

ENGINEERING GEOLOGICAL MAPPING FOR DAM FOUNDATIONS - EXAMPLES FROM RECENT WORK

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ABSTRACT

This paper explores the importance of engineering geological mapping of dam foundations to enable the assessment of engineering geology characteristics that influence geotechnical parameters, analysis and design of dam foundation design.

The paper provides examples from recent project work where foundation data is recorded by the engineering geologist using technology such as drone - mounted Light Detection and Ranging (Lidar). This approach improves the spatial accuracy of mapped geological features and aids the engineering geologist in producing geological foundation records for as built records.

The paper also describes the process for identification and description of geological features exposed at the foundation surface and includes a methodology for description of geological features using Australian Standard AS1726 - Geotechnical Site Investigations to assist with the assessment of the origin of each defect and describe the associated engineering properties.

Correct assessment of engineering properties is critical for developing a foundation geotechnical model and assessing the foundation kinematics. Recent project work has demonstrated that detailed engineering geological mapping is essential in developing a comprehensive engineering geological model and geotechnical model as required by ANCOLD (2020) and IAEG/C25 (2022) guidelines.

1 INTRODUCTION

It is best practice that foundations of large infrastructure dams and those with significant risk profiles are carefully documented from an engineering geology and geotechnical viewpoint to provide a record of conditions which become permanently hidden once construction is complete. This paper focuses on the engineering geological mapping of rock foundations and explores:

- The purpose and historical approach of engineering geological mapping for dam foundations.
- The importance of understanding the geological model, engineering geological model and geotechnical model, and origin of defects in engineering assessment and design.
- The use of technology to aid data collection during engineering geological mapping of foundations.
- The application of engineering geological mapping to design and construction.
- The benefits to asset owners of having detailed engineering geological mapping.

Project work from three recent example projects, 'Project A', 'Project B' and 'Project C' are presented herein and are used to demonstrate the importance of detailed engineering geological mapping for dam construction and post-construction dam needs. 'Project A' focuses on engineering geological mapping undertaken for a dam risk assessment, 'Project B' focuses on engineering geological mapping undertaken for design and 'Project C' focuses on construction phase engineering geological mapping.

2 ENGINEERING GEOLOGICAL MAPPING OF DAM FOUNDATIONS

Throughout the history of dam construction varying levels of engineering geological mapping of foundations have been undertaken - often dependant on available time, budget, resources, technology and perceived needs. The engineering geologist must balance these variables and apply them (as required) to processes such as high-level geological reconnaissance mapping, detailed engineering geological mapping during construction and post-construction engineering geological mapping to fill data gaps identified in the engineering geological model or geotechnical model.

2.1 PURPOSE OF ENGINEERING GEOLOGICAL MAPPING AT DAM SITES

The practice of engineering geological mapping at dam sites extends from initial green field assessment through to the construction and post-construction phases. Initial geological reconnaissance mapping of a proposed dam site provides input to site selection and preliminary design and may feed into later construction stage activities and post construction monitoring. Construction phase engineering geological mapping is typically performed to provide a record of encountered ground conditions for design verification and to guide foundation preparation. Construction phase and additional post

construction engineering geological mapping may be used for future input to risk assessment, forensic engineering and the design of further investigations at the site.

For dam foundation mapping in Australia, guidance is provided by the Australian National Committee on Large Dams' (ANCOLD) Guidelines for Geotechnical Investigations of Dams their Foundations and Appurtenant Structures (ANCOLD, 2020). More explicitly, the ANCOLD guidelines for Concrete Gravity Dams (ANCOLD, 2013) identify adequate engineering geological mapping of a dam foundation as a specific input to determining if 'well defined' strengths and their associated factors of safety can be adopted. Further guidance on engineering geological mapping for engineering purposes and its place in the Engineering Geological Model is provided in the International Association of Engineering Geologists' (IAEG) C25 Guidelines for the Development of Engineering Geological Models on Projects (IAEG, 2023). Several other publications are available that provide more general guidance on the mapping and information gathering process to assist in planning and logistics (e.g., Basic Geological Mapping by Lisle et al., 2011).

The basic engineering geological mapping process is similar for all dam types, however, must be tailored for the specific site and project conditions. Site specific requirements for mapping may be guided by the site geology, access constraints or the availability of resources (personnel and technology).

Engineering geological mapping for dam foundations needs to adequately record ground conditions for purposes specific to dam design and safety that include assessment of:

- The presence of low strength material that may control foundation strength or be susceptible to erosion.
- The presence of leakage pathways.
- The presence of kinematically unfavourable failure mechanisms.
- The adequacy of the rock mass to resist deformation.
- The shear strength of the foundation.
- The appropriate level of the foundation.

2.1.1 Historical Approach

The role of engineering geology in dam construction is well documented since in the early 20th century and mapping of ground conditions is a long - recommended practice. Herbert Lapworth in his lectures describes "geological mapping" and provides examples of the economic benefits to dam construction of adequate geological investigation (Lapworth, 1908) and further describes the importance of investigation trench mapping in dam foundations as part of site evaluation/selection (Lapworth, 1912).

The importance of engineering geology in dam design and construction was further demonstrated throughout the early 20th century following several dam failures that were attributed to geological conditions in the foundation. The failure of the Saint Francis Dam and the loss of more than 430 lives, in part resulting from 'defective foundations' (Wiley, 1928), became somewhat of a catalyst in the United States for the enlightenment of engineers as to the importance of understanding the geological conditions at a dam site (Burwell and Money-maker, 1950).

The basic approach to engineering geological mapping for foundations is relatively unchanged from 100 years ago, with fieldwork focussing on the survey of rock exposures and defects, the measurement of feature orientation (strike / dip, dip / dip direction), properties (e.g., thickness and spacing), and sketching of these features to show their distribution and to allow interpretation of 'unseen outcrops' (Lapworth, 1908). Similarly, the basic tools of mapping remain the same, with early dam foundation engineering geological mapping utilising tools that are still used by geologists today including a pocket-book, compass, clinometer, tape and hammer (Lapworth, 1908).

Through the 20th century, advancements in digital technology were reflected in changes to mapping processes and the introduction of cameras, hand-held GPS, computers and GIS allowed for improvements in data capture and processing. McAffrey et al. (2005) identified that the cost and physical bulk of digital field equipment in the early 2000s was prohibitive to their widespread use, however, accurately predicted that in future these would become "more streamlined physically, durable, with long-life batteries and wireless connectivity". In recent years, engineering geological mapping of dam foundations has moved in step with significant advancements in technology and now regularly includes the use of drones, photogrammetry, digital logging tools and 3D models. However, technology should provide a supporting role as nothing supersedes the importance of physical observations made by an engineering geologist in the field.

2.2 GEOLOGICAL, ENGINEERING GEOLOGICAL AND GEOTECHNICAL MODELS

ANCOLD (2020) describe the progressive development of geological, engineering geological and geotechnical models:

1. Geological Model: a conceptual model based on the tectonic setting and regional geology of the project site.

2. Engineering Geological Model: builds upon the Geological Model, highlights the geological aspects of the project site and present them in a way engineers understand, incorporates field investigations.
3. Geotechnical Model: builds upon the Engineering Geological Model, characterises the geotechnical properties of critical to the project site and is used by civil and geotechnical engineers to assist analysis (stability, groundwater flow, erosion potential etc), incorporates laboratory testing and instrumentation results.

Establishing a geological model will help with understanding the geological setting of dam foundations and dam sites. A good geological model will then be used to inform future ground investigations (geotechnical drilling and engineering geological mapping) and be developed into an engineering geological model and subsequently a geotechnical model. These models will develop and evolve over the life of the asset and assist in inform future design. Geotechnical investigations (engineering geological mapping and geotechnical drilling) will confirm the assumptions made to develop the models or assist in developing and changing the models further. Geotechnical investigations feed into model development and vice versa; the geological, engineering geological and geotechnical models feed into the development of geotechnical investigations.

