering structures are built, three components always need to be understood –

(i) controlling rock block size relative to the engineering structure of concern;

(ii) intact material strength of the defined scale-specific blocks; … and …

(iii) controlling material/fabric character of the material comprising these blocks.

Recommendations for assessing each of these in turn (and at appropriate scales pertinent to typical surface and underground projects) follow in the next few paragraphs.

For a large open pit, for example, rockmass strength and behaviour control may be different at each scale upwards from small height bench scale cuts to the 1000 m high overall pit slope – with kinematics controlling bench scale stability and global rockmass strength controlling overall wall stability. The scale at which a domain needs to be defined in the vertical plane may thus differ depending on whether considering bench or wall scale stability, with more granularity of detail needed for the bench scale problem. This also would be the case for the scale of the domaining necessary in plan geometry – with again greater definition perhaps being needed to consider differences in kinematic condition along the benches than needed for full pit wall scale. In fact, often it can be best to domain the bench scale geology around the entire pit per bench level by "Cell or Window Mapping" techniques so that bench scale stability analyses can be readily accomplished with appropriate data (Priest, 1993). These bench scale domains can then be evaluated and compared level by level so that similarly structured domains (as verified by stereonet plotting) can be grouped together based on consistent joint sets and character to create larger pit-scale domains (commonly called sectors) that will be of a scale size suitable for analysis considerations for global stability.

For tunnels and large underground excavations, the same principles apply – and always the same three components need evaluation – but again at different scales appropriate to the engineering structure design.

For a typical tunnel or bench scale cut in a large open pit if fracture intensity is high such that the size of the controlling blocks is well less than a tenth of the span of the tunnel or the height of the bench face, the controlling rock-block size can be expressed in *GSI* terms utilizing *RQD* or *FF* (P_{10}, Dershowitz & Herda, 1992) for definition of the fracture intensity (Gillespie et al, 1993, Hoek, et al, 2013, Carter & Marinos, 2014). If, however, the size of the blocks is moving towards that of the span of the tunnel or the height of the bench face, then an approach using GSI would be inappropriate as kinematics most likely would completely rule stability assessments. A better volumetric measure than *RQD* would also be advisable – something that captures the geometry much more effectively (e.g., *VFC* per Schlotfeldt and Carter, 2019). This scale of block size, however, relative to the full height pit wall could still be assessed with *GSI*, but now scaled relative to the global rockmass character and strength appropriate for the full wall height.

For tunnels of significant length, several domains may need definition along the tunnel alignment as the geology changes from place to place. In such situations each defined domain in plan length would need to reflect again the same three basic components – each defined appropriately according to the different geology expected to be encountered in each domain. These definitions of geological character per domain, which would of necessity include stereonet plots and definition of joint sets and character, would then in turn define the basics needed for support design – thus setting, for example, rock-bolt length and spacing stipulations.

Rockmass and material characteristics for each lithology within a domain also needs definition, but at appropriate scales for the engineering structure of concern. The same basic information is needed irrespective of scale, but then scale definition of appropriate variability needs to be applied. Whether considering a small tunnel or a large open pit, it would always be expected that there would be a need to determine the basic intact strength of the undisturbed rockmass material.

For a tunnel portal this might be accomplished from just a few lab tests on core from one borehole near the portal. For a large open pit, a database of lab testing on hundreds of samples across the entire pit volume would be expected so that enough data would be available to characterize the rock per sector or even per bench level domain such that adequate statistical reliability is achieved. The lab scale testing would be aimed towards, for example, defining intact compressive and tensile strength parameters and Hoek-Brown m_i values so that design can be conducted at any required prototype scale.

Similarly, description and measurement of discontinuity surface character in terms of *JRC, Ja, Jr, JCond,* etc. also need documenting per domain fabric, and also at scales that are appropriate for the analysis requirements. JRC, for instance, has well documented scale correction relationships that need to be applied, but differently for bench scale or pit scale analyses.

