# 3D GEOLOGICAL MODELS FOR MANAGING GEOLOGICAL HAZARDS FOR DAM SAFETY ASSESSMENTS

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## ABSTRACT

*Digital 3D Geological models are rapidly playing a critical role in managing geological hazards and geotechnical risk associated with safety reviews and comprehensive risk assessments of sensitive dam structures. The claim that any 3D modelling approach 'reduces geological risk' hinges on the assumption that geologists and the software can model accurately what is really there. However, the model interpretations are only as good as the geological assumptions and data available.*

*Based on practical experience, this paper explores a number of issues around what data sources can be used to form 3D geological models and decision making on what data is useful, the quality of that data and how is misleading or irrelevant data excluded from the modelling process and documented. Consideration needs to be given as to who formulates these models and how feasible it is to review and validate the 3D geological models and the inherent assumptions in them by peer review. Increasing data integration and software interoperability create important interfaces with the 3D geological model and has the potential to dictate the required detail and accuracy of the model.*

*Communicating the assumptions and limitations of the 3D model is a critical part of the modelling process and this requires a detailed explanatory report accompanying the geological model, which sets out how it was formulated and where the areas of uncertainty are.*

## 1. INTRODUCTION

A thorough understanding of the Engineering Geological Model beneath an existing dam foundation is a critical for assessing the risk of foundation failure for both new and existing dams. Integrated digital 3D geological models, which synthesize all relevant geological and geotechnical information into a single ground model have significant potential for informing the hazards and risks associated with dam foundation failure.

Dam safety assessments and foundation risk assessments should include a comprehensive assessment of the assumptions and uncertainties associated with the geological and geotechnical data used to construct the Geological Model to inform the estimation of conditional probabilities of failure. For existing dam structures, this requires a detailed assessment of all the historical geological and geotechnical investigations relevant to a particular structure by an experienced engineering geologist, in conjunction with the geotechnical engineer.

Historical geological and geotechnical information for dam structures generally consists of drill holes, permeability testing (e.g. downhole packers), downhole and surface geophysics (e.g seismic refraction/reflection), aerial photographs, LiDAR, pre-construction topographic surveys, published and unpublished geological maps and geological mapping of excavations. Other relevant data for dam safety reviews includes groundwater monitoring records from installed instrumentation.

Much of this information is either in hard-copy or soft-copy scans of original hard copies and is often in variable formats, of varying quality and at different scales. The large amount of data associated with existing dam structures and various data formats make it a time-consuming and difficult task to produce a comprehensive and integrated geological model which captures the critical geological conditions and associated hazards that can affect dam safety and influence the risk assessment.

For dam safety and risk assessments, it is critical that the assumptions inherent in the geological model and the uncertainties associated with the input data and subsequent interpretations are clearly communicated. These uncertainties should be accounted for in the Dam Safety assessment system, including the use of Event Tree's, and where required, additional geological and geotechnical investigations may be required to better inform the risk assessment process.

This paper discusses the use of 3D geological models for undertaking dam safety assessments and risk assessments using unnamed case-studies and practical experience.

## 2. 3D GEOLOGICAL MODELS FOR DAM STRUCTURES

The importance of constructing a 3D geological model of an existing dam structure for undertaking dam safety and risk assessments associated with foundation failure modes is to provide the most representative interpretation of the inherent ground conditions beneath the foundation in terms of potential failure modes, as well as constructability aspects and long-term performance of such sensitive structures. Most potential failure modes can be broadly grouped into those which are related to internal seepage erosion, due to bearing capacity issues, potential kinematic failure modes or by excessive flows through high permeability zones of the rockmass foundation. These major failure modes are usually considered during the detailed design process, but sometimes these issues can develop over the operational lifetime of the structure.

The overall advantage of the 3D geological model is the integration of complex data sets to build more complete and realistic models, which can then be used to delineate areas of geological uncertainty and risk, to be further investigated through targeted additional investigations. A major advantage of the 3D geological model is that it is dynamic and can be updated and modified at any time by integrating additional data from ongoing intrusive or non-intrusive geotechnical investigations.

### 2.1 Potential Foundation Failure Modes

In terms of the potential foundation failure mechanisms, geological conditions beneath the foundation has significant influences on the following:

1. High permeabilities in the rock mass beneath the dam foundation which are related to the geological history of the site in terms of tectonic / structural evolution and weathering, which may lead to piping failures below the dam footprint, heaving of the foundation or loss of yield within the impounded area. The value of a 3D geological model for assessing these issues is in providing a means by which complex structural relationships and their impact on weathering profiles can be effectively assessed in terms of their influence on the horizontal and vertical permeability of the soil and rock mass beneath the foundation;
2. Identifying the existence, nature, trend of potential major structures and their inter-relationships (e.g. folds, faults and intrusions) beneath dam foundation;
3. Unfavorable discontinuity orientations within the rock mass resulting in increased probabilities of potential kinematic failure modes for both dam wall and abutment stability and reservoir slope stability. The use of 3D geological analysis provides one of the most appropriate means of identifying discontinuity sets and their contribution to potential kinematic failure modes;
4. The identification of appropriate founding strata and levels for all types of dam structures in terms of adequate bearing capacity and stiffness (thereby minimizing excessive settlements) and avoidance of deep-seated failures, which is best assessed using a 3D model approach; and
5. The potential for liquefiable soils beneath the dam foundation beneath the dam foundation and the lateral and vertical variability of these deposits across the foundation footprint.

In addition to identifying dam safety issues, geology and its 3D representation have additional advantages for dam projects in terms of their constructability and cultural heritage assessments.