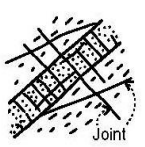
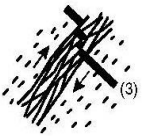
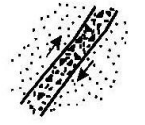

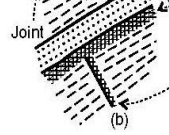
Engineering geologists need to have a good grasp of the civil engineering design intent when undertaking engineering geological mapping so they can better assess and anticipate key ground conditions within the foundation or surrounding rock exposures. From a project perspective, this will require involvement in the design development process with the engineering design team to ensure that the full exposure to the civil engineering design aspect is provided. Without the understanding, engineering geologists run the risk of incorrectly identifying the defect type described in Section 2.3 while undertaking geotechnical investigations and critical engineering geological risks associated with the intended design.

Our example 'Project B' first developed a conceptual geological model using available literature and existing geotechnical investigation information. The model showed the different geological units present at the dam site and large regional type faults. The geological model was then developed into an engineering geological model, followed by a geotechnical model as our understanding of the geological conditions grew as further geotechnical investigations (geotechnical boreholes and engineering geological mapping) were undertaken at the dam site. The geotechnical model shows the distribution of the geotechnical units within the dam foundation as well as investigation data such as engineering geological mapping and laboratory test results. The models have been built using three-dimensional (3D) modelling software to help visual the geological information in three-dimensional space. The geotechnical model was instrumental in informing the geological and geotechnical conditions during dam upgrade design work and assisting in the analysis need to support design.

2.3 IMPORTANCE OF UNDERSTANDING THE ORIGIN OF THE DEFECT

Understanding the origin of geological defects is a key element to assessing the geotechnical parameters needed to undertake design and analysis for dam foundations. Recording the geotechnical properties of each defect in detail during engineering geological mapping assists in understanding the foundation rock mechanics and geotechnical parameter development.

Australian Standard AS1726 - Geotechnical Site Investigations (AS1726) defines a defect as a (natural) “discontinuity, fracture, break or void in the material or materials across which there is little or no tensile strength”. The process in which a defect is formed relates to the geological setting (depositional history) and structural development (phases of deformation) of the project area. Understanding the geological setting and structural development of a project area will guide an engineering geologists initial understanding of what types of defects may be present locally within a dam foundation. A detailed description of the geological and geotechnical properties enables the connection between the two scales (regional and local). The connection between how a defect is formed and its geological and geotechnical properties is described in Figure 1 (Fell et al., 2015). Correlation of geological defects with their intrinsic geotechnical properties is noted in historical engineering geological mapping of dam and hydropower projects such as at Tumut 2 Underground Power Station and Kangaroo Creek Dam by David Stapledon (1961 and 1967).

	DEFECT NAME	DESCRIPTION	TYPICAL EXTENT/OCCURRENCE	FORMED BY
	Joint	Almost planar surface or crack, across which the rock usually has little tensile strength. May be open, air or water-filled, or filled by soil substance, or rock substance which acts as cement. Joint surfaces may be rough, smooth or slickensided.	From less than 1 metre, up to 10 metres.	Shrinkage on cooling (igneous rocks). Extension or shear (any rocks) due to tectonic stresses, or unloading.
	Sheared zone (Fault) (1)	Zone with roughly parallel almost planar boundaries, of rock substance cut by closely spaced (often <50 mm) joints and or cleavage surfaces. The surfaces are usually smooth or slickensided and curved, intersecting to divide the mass into lenticular or wedge-shaped blocks.	More than 10 metres, up to kilometres.	Faulting, during which small displacements occurred along slickensided surfaces distributed across the width of the zone.
	Crushed seam (fault) (1)	Seam with roughly parallel almost planar boundaries, composed of usually angular fragments of the host rock substance. The fragments may be of gravel, sand, silt or clay sizes, often mixtures of these. The finest fragments are often concentrated in thin layers or 'slivers' next to and parallel to the adjacent rock. Slickensides are common in the sliver zones and along the rock boundaries.	More than 10 metres, up to kilometres.	Faulting, during which relatively large displacements occurred within the zone.
	Soil infill seam	Seam of soil substance, usually with very distinct roughly parallel boundaries. Thin seams usually CH; thick near-surface seams sometimes GC or GC-CL (2).	Less than 10 metres, within near-surface mechanically weathered zone, or in rock disturbed by creep or landsliding.	Migration of soil into an open joint or cavity.
	Extremely weathered (or altered) seams	Seam of soil substance, often with gradational boundaries. The type of soil depends on the composition of the host rock.	Varies widely, but extremely weathered seams are usually within or near the near-surface weathered zone.	Weathering (or alteration) in place, of rock substance, usually next to or within a pre-existing defect.

NOTES
(1) In the geological sense.
(2) Group symbols as defined in the United States Bureau of Reclamation Earth Manual, 1963, Figure 3.1.
(3) A 'marker' feature, showing the nature of the displacements. Such features are observed only rarely.

Figure 2.1 Common defects in rock masses.

Figure 1: Figure 2.1 from Fell et al., (2015) describing common defect / features and origins

Whether the engineering shear strength of a rock defect should be assumed to be at peak shear strength or residual shear strength, is inferred by its origin. Rock defects formed through faulting (movement) such as crushed seams, sheared surfaces, sheared seams and sheared zones are assumed to have already overcome peak shear strength to generate movement and are therefore assumed to be at residual shear strength. Rock defects that do not display any form of movement such as partings and joint are assumed to be at peak shear strength as the peak shear strength has not been overcome to generate displacement along the defect. AS1726 provides a framework for defect descriptions and is reproduced in Table 1 with interpretation of the appropriated shear strength applicable to each defect type (peak or residual).

Table 1: Summary of defect types, descriptions origin and engineering shear strength. Descriptions modified based on Table 22, Clause 6.2.5.2, AS 1726-2017, Geotechnical Site Investigations.

Type	Description	Engineering shear strength
Parting ¹	Tensile crack / fabric related. A surface or crack across which the rock has <i>little or no tensile strength</i> . Parallel or sub-parallel to layering (e.g. bedding) or a planar anisotropy in the rock material (e.g. cleavage). May be open or closed. Includes bedding, cross bed, foliation, cleavage partings. Formed without movement of the rock mass and is a part of the rock fabric.	Peak shear strength – rock on rock contact.
Joint	See Figure 1 above. Tensile crack. Formed without significant movement of the rock mass.	Peak shear strength – rock on rock contact.
Extremely Weathered Seam	See Figure 1 above. Weathered in-situ material. Shear strength depends on the extent of weathering across the seam and consideration should be made on the scale and thickness of the defect.	Peak shear strength – soil/rock strength.
Infilled Seam	See Figure 1 above. Opening infilled with transported material. Scale and thickness are important, and soil characteristics should be described, especially plasticity.	Residual shear strength – soil strength.
Sheared Surface ²	Fault related surface. A near planar, curved or undulating surface which is, polished or slickensided and which <i>shows evidence of shear displacement</i> . Formed by movement.	Residual shear strength – rock on rock contact.
Crushed Seam	Fault related seam. Seam of <i>soil material</i> with roughly parallel almost planar boundaries, composed of <i>disoriented, usually angular fragments of the host rock</i> material which may be more weathered than the host rock. The seam has <i>soil properties</i> .	Residual shear strength – soil and rock fragment interaction.
Sheared Seam	Fault related seam. Seam of <i>soil material</i> with roughly parallel almost planar boundaries, composed of soil materials with roughly parallel near planar, curved or undulating boundaries cut by closely spaced joints, <i>sheared surfaces</i> or other defects. Some of the defects are usually curved and intersect to divide the mass into lenticular or wedge-shaped blocks.	Residual shear strength – soil strength integration.
Sheared Zone	Fault related zone. <i>Zone of rock material</i> with roughly parallel near planar, curved or undulating boundaries cut by closely spaced joints, <i>sheared surfaces</i> , crushed seams, sheared seams or other defects. Some of the defects are usually curved and intersect to divide the mass into lenticular or wedge-shaped blocks.	Residual shear strength – combination of rock on rock contact and soil / rock interaction.