The last component of the three is where pervasive changes occur that may affect both of the other components – here is where alteration and weathering degradation corrections need consideration – also at all scales. In tropical areas, deep weathering may affect whole domains or even sectors or geological regimes through which tunnels are to be driven, or a pit excavated. In other areas, pervasive weathering may only be confined to the uppermost zone of the rockmass along prominent discontinuities – but each aspect of such change in character away from the unaltered, unweathered intact state needs to be captured in the domain definitions, and with sufficient data to be statistically representative at the scale that is appropriate for the engineering structure under consideration. For UCS testing, for example, a minimum of half a dozen weathered samples need testing to one or two intact unaltered samples, as weathering variability can be very much greater than intact unaltered strength variability.

While material characteristics can change quite rapidly from place to place with the geology and fracture character of the rockmass, such that multiple domains may need definition, groundwater conditions may remain similar throughout many domains. Stress state may also remain consistent also through many domains. But both can change in proximity to faults and dykes and major structural boundaries. So where these two change one could consider that one might be entering a different “Regime”. Thus, for a small pit or civil project the entire engineering structure may be sited in just one regime (wherein stress and hydrogeological conditions remain broadly similar, although there may be a number of structural domains around the pit that may control different kinematics). However for a large pit or a long water transfer tunnel of many tens of kilometres length, the engineering project may cross multiple regimes with different stress states or groundwater conditions. Internally though each regime likely would be comprised of many smaller domains.

2.4. Domain Extrapolation

In addition to providing a method for grouping together zones of consistent rock structure and fabric character, domain delineation serves another important, practical function, by allowing the interpolation of structural patterns from a location that is well-supported by data, to a volume of rock that has limited or no data, such as illustrated in the shaded sections within Figure 3.

Projection into each new area within the same domain can then be readily achieved if domain boundaries in the existing area have been well defined and can be reliably extrapolated along known structural trends into the new area of interest, but still within the already defined domain boundaries. Significant faults, (for example those shown in heavy linework in Figure 3), are commonly domain boundaries that can be projected hundreds of metres with quite reasonable confidence. Such faults may, in addition, have been intersected with additional deep drillholes away from the already domained zone, such that the intersections help provide high confidence in continuity (particularly where large intersection widths have been encountered).

Most domains likely will exhibit 2nd or 3rd order structures of limited continuity that will still need to be included in the analyses of the data-deficient parts of the same domain. The extrapolation of a domain’s data to areas of limited data can then be straightforwardly accomplished by porting the known characteristic fabric of the known domain into the data-deficient parts of the same domain but into a data deficient area. Any available data pertinent to the data-deficient parts of the domain should be used to thoroughly verify that the ported structural fabric fits with the “real” data. Stereonets provide one of the best methods for checking that consistency is achieved.

The domain characteristics of the major and minor faults and structures as a system (i.e., defined by frequency, continuity, orientation and physical properties, as observed where exposed), can then be assigned as a controlling fabric entity that would be applicable to all parts of the same domain, such that this “system” can be readily extrapolated throughout the domain for design purposes. For domains where inadequate detail exists across its extent, subsequent infill drilling can then also be programmed to firm up or revise these inferred domain-wide characteristics.