3 ENGINEERING GEOLOGICAL MAPPING TECHNIQUES

The fundamentals of engineering geological mapping have not changed significantly over time however, the techniques used to acquire and document data has significantly improved, largely as a result of improvements in technology and because of standardisation. Recent projects have utilised drone survey and imagery to complete engineering geological mapping in an efficient and effective manner. They have also used mobile photograph applications to take and document photographs of defects as well as recording defect characteristics using scanline mapping techniques.

3.1 USE OF TECHNOLOGY TO AID IN DATA COLLECTION

Engineering geological mapping of dam foundations was originally performed using traditional survey techniques with basic instruments such as grid paper and measuring tapes and utilised photographs where available (e.g. photographs taken from above in crane boxes during construction). As technology has advanced and become more readily accessible, engineering geological mapping techniques now include tools such as digital cameras and compasses (including mobile phones), drones, hand - held GPS and LiDAR, that have significantly improved the quality and speed in which geological data can be captured and documented.

3.1.1 Unmanned Aerial Vehicles (UAV or Drones)

Technology such as UAV or drones can assist the engineering geologist during mapping to improve accuracy and efficiency. Images captured by drones of cleaned foundations can be used to generate base maps that enable the engineering geologist to spatially capture geological features with a high degree of accuracy, in terms of feature shape, length, width and position. Engineering geological mapping can be carried out by hand on sheets overlaying the base map utilising drone imagery. This method allows for efficient data collection and line work compared to other methods such as grid paper using a chainage and offset approach.

Drone images can help engineering geologists identify the large scale geological features that might not be clear when standing on the ground. The image captured provides a bird's eye view of a dam foundation or rock outcrop and geological features with a long persistence will be easier to spot and trace. This helps to reduce bias in data collection and allows for defect persistence to be recorded more accurately.

In some cases, drone imagery might be captured during or after mapping has been completed. The engineering geologist is then able to transpose their work onto the latest imagery, adjusting and amending line work as required.

Drone images of cleaned foundations also provide a good photographic record of construction to supplement the engineering geological mapping sheets produced by the engineering geologist.

In our example 'Project A', drone images were captured part way through engineering geological mapping (during the foundation cleaning process), allowing the engineering geologists to mark out and record coordinates for mapping control points. These control points were used to geospatially rectify the images captured by drone. The engineering geologists on site were then able to quickly record geological boundaries and defects / features allow for more time to be spent describing geological and geotechnical properties and addressing the design purpose the engineering geological maps needed to address. Drone images streamlined the mapping workflow and allowed for efficient data collection over a short time frame. An example of the aerial imagery capture by drone is presented in Figure 2 and the corresponding engineering geological mapping is presented in Figure 3.

In our third example 'Project C', high resolution drone images were captured daily throughout the foundation preparation process by project surveyors, with timing scheduled around the morning and lunchtime construction breaks to maintain project consistency with other teams. The geospatial accuracy of these images was very high (centimetre - scale image resolution) and the resulting base images also contained valuable foundation level information and key foundation control point information that defined the extents of discrete construction lots. An example image is presented in Figure 4.

The resulting engineering geological mapping was able to document geological features to a high resolution while also accurately recording foundation levels. The foundation images, engineering geological mapping and levels were then stored and manipulated digitally as the construction work progressed, allowing an as-constructed foundation model to be produced using 3D geological modelling software. The high level of documented foundation detail will be invaluable in the event that foundation conditions should need to be interrogated in future (e.g. during future safety review or future risk assessment).

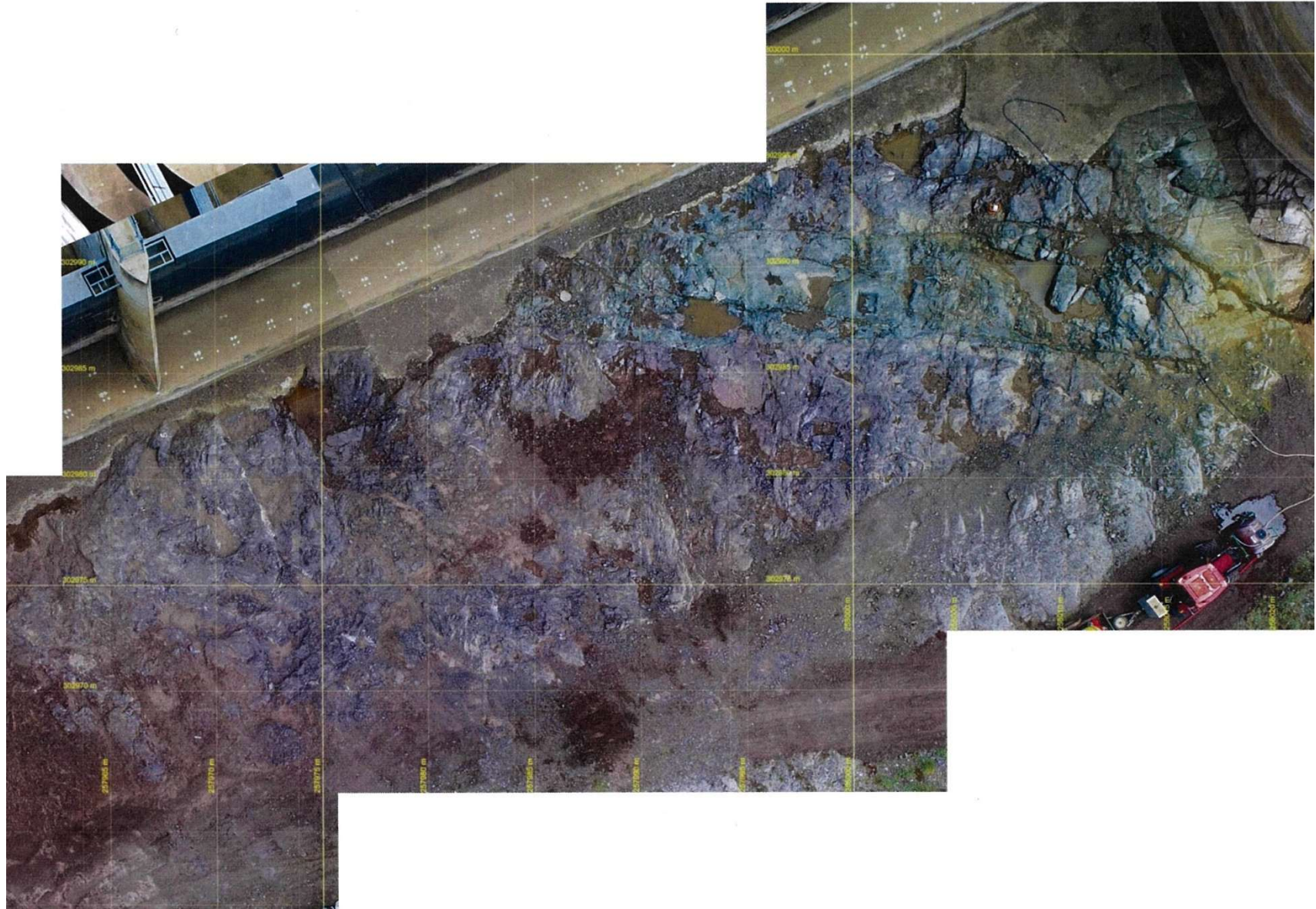


Figure 2: ‘Project A’ base map created from stitched drone images. The drone imagery has captured the rock foundation near the end of the cleaning process. Different lithologies can be identified by the different colours of the rock and defects can be identified as lineaments

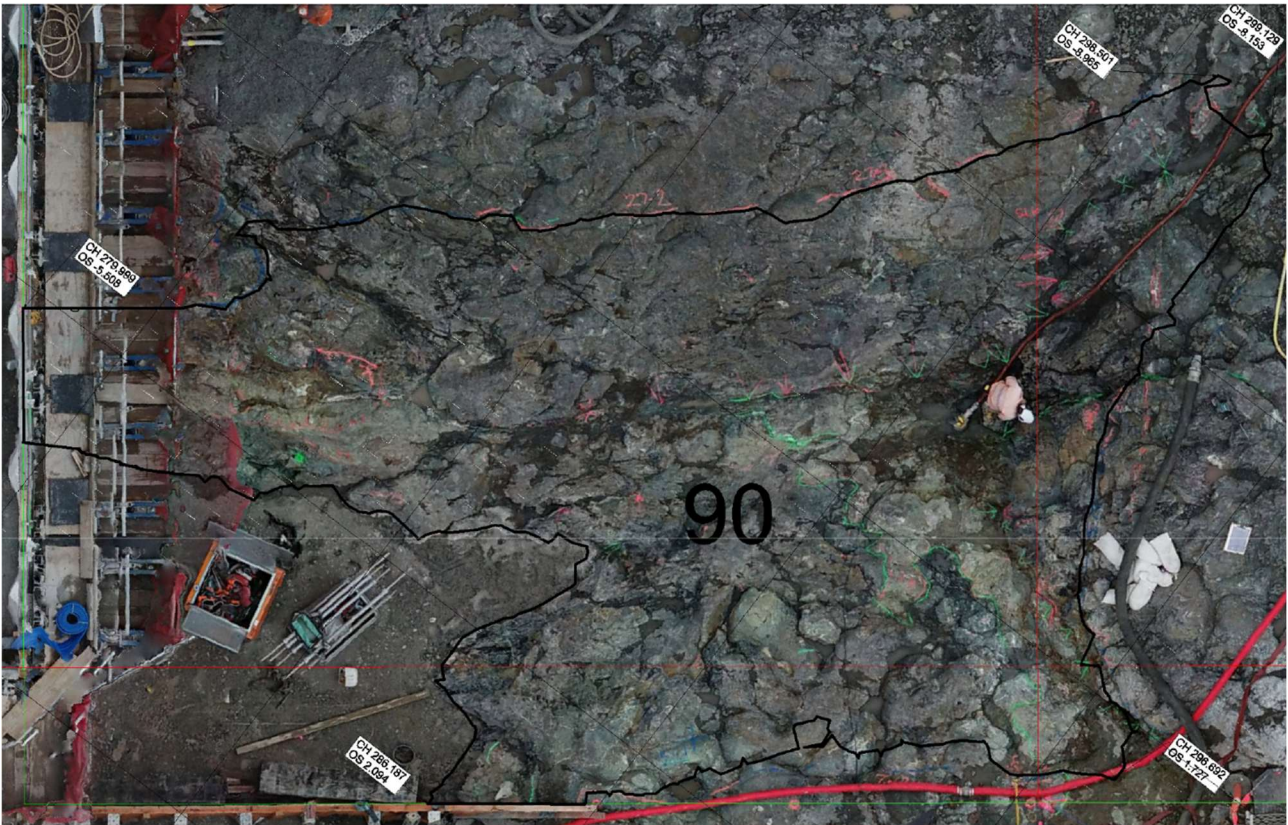


Figure 4: “Project C” example of a base mapping sheet for a specific foundation area showing foundation extents and construction limits. In the example, foundation lot 90 is delineated by the black outline and engineering geologists used this aerial image to complete engineering geological mapping for this foundation lot

3.1.2 Photographs

A consistent documentation process undertaken as part of engineering geological mapping includes providing a photographic record of mapped geological features such as lithologies, geological faults and rock defects. These photographs supplement the engineering geological mapping sheets and are valuable tools for communicating to others the geological conditions of the site. Nowadays, the cameras inbuilt into cell phones are of better or equal quality to that of basic digital cameras making this a readily available tool for engineering geological mapping.

In our examples ‘Project B’ and ‘Project C’, hundreds of photographs were taken during engineering geological mapping. Photographs captured each mapped defect and geological features, as well as general photographs of each mapping lot or cleaned rock outcrop. The volume of photographs highlights the need to have an effective and efficient data management system to track and store all the photographs. Photographs were marked on mapping sheets with an identification (ID) and a direction arrow to denote the field of view the photograph has captured. Photographs were taken using a camera application that watermarked photographs with geospatial information such as, the GPS position the photograph was taken from, what direction the photograph is looking in and the feature number and photograph ID. These photographs will be reviewed in the future alongside the mapping sheets throughout the life of the dam.

3.2 DEFECT DATA

The importance of recording detailed data during engineering geological mapping was highlighted during the construction boom of large infrastructure during the 1960s to 1980s, where the emphasis was on meticulous collection of observational data and accurate descriptions of materials and processes (Legget, 1979 and Griffiths, 2014). Observations taken in the field by engineering geologists are crucial to later phases of design and understanding foundation conditions. Figure 5 from Griffith (2004) highlights the information that engineering geology maps should contain and the importance of understanding the purpose of this information and why it is being documented.

Table 8. Data to be recorded on an Engineering Geology map (Griffiths 2004)

Geological data

- Map units (chrono- and/or lithostratigraphy)
- Geological boundaries (with accuracy indicated)
- Description of soils and rocks (using standard engineering codes of practice)
- Description of exposures (cross-referenced to field notebooks)
- Description of state of weathering and alteration (note depth and degree of weathering)
- Description of discontinuities (as much detail as possible on the nature, frequency, inclination and orientation of all joints, bedding, cleavage, etc.)
- Structural geological data (folding, faulting, etc.)
- Tectonic activity (notably neotectonics, including rates of uplift)

Engineering Geology data

- Engineering soil and rock units (based on their engineering geological properties)
- Subsurface conditions (provision of subsurface information if possible; e.g. rockhead isopachytes)
- Geotechnical data of the engineering soil and rock units
- Location of previous site investigations (i.e. the sites of boreholes, trial pits, and geophysical surveys)
- Location of mines and quarries, including whether active or abandoned, dates of working, materials extracted and whether or not mine plans are available
- Contaminated ground (waste tips, landfill sites, old industrial sites)
- Man-made features, such as earthworks (with measurements of design slope angles, drainage provision, etc.), bridges and culverts (including data on waterway areas), tunnels and dams

Hydrological and hydrogeological data

- Availability of information (reference to existing maps, well logs, abstraction data)
- General hydrogeological conditions (notes on: groundwater flow lines; piezometric conditions; water quality; artesian conditions; potability)
- Hydrogeological properties of rocks and soils (aquifers aquicludes, and aquitards; permeabilities; perched water tables)
- Springs and seepages (flows to be quantified wherever possible)
- Streams, rivers, lakes and estuaries (with data on flows, stage heights and tidal limits)
- Man-made features (canals, leats, drainage ditches, reservoirs)