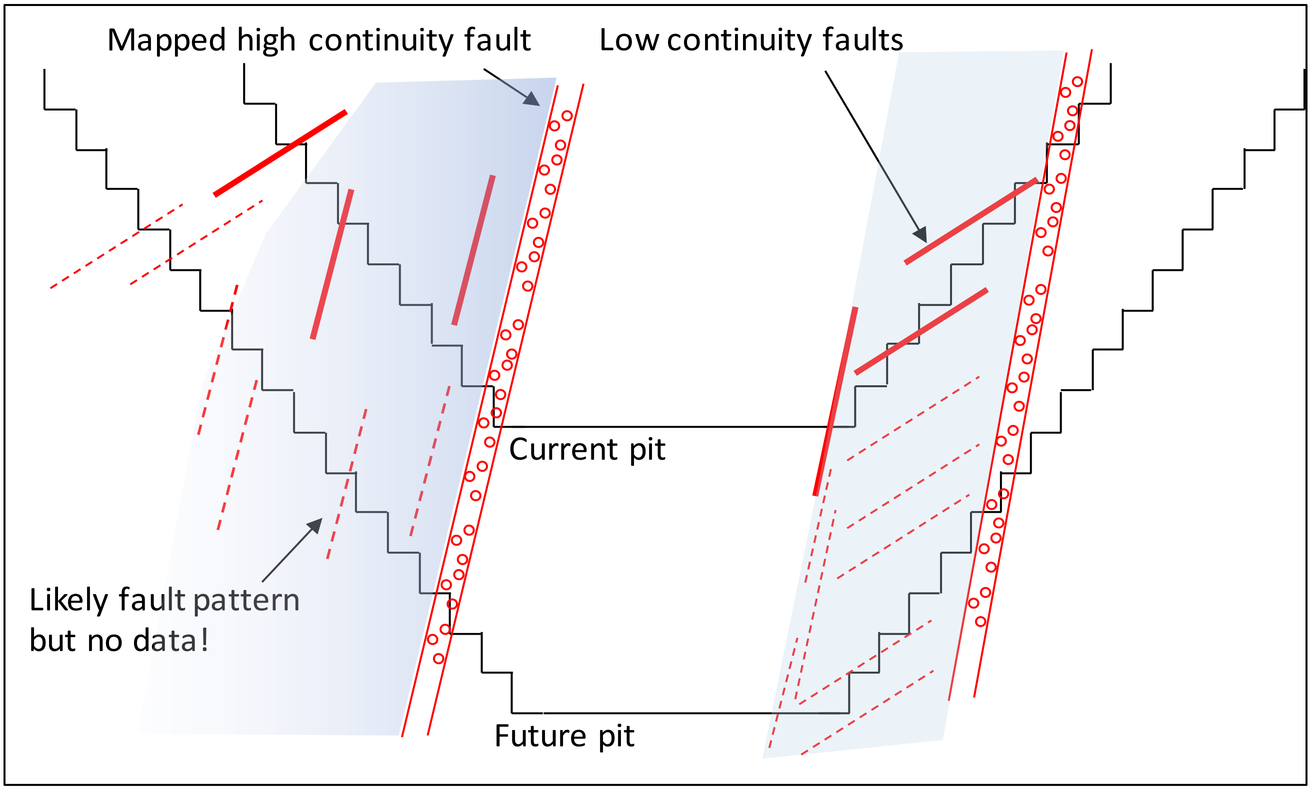

Figure 3: Schematic illustration of structural mapped features in an open pit. Large 1st order structures can be interpreted with continuity to the depths of the planned future pit. Non-continuous 2nd and 3rd order faults lack continuity to be projected to the design pit depth and thus may only be described as part of the rockmass characteristics (inferred dashed faults) of the example domains (shaded blue), inclusive of frequency, continuity, orientation and physical properties.

3. TYPES OF GEOLOGICAL CONTROLS ON DOMAINS

3.1. Bounding Structures

Figure 1 defines two types of domain boundaries. The easiest to characterize are the sharp bounding features, such as a fault or fault zone, or fold axial plane (Nicholas and Sims, 2001). Fault bounded domains often displace the rock units either side of the structure, such that the rock type and rockmass properties may be completely different across the fault domain boundary. Faults also typically cause rotation of any inter-fault blocks relative to the adjacent rockmass. In such cases the pre-fault rockmass fabric most usually will also have been rotated. In some of these types of situations, inter-fault blocks may show significant contrasts also in rockmass quality as well as fabric re-orientation with respect to the two opposite sides of the fault block. In such cases, the whole inter-block zone may warrant being described as a new domain, particularly when the inter-fault block zone is of significant width and of different character to the adjacent rockmasses.

Shear zones, such as that shown in Figure 4 can similarly mark significant change points from one rockmass fabric in one domain to a different one in the adjacent domain. Major shears, such as illustrated, are most commonly regarded as ductile fault zones exhibiting a transitional rather than abrupt strain gradient from one side of the shear zone to the other (Passchier and Trouw, 2005). Displacements across a shear zone can however also be significant and thus major shears and shear zones commonly also can serve as domain boundaries. Lithological contacts (and both disconformities and unconformities) may also constitute domain boundaries when sufficient contrast in characteristics occurs across the change from one rock type to the next. In cases where the properties of the rocks vary significantly from one rock type to another, the structural fabric, joints, foliation and rockmass properties will commonly also change enough to define a new domain. Similarly, a fold axial plane can often also form a distinctive, sharp domain boundary across which the rock fabric has been altered, in this instance by rotation.

Other common examples of sharp lithological domain boundaries are intrusive contacts, such as granitoid contacts associated with porphyry deposits, or kimberlite contacts associated with diamond deposits. These contacts themselves, may, in addition, also be zones of weakness that may have been sheared or altered and may therefore have distinctly different properties necessitating definition of a smaller but still important contact domain.

Figure 4: An adversely oriented pit-scale foliated ductile shear zone (image is approximately 10 m high)

3.2. Zones of Consistent Internal Structure

The second type of domain boundary structure identified in Figure 1 tends to be more difficult to characterize as these types of boundary are essentially gradational. Strain changes affect joint characteristics across a rockmass and may be important enough to mark a zone as a domain boundary.

Typically, such boundaries need to be drawn at locations of maximum strain change, where it is conjectured that a fault-feature might have developed if further strain accumulation had occurred. In many such instances, even though significant rock deformation may have occurred as a result of strain accumulation, often the local strain magnitude has not been sufficient to have created a specific fault plane with adequate displacement such that this would clearly bound the domain. Rather the strain has been distributed over a wider volume of rock thereby changing the rockmass properties through formation of micro-fractures, joints and/or systems of segmented minor faults with limited displacements.

The distribution of strain and associated micro- and macro-structures often causes the rockmass properties in such transitional areas to be sufficiently different from the adjacent margins to form a domain in its own right. In other cases, where the deformation extent is more laterally limited, a transitional boundary may need to be drawn. The boundaries of either of these types of domains may be diffuse and difficult to position precisely. Furthermore, even when a high strain zone is delineated as a separate domain, often within such a domain the fracture frequency, foliation spacing, and micro-fracture intensity may vary significantly over metres (Baecher, 1983). In such situations, delineation of domain boundaries should be guided by project-goal related significant rockmass changes, and by the scale of the required domains needed for the dimensions of the engineering structure under study.

Often in these types of situation a visual assessment of a boundary location may prove difficult. Accordingly, in cases where a gradational domain boundary must be drawn, recourse to use of engineering statistical decision analysis methodologies may help to better position the required boundary. In such cases statistical non-stationarity tests should be considered – see section 4.3.

One situation where transitional boundaries need to be carefully considered is where a fault is enshrouded by a pronounced zone of distributed rock strain, such as often occurs between a fault zone and its adjacent wall rock. Such zones are termed fault damage zones (Kim et al, 2004) and distinguished from the fault core zone itself, as shown in Figure 5, by virtue of the latter zone containing fault breccia and gouge (Caine et al., 1996; Ben-Zion, 2003).