Geomorphological data

- General geomorphological features (ground morphology; landforms; processes; Quaternary deposits)
- Ground movement features (e.g. landslides; subsidence; solifluction lobes; cambering)

Geohazards

- Mass movement (extent and nature of landslides; type and frequency of landsliding; possible estimates of runout hazard; snow avalanche tracks)
- Swelling and shrinking, or collapsible, soils (soil properties)
- Areas of natural and man-made subsidence (karst, areas of mining, over-extraction of groundwater)
- Sand and dust hazard, mainly but not solely in areas of limited vegetation cover
- Flooding (areas at risk; flood magnitude and frequency; coastal or river flooding)
- Coastal erosion (cliff form; rate of coastal retreat; coastal processes; types of coastal protection)
- Seismicity (seismic hazard assessment)
- Vulcanicity (volcanic hazard assessment)

Figure 5: Extract from Griffiths (2004) Table 8 - Data to be recorded on an engineering geology map

In our example 'Project B' defect data was captured using a scanline template developed from Wyllie and Mah (2004) presented in Figure 6. The standardised template was implemented to assist the engineering geologists in recording the relevant geotechnical data in a methodical and consistent manner. AS1716 was used as a framework for the defect descriptions recorded on the scanline sheets.

4.1 UNDERSTANDING DATA FROM ENGINEERING GEOLOGICAL MAPPING

Engineering geological mapping should provide a multitude of geology and geotechnical data of the dam foundation or surrounding rock exposures that needs to be processed in such a way that it can be used to input into design or analysis. The collected data needs to be able to answer the purpose which it was intended for – the design / analysis needs and objectives.

Engineering geological mapping data provides an opportunity to characterise geological features / defects in a way that geotechnical drilling does not allow for. Geotechnical drilling provides a small physical sample (millimetre / centimetre scale) with the expectation to inform the geological and geotechnical conditions of a large area (boreholes are often hundreds of metres apart), whereas engineering geology mapping is undertaken on rock exposures (large areas) and provides larger scale (metres) geological / geotechnical information. This enables the engineering geologist to see more of the foundation conditions on the basis that more rock is exposed. Geological features can be traced into the foundation and matched with defects when engineering geological mapping is paired with geotechnical drilling data.

Understanding of the geological and geotechnical characteristics of geological features allows for design to be undertaken with more certainty. ANCOLD (2013) has specified that engineering geological mapping is one of the requirements to achieving ‘well defined’ parameters. For many existing dams, engineering geological mapping undertaken during construction does not contain enough detail to satisfy the ‘well defined’ criteria and additional engineering geology mapping of nearby rock exposures maybe a necessary step to try achieving ‘well defined’ parameters.

Data from engineering geological mapping can be brought back into the engineering geology model and / or geotechnical model to undertake the processes shown in Figure 7.

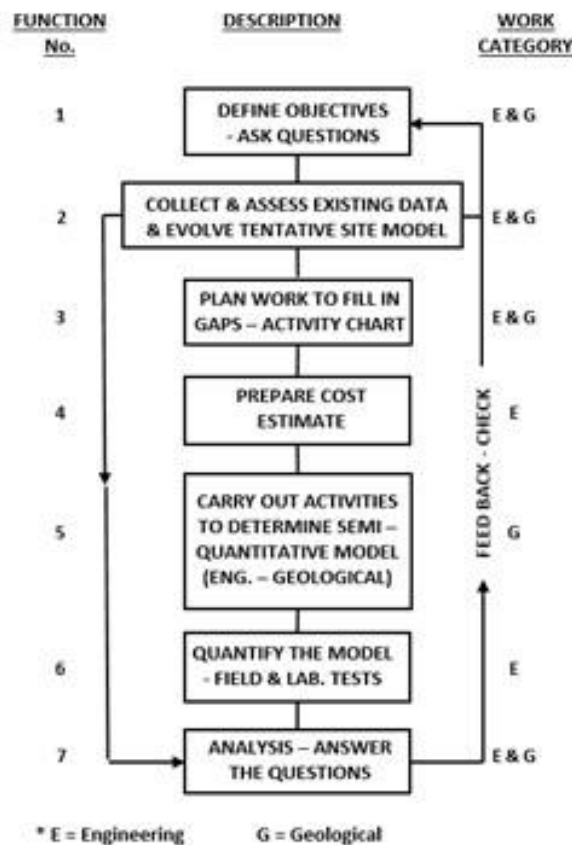


Figure 7: Extract from Stapledon (1982) showing the proposed approach to how investigations and design / analysis integrate with one another

In our examples ‘Project B’ and ‘Project C’ engineering geological mapping has been incorporated into the engineering geological models and geotechnical models. This data has been used to assist in understanding and communicating the

geological conditions within the foundation and to identify further data gaps where future geotechnical investigations may be required.

4.2 DEVELOPMENT OF KINEMATIC SECTIONS

Kinematic sections are required to allow assessment of foundation stability for different potential failure modes including those identified in ANCOLD (2013 and 2020). The guidelines illustrate eight basic modes of kinematic failing to be assessed. Sliding within the foundation, along kinematically viable failure surfaces and overturning at the base of the kinematically viable failure surface are highlighted as the most important potential failure modes for concrete gravity dams (Figure 8). Engineering geological mapping data should be sufficient in detail to allow for the development of sections that reflect foundation conditions at different sections of a dam and hence the development of kinematic sections based on that data.






Detailed engineering geological mapping (1:100 and 1:50 scale) will assist in identifying potential failure paths within the foundation. Different failure paths and potential failure modes may exist for different areas a dam, and it is important that the geological mapping is able to document geological defects / features and their geotechnical properties that will contribute to these potential failure pathways and failure modes.

To develop suitable kinematic sections, defect characteristics / sets should be defined using data collected during engineering geological mapping (construction or subsequent investigations). Each set will have an influence on foundation stability. Defect sets of a low angle (dipping upstream or downstream) will create potential sliding surfaces, whereas steeply dipping defects sets with a similar strike to a dam's axis can act as back release surfaces. For each defect set, an average orientation, defect type, persistence, spacing, wavelength, shape and roughness can be determined from engineering geological mapping data. Defect sets can then be presented on kinematic sections representing real defect data.

Engineering geological mapping provides large (metre scale) and small (millimetre) scale defect data. True defect roughness, shape, waviness and persistence cannot accurately be determined by geotechnical drilling data. Defect data gathered by drilling only shows the small scale geotechnical properties which are not always incorporated into stability analysis. The large scale geotechnical properties will likely govern stability, however this is dependent on their nature.

Kinematic sections developed for our example "Project B" have combined engineering geological mapping data from different phases of investigations. Engineering geological mapping completed at the time of construction does not adequately describe the geotechnical properties of each mapped geological feature and therefore only orientation data and defect type have been included in the development of project sets (Figure 9). Subsequent engineering geological mapping has documented the geotechnical properties of over 1000 defects (predominantly crushed seams and sheared seams / zones as they have been assessed to govern dam stability), allowing for development of defect sets, their geotechnical properties and detailed kinematic sections (Figure 10).

Kinematic sections have been developed for each dam foundation area (left abutment, primary spillway and right abutment) to cater for differences in dam load conditions and also for different geological foundation conditions. Using mapping data collected in each area to address the different potential failure modes, the changing orientation of the dam axis and geological conditions across the site. The foundation conditions do not allow for defect data to be easily matched between boreholes; therefore, geological mapping has been pivotal in enabling stability analysis to be undertaken. An example kinematic section is presented in Figure 11. Geological materials sampled during mapping has allowed for the refinement of preliminary geotechnical parameters.