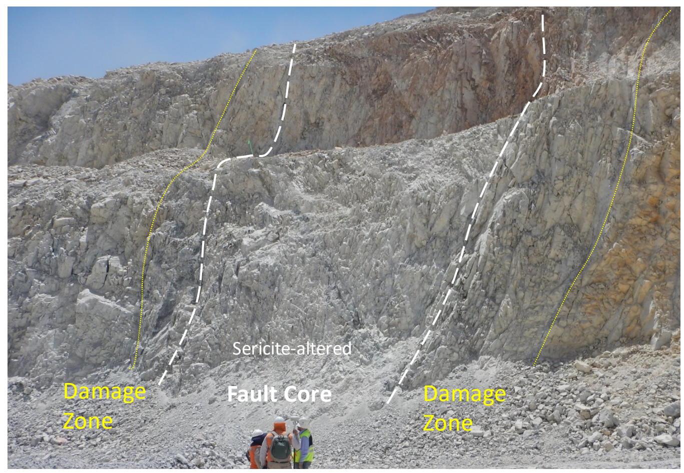

Figure 5: Characteristics and components of a typical large pit-scale fault zone, with clearly defined fault core and damage zone margins that may be transitional with the adjacent jointed country rockmass.

In cases of regional fault zones, such damage zones can be over 100 m in width. Occasionally such damage zones may have relatively sharp boundaries, but more commonly they are represented by a zone with diffuse boundaries as strain and associated fracturing diminishes with distance from the fault core (Faulkner et al., 2010).

Faults and fault zones, and particularly fault damage zones are important controls on groundwater flow and permeability. Dyke margins too, can constitute major permeability channels. Thus, where evidence supports such interpretations, fault damage zones or dyke margins should be considered for groundwater domaining.

Last, but by no means least in influence on domaining, are effects of weathering and alteration. Weathering-related degradation fortunately mostly occurs with diminishing effect with increasing depth. Accordingly, most often, if weathering is significant enough to affect rockmass characteristics in a given structural domain, the influence can be accounted for by introducing a sub-horizontal sub-domain boundary – vertically splitting the weathered from the unweathered rockmass with depth. Where such sub-domaining is necessary care should be taken to observe and account for the probability that deeper weathering may occur associated with structural features – and these zones may merit separate domaining dependent on degree of weathering-induced degradation.

While deep weathered zone influence is rare it can be present associated with unconformities and old palæo-surfaces. More commonly though, weathering effects are only of concern to shallow depth, whereas rock alteration zones may extend to considerable depth associated with the main mineralization of the mine. Significant alteration zones for instance can still be recognized in many deep underground mines and are a common feature of large open pits. In many cases such zones may need to be defined as separate domains, as the alteration may have changed the mineralogy and rockmass properties so much so that the unit bears little resemblance to its parent unaltered character. Alteration, however, often can vary greatly in intensity across a project footprint and is therefore challenging to describe in terms of its impact on the rockmass. Alteration also, like weathering effects, is commonly found (or more intensely found) in spatial association with fault systems that have historically provided permeability for upwelling fluids. Alteration zones may thus be quite difficult to partition as rockmass domains as commonly alteration zones exhibit quite diffuse boundaries. Nevertheless, if geotechnical character changes drastically enough across such zones, they too should be delineated as boundaries in much the same way as recommended earlier for strain change zones.

4. DOMAIN CHARACTERIZATION

4.1. Project Objective

Domain characterization is strongly dependent on the objective of the study. It is thus important to clarify early on with all stakeholders what the objective is and what the final product will look like and how it will be used further in the study. This will condition the detail that will be needed in undertaking the domaining.

The focus should be on defining the attributes of the rockmass that are required for the subsequent analysis. It may sometimes be possible to focus only on a specific problematic lithology, or specific structural system or fabric, rather than on the entire rockmass, thereby saving much time and expense in the domaining.

Typical outputs of the study may be a table description of each domain containing statistical descriptors of the measured and calculated rockmass (Bieniawski, 1989) and rock material (lithotype) parameters (e.g. m_i, UCS_i, E_i, *JRC, Jr, Ja, JCond, GSI/Q/RMR*). The statistical listings that commonly will need to be tabulated are mean value, standard deviation, and extreme values. In cases where statistical results are needed for input into numerical models with discrete structural features, or into discrete fracture networks (DFN's), additional discontinuity descriptors are required (e.g. cohesion, friction angle, and orientation and continuity of discrete features).