Mode	Condition	Comments
1. Shear along concrete-rock contact 	Shear along weak discontinuity at or near concrete–rock contact.	<p>Possible if weak foundation or poor excavation and/or foundation treatment.</p> <p>Infrequent mode. Check for condition, particularly in old dams.</p>
2. Development of non-compression zone leading to shear 	Development of non-compression zone (a computed crack) leading to shear along the concrete–rock contact.	Can occur even in good foundations.
3. Shear along planar discontinuity 	Shear along planar or near planar discontinuity in rock foundation.	Frequent mode.
4. Shear along stepped discontinuities 	Shear along stepped discontinuities or along surfaces stepping down between parallel discontinuities in rock foundations.	<p>If step(s) not large then failure surface may be approximated by an inclined plane.</p> <p>Large steps may require higher level of analysis.</p>
5. Shear through jointed rock mass 	Shear through highly jointed rock mass (both natural or blast induced) or through weak rock mass.	<p>Infrequent mode.</p> <p>May be used in moderately jointed rock masses (with an adjustment to the assigned Hoek-Brown rock mass strength).</p> <p>Failure surfaces usually approximated as being planar.</p>



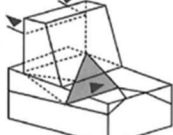
Mode	Condition	Comments
6. Shear along combined discontinuities 	Shear along a combination of two or more discontinuities.	<p>Occasional: usually assume planar mode (3) during initial assessment.</p> <p>Limit equilibrium analysis can be used for more detailed analysis.</p>
7. Toppling 	Loads at toe of dam causing toppling of bedded rock formation.	<p>Infrequent but should be evaluated in bedded or highly jointed (parallel) rocks.</p> <p>If dam heel lifts block may continue movement by shearing through toe (mode 2).</p>
8. Wedge 	Wedge formed beneath block by combination of major faults, shears and/or joint sets.	<p>Infrequent but should be evaluated where major features such as faults/shears cross foundation and combine with jointing.</p> <p>Rigid body, 3-dimensional analysis.</p>

Figure 8: Extracts from ANCOLD (2013) (Figure 7.1 and 7.2) illustrating kinematically feasible failure modes

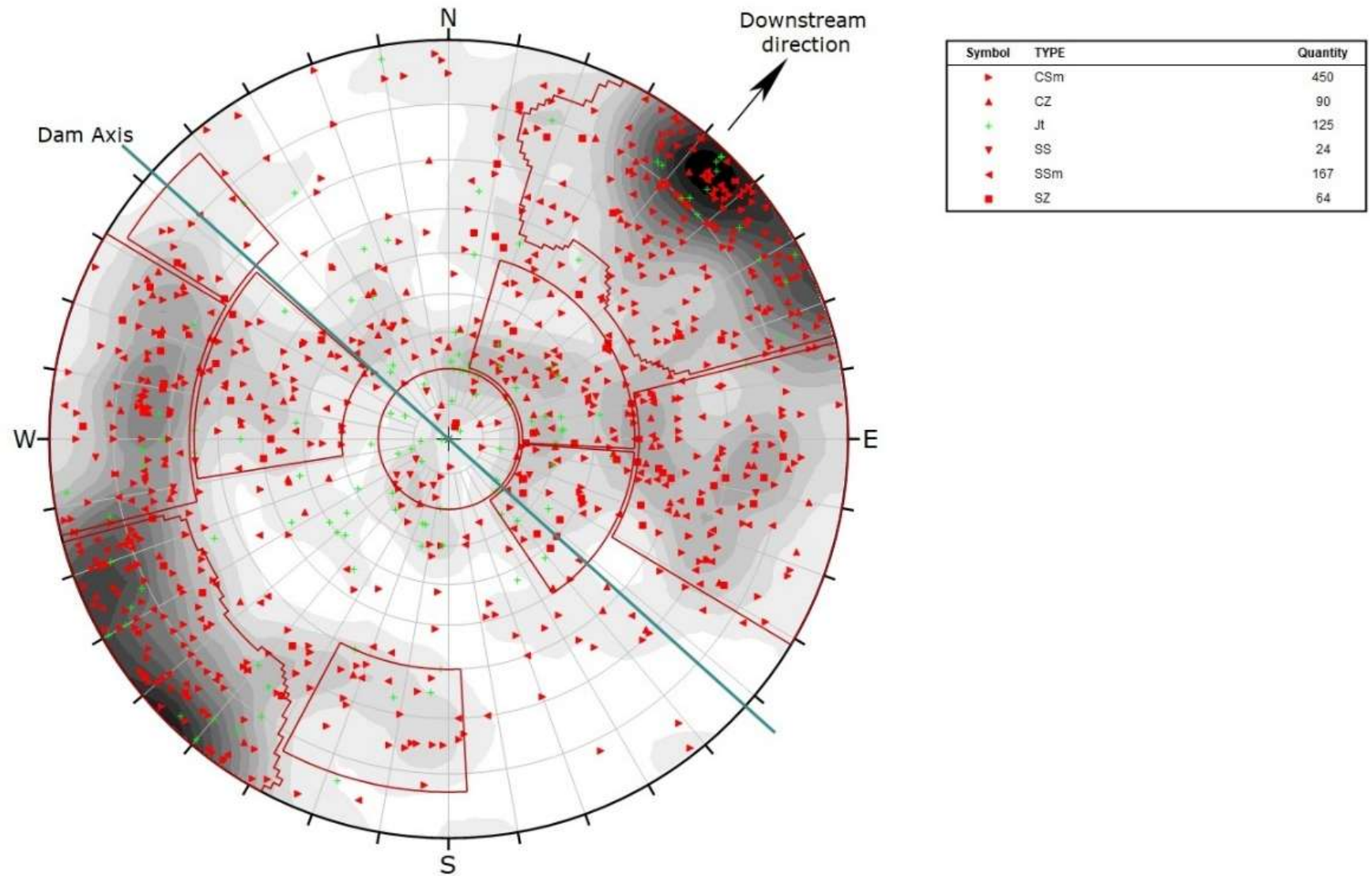


Figure 9: Stereographic projection of engineering geological mapping data from 'Project B', identifying set windows of defect data documented during engineering geological mapping