More sophisticated computerized estimation tools can be used to produce statistical results in more practically useful formats, like within 3-D block models and fault wireframe geometries that can then be ported directly into 3-D numerical geomechanics models.

4.2. Data Analysis Methods and Analytical Pitfalls

In the process of domaining the rockmass, various methods of analysis will need to be applied in order to adequately capture variability sufficient for design evaluation – usually focusing on stability, but often also on groundwater flow.

Methodologies should focus on the simplest, most accurate approach to correctly document the required information rather than in overly complicating the process with esoteric over-analysis. Thus, tabulation of domain properties in a main report should concentrate on listing simple parametric statistical results and ranges of credibility and reliability. This summary should however be backed up as needed in a data appendix complete with graphical plots and composite 3D images of domain characteristics, plus listings of pertinent other computerized geostatistical estimation details.

Great care however must be taken with use of the more complex geostatistics 3D rendition software as erroneous results are all too easy to generate. Calibration techniques must be routinely employed to ensure credibility of complex results where such techniques are employed. Here only the broad guidelines are outlined, and no description is given of the myriad of all possible geostatistical analysis tools available today, however some of the most common pitfalls (and some practical guidelines to help avoid these) are outlined.

4.2.1. *Analysis Approach*

The first part of any domaining analysis should be to review and understand the data. Typically, for domaining purposes data needs to be collected in each of the different stages of project development with increasing sophistication applied further into the design process. Often available project data when domaining is first initiated is of variably quality and therefore possesses variable ranges of inherent statistical error.

Decisions should be made on how to manage such data when of variable quality and particularly for poor data, documentation should be rigorous on decisions on what data to ignore. Even though often such decisions are made during the analytical process as data value distributions are determined, it is critical to document what and why certain data is not utilized. It has happened that such data might be real and really should be reinforced in order to condition other information (Carter, 2018 provides an example of such a case resulting from not being able to see the wood for the trees, while analyzing mountains of stereonet data, such that a critical joint data concentration was not highlighted by stereonet analyses).

Data collected from drillcore can often be problematic due to core handling issues and poor original logging consistency. While such data can be manipulated and synthesized to yield uniformly based measurements – base data should be collected to ISRM standards so that consistency can be assured. Once raw data on RQD, TCR and SCR are documented, which of necessity must match actual drilling performance and thus will be based on variable lengths of core, it is straightforward to work with the collected data and reprocess it if needed.

Frequently it may be necessary to re-composite the data to equal length sections of core in order to obtain statistically representative values for a domain within a drillhole. This process should however be done in a manner that does not lose vital information about the spatial variability of the data values.

4.2.2. *Parameter Variability*

The most basic inputs required for calculating any of the quantitative (*GSI/Q/RMR*) classification indices are rock strength (*UCS*), fracture frequency (*FF or RQD or VFC*) and joint condition (*JCond, JRC, Jr/Ja*).

Even within a single domain these parameters can vary significantly. In addition, geological controls on their variability are different, viz:

- Rock type and alteration impact *UCS.*
- Variations in geological and mining-induced strain influence the spatial distribution, frequency and orientational anisotropy of fracture systems.
- Variations in geological strain, fluid type and fluid pressure influence joint conditions.

Statistical variography of these parameters can therefore yield very different results. Individual parameters quite commonly must be considered as independent variables. For this reason, combining these parameters into a single rockmass classification value, before having undertaken a variography exercise may lead to non-sensical results. Rather, statistical estimation of the individual component parameters in classifications (viz *UCS, FF/RQD* and *JCond, etc.)* should be done first using variogram statistics, and then locally combined (such as on a block by block basis in a block model) and then incorporated into the overall rockmass classification model afterwards.

4.2.3. *Statistical Estimation Methods*

Commonly used estimation techniques for interpolating geotechnical parameters are inverse distance and kriging, but there is a fundamental problem with both estimation techniques when applied to the evaluation of typical geotechnical data. This is because such data is typically non-additive. This means that adding two nearby *UCS* values (or *FF or RQD* values, or any of the joint condition parameters) produces an averaged value that is not necessarily representative of any part of the domain. It is common, for example, to observe clustering of high *FF or low RQD* values, or two distinct populations of *UCS* (representing altered and unaltered zones). It is therefore preferable to use statistical techniques that generate probabilities of certain geotechnical parameters.

Multiple Indicator Kriging (MIK; Gómez-Hernández and Srivastava, 1990) is one of simplest tools that can produce a probability of a geotechnical parameter being above or below a particular value (e.g. % probability above a specific RMR value) Utilizing conditional simulations (Journel, 1974) provides better results (there are several variants of simulation techniques), but require more advanced computational techniques for determining the probabilities of rockmass classification parameter values being above or below thresholds (e.g. RMR > 50 per the example plots in Figure 6).

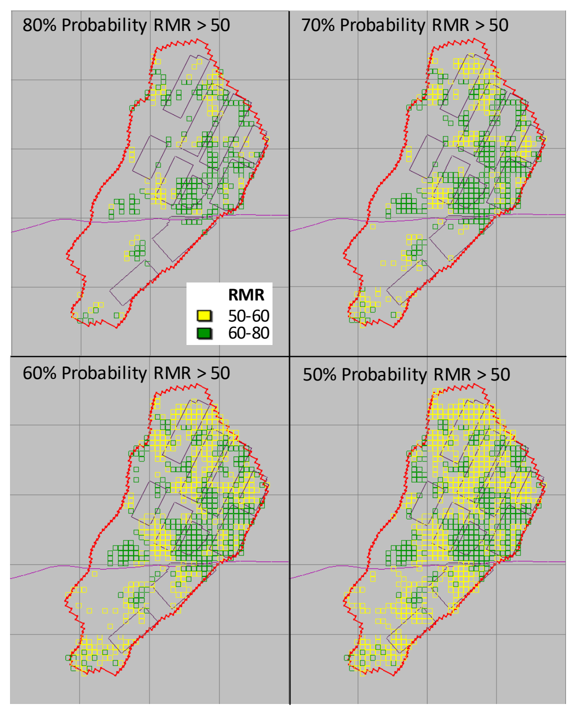

Figure 6: Example product of conditional simulation of porphyry orebody domain (red outline) with rockmass characterization results showing blocks in which estimated RMR > 50, at the stated minimum probability % threshold. Such analysis are useful for risk-based design decisions.

Alternatively, simulations can be applied to determine the spatial distribution of any given parameter (e.g. *UCS*) across a domain at a specific probability.

4.3. Non-stationarity

As discussed earlier, on occasion in some situations it is necessary to explore changes in a specific property progressively as one moves across the rockmass, where it is not possible to determine an average value and statistical distribution for the zone of interest. The geostatistical term for a domain with a consistent mean value and distribution of values is "stationarity" (Clark, 1979; Guibal, 2001). Non-stationarity implies a spatially progressive change in mean and distribution across a volume of interest. Thus, if the rockmass characteristic of interest can be adequately described using non-stationarity statistics, then it is reasonable to define that rockmass volume as a domain.

5. CONCLUSIONS

Domaining in Engineering Geology and Geotechnical Engineering needs more attention in order to better characterize rockmasses for design. Characterization is often undertaken without properly domaining the rockmass around a project site, thus apples and oranges get mixed in parameter groupings. Some methods have been suggested in this paper to improve current practice. Procedures for careful "domaining" of the region around (and including) the project site, are suggested so that unique, unambiguous zoning is achieved of the entire site area of engineering importance.

Throughout this process, it is important to stress that there is always a need to synthesize and simplify complex geology, but without losing the essence of variability in diagnostic conditions. Care must therefore be exercised in undertaking a domaining process to not overly complicate design by creating too many domain divisions. Obversely, too restrictive a domaining approach is also not sensible.

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