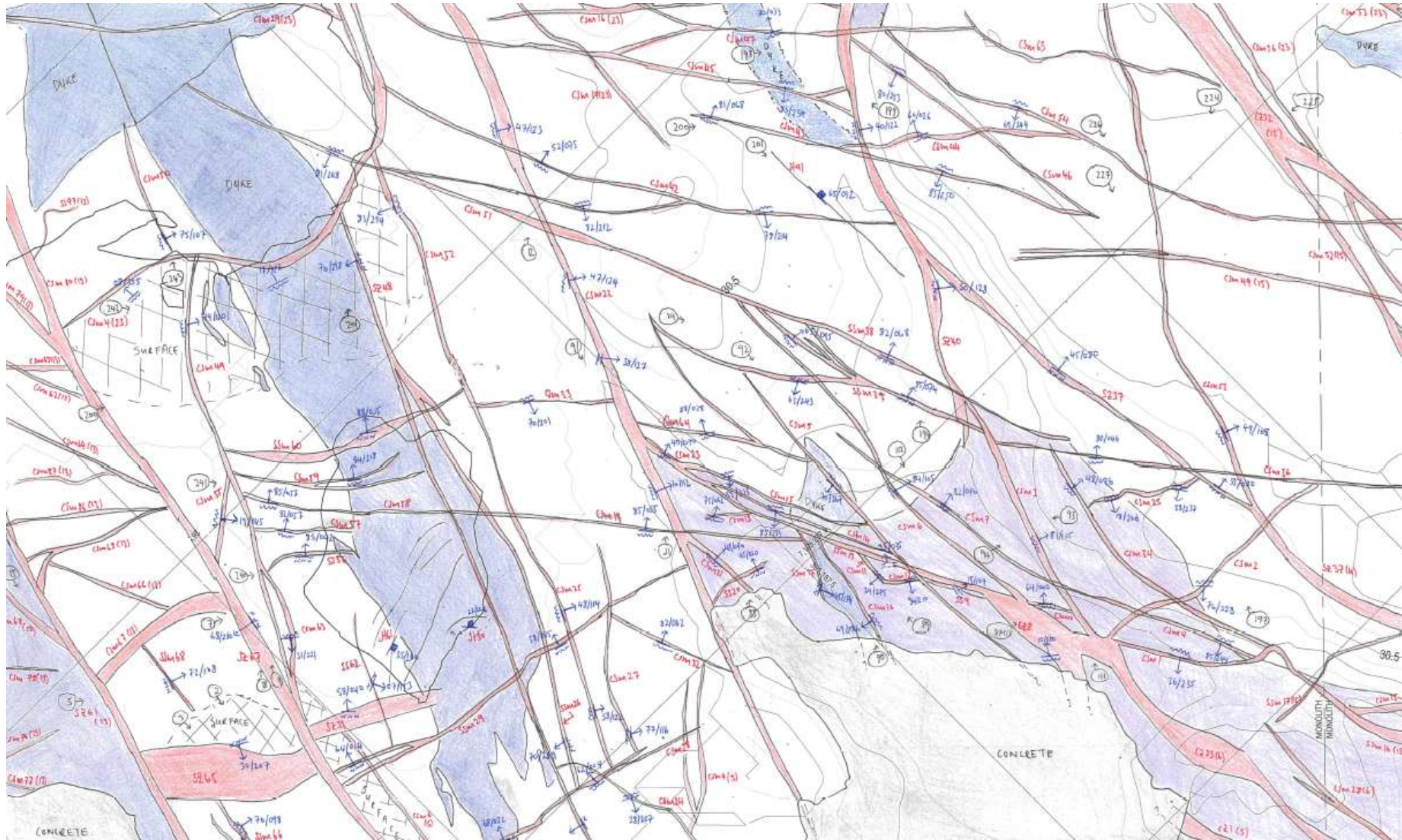


Figure 10: Engineering geological mapping sheet from example 'Project B', mapping has been undertaken at 1:50 scale showing key defects and lithology outlines. Key defects are identified as defects likely to govern dam stability and are important to assess dam stability

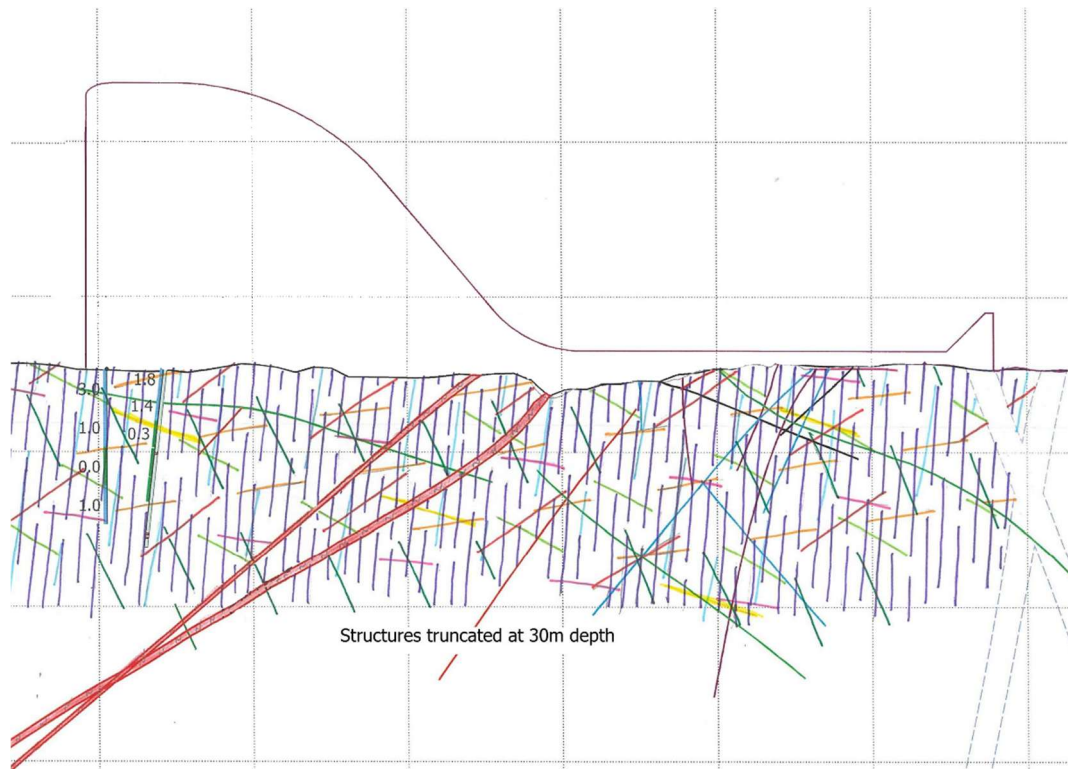


Figure 11: Typical kinematic section for dam stability assessment from ‘Project B’. Project defect sets are shown in different colours, the persistence and spacing of each set as been determined from engineering geological mapping

4.3 FOUNDATION EXCAVATION AND MAPPING DURING CONSTRUCTION

The role of an engineering geologist on site during construction is to assess that a suitable foundation material has been achieved during excavation, adverse kinematic blocks are removed, adverse geological features are treated, and the final foundation surface has been engineering geologically mapped before construction materials are placed. The engineering geologist is often under a tight timeframe / budget to complete all these tasks to allow construction to progress as planned. It is important to budget enough time to allow the engineering geologist complete detailed engineering geological mapping as once the foundation is covered by concrete or construction materials it is not seen again, and the mapping data will be relied upon throughout the life of the asset. The design and construction team should be aware of the importance of engineering geological mapping and the role it plays as part of the overall excavation, preparation and material placement process during construction.

As is the nature of dam construction sequencing, the foundation is often revealed gradually and sporadically, and progress is typically at the whim of the construction process. Adequate personnel and processes should be in place to account for this uncertainty, and a full time site presence is therefore typically required on larger projects to ensure that a record of the foundation can be made with minimal impact to construction activities.

The engineering geological mapping should document the key geological features that may influence and govern dam stability. Due to time constraints, it is not possible to map every defect, so it is important the engineering geologist understands the engineering geological model and / or geotechnical model to help identify the key geological features.

In the event that encountered ground conditions are not as anticipated, a feedback process should be in place that includes independent assessors, designers and constructors to ensure agreement is reached as to a particular course of action (e.g., additional excavation, stabilisation or re-design). A Foundation Inspection Committee has been found to be a favourable way of managing this process and helps avoid a potentially adversarial relationship between engineering geologist, designer and constructor due to competing project drivers. The project lead engineering geologist is a key member of the Foundation Inspection Committee.

Construction phase engineering geological mapping of dam foundations typically seeks to provide a record of the rock mass for the purpose of guiding foundation preparation, verification of design and as a future record of the ground conditions encountered. The process of verification may reveal conditions that are adverse and were not anticipated that may require additional design consideration and / or construction activities (and ultimately cost); it is therefore vital that

the mapping process forms part of the construction quality assurance (QA) process (e.g., as part of the Specification and Inspection and Test Protocols). Engineering geological mapping should form a hold point in the construction QA process and the requirements of mapping should be clearly stated in the construction specification.

In our example 'Project C', it was important engineering geological mapping documented the crushed seams, sheared seams and sheared zones located at the boundaries of different geological lithologies as they were assessed to government dam stability. Engineering geologists on site were responsible in ensuring that foundation met the specified design criteria, that no adverse material had been left within the foundation and kinematically adverse features had been either be appropriately treated or removed. Engineering geological mapping formed a hold point within the construction sequence, before the Foundation Inspection Committee would meet to agree that all the additional hold points had been completed to a satisfactory standard, such as the foundation and mechanical clean down. Once all the hold points have been signed off and the Foundation Inspection Committee was satisfied with the foundation preparation, concrete placement was able to commence. Engineering geological mapping was incorporated into the engineering geological model in almost real-time and used to inform the engineering geologists on site of potential adverse kinematic blocks in future foundation lots. An example mapping sheet is presented in Figure 12, this mapping sheet was produced utilising the base mapped present in Figure 4 in Section 3.1.1.

Throughout the life of a dam, there is a requirement to undertake risk assessments and dam safety reviews to ensure that the asset is still safe and performing as intended. Engineering geological mapping will be assessed and relied upon to inform stability and erosion assessments. As outlined in Section 3.2, engineering geological mapping data should record the geological engineering properties of the rock mass and geological features / defects as this will directly inform the assessments.

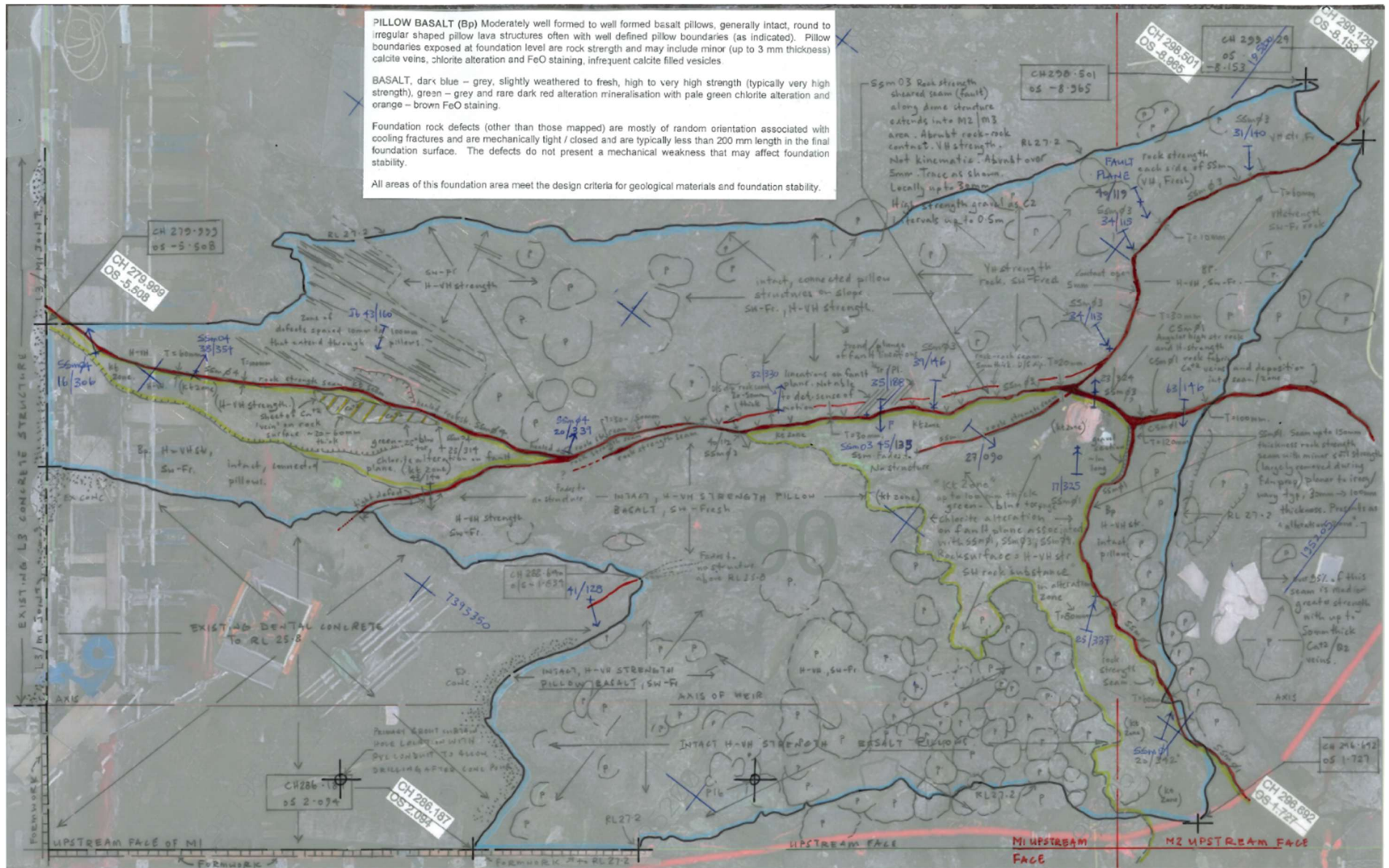


Figure 12 “Project C” example of final mapping sheet for the foundation area shown in Figure 4. Note the manual production method for the mapping sheet overlay.

4.4 KEY BENEFITS TO THE DAM OWNER

Throughout the life of a dam, the dam must comply with dam regulatory bodies and meet current day regulations. A dam will be expected to have regular risk assessments and dam safety reviews carried out and may even need upgrades to meet newer regulations. Detailed engineering geological mapping will be advantageous to owners in terms of time and budget. If engineering geological mapping undertaken during construction and subsequent investigations are completed to a high standard and have captured sufficient geological defects / features and geotechnical parameters, it will be adequate to assist in the required safety reviews and risk assessments and subsequent tasks / assessments. For existing dams where engineering geological mapping completed during construction has not been able to capture the required detail (due to time, budget and technology constraints), owners will need to undertake further investigations to answer gaps in the existing data. This not only adds financial costs to owners, but it also adds to the time taken to complete the safety review or risk assessment.

Where dams are required to undergo upgrades to meet present day regulations, detail engineering geological mapping will again be advantageous to the owner. As outlined in Section 4.1, engineering geological mapping allows for more certainty in design and gives owners the opportunity to achieve 'well defined' parameters. To gather geological data is a costly and timely exercise if no detailed engineering geological mapping is available.

In our example 'Project A', data gaps were identified during a risk assessment of the dam and no engineering geological mapping was available for the dam. Unfortunately for the owner, this meant engineering geological mapping needed to be undertaken at additional cost and time to fill in the identified data gaps. The completed engineering geological mapping will be used to complete future assessments and analysis.

5 SUMMARY

Engineering geological mapping will always be a key piece of data required to understand the geological conditions present at a dam site and specifically within the foundation. The methodology for engineering geological mapping has developed with advancements in technology and this has allowed for data to be collected faster and with greater spatial accuracy. Understanding the geological setting prior to commencing mapping is critical to ensuring that data recorded during engineering geological mapping (such as the origin of the defect) is in accordance with the geological, engineering geological and geotechnical models and defect properties critical to the success of the design are appropriately evaluated.

It is important that a suitably trained engineering geologist undertakes engineering geological mapping and other geotechnical investigations for dams to ensure that observations are recorded correctly, and the appropriate engineering geological information is documented. Data from engineering geological mapping should be appropriate for further design (e.g. construction and dam upgrades) and analysis (e.g. stability assessments, erodibility assessments, risk assessments, dam safety reviews) and its potential future uses should be considered during the planning of the engineering geological mapping. If engineering geological mapping is lacking in data or has not sufficiently addressed the design purpose, performing further engineering geological mapping and geotechnical drilling post-construction maybe a complex and costly undertaking.

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