## 3. 3D GEOLOGICAL MODELLING PHILOSOPHY AND APPROACH

For each 3D geological model, it is imperative that the model is accompanied by a comprehensive Geological Model Report. At a minimum, this report should provide a detailed explanation of the of the geological relationships (both structural and stratigraphic – including deposit architecture) based on a first principals' geological approach. In the authors' experience engineering geologists producing 3D geological models maynot exercise sufficiently first principals geological reasoning in the models they produce, whether this be a 2D or 3D construction.

When producing 3D geological models for dam safety risk assessments, there is a very real risk that an illusion of knowledge is created by the 3D model, particularly when presented to client asset owners. It is critical that the modeler, reviewers and clients understand the assumptions, uncertainties and limitations associated with the geological model.

Before construction of the 3D Model, the modeler should consider the purpose of the model, which needs to be clearly defined in the Geological Model Report to avoid ambiguity. The overall purpose of the model will be defined by the quality of the available data. Where poor data sets exist, the 3D Geological Model should be considered as either conceptual in nature, or at the very most a geological sketch.

The Geological Model Report should clearly state the relevant aspects of the real-world system which are being modelled and the level of detail required. During the Dam Safety Review process, no single model can include enough detail to accurately represent the geological complexity inherent at a particular dam site. The geological modeler must decide which information should be included and which information can be excluded from the model, while providing an insight into the controlling geological features relevant to the Dam Safety Review and Risk Assessment Process.

The Geological Modeler needs to understand how the 3D shapes and surfaces they are creating relate to actual geological processes and be able to provide a geologically reasoned argument for why the shape is the way it is and its relationship to both the structural geological, geological history and sedimentary environment in which sediments were deposited. The experience of the authors suggest that a significant number of the 3D Geological Models being produced for Dam Safety Reviews may be created with limited geological knowledge of the processes operating at a site, with very little geological thought guiding the modelling workflow. While it is easy to go through the workflow of importing data, clicking buttons and creating an output which appears reasonable to the uninformed, there may be often very little or no geological logic to the modelling workflow.

More often than not, geological logic does not enter into the modelling process such that individuals constructing the models are often under the illusion that they are doing the right thing, yet they do not know if they actually are because they are unable to know what they don't know. In this process, the geologist (or modeler) is simply going through a shape generating exercise, which has little geological basis or reasoning.

Most 3D Geological Modelling software packages have in-built user support as part of the subscription package. Where the modeler does not know what they are doing it is usual to ask for user support. However, this potentially creates a situation where the software providers may help solve the 'issue' which the modeler is having and may help to create a "nice-looking" 3D surface, but this is often done without any regard to the geological processes or inter-relationships. In this case, neither the software help desk or the geologist can judge what is right or what is wrong – a classic case of the blind leading the blind. For Dam Safety Reviews and the assessment of foundation failure mechanisms this has the potential to result in conclusions being drawn from geological models which provide little insight into the geological conditions influencing the foundation failure modes.

Many geological modelling software packages claim that they 'reduce geological risk' hinges on the assumption that the geologist undertaking the modelling can model accurately what is really there. The model is only as good as the geological assumptions and data available. For many geological models constructed for Dam Safety Reviews, the claim that a visually striking 3D geological model actually reduces risk is pure fantasy. The Geological Model Report should be very clear in stating to asset owners that a visually striking 3D model does nothing to reduce geological or geotechnical risk on its own. In fact, a poorly constructed 3D model could actually increase risk, by creating the illusion that the geology of a site is far better understood than it actually is.

When using 3D geological models as input into Dam Safety Reviews, these issues need to be fully understood as they are likely to influence the estimation of conditional probabilities of failure. Without a full understanding of how the model has been constructed, the assumptions, limitations and uncertainties, using model outputs for the estimation of conditional probabilities carries the risk that probabilities are reduced due to the illusion of increased knowledge or certainty. This creates a potentially serious situation, particularly if model outputs (e.g. geological sections) are used to undertake further analyses.

## 4. CONSTRUCTING THE 3D GEOLOGICAL MODEL

The construction of useful, integrated 3D models for dam safety reviews requires a structured approach. The most comprehensive and reliable models have a relatively uniform distribution of geological investigations across the dam site area. However, this level of detail is hardly ever encountered, such that the geological modeler and modelling approach should be able to account for differences in the spatial distribution of data across the site.

For many dam projects the amount of geological and geotechnical data available is significant. The process of sorting through this information and compiling into a format which can be imported into a 3D geological model is extremely important for understanding foundation characteristics and how these relate to potential failure modes. Based on experience, the main processes involved in construction of an integrated 3D geological model for informing dam safety reviews is shown in Figure 1A.

The construction of the 3D geological model involves several key steps:

1. Data handling. This step involves the acquisition, compiling, digitisation and standardization of all the relevant data for the particular dam site. Available data comes in many different formats ranging from hard and soft copy maps and plans, historical drill hole data and a range of geophysical data, which is often provided in the form of plans and sections. It is critical during this stage that standardization of geological and geotechnical units is undertaken to ensure consistency between multiple investigation phased. The standardized geological units should

be defined to maximize the usefulness of the geological model for the dam safety review. Given the significant effort involved in interpretation historical data it is critical that an experienced engineering geologist directs this process;

2. Model Construction. Once all the data has been assembled, digitisied and converted into suitable formats, this data can be used to construct the preliminary 3D geological model. This process relies on having an accurate Digital Elevation Model (DEM) on which the model is based. Where historical data are being used it is also useful to import the pre-construction topographic surface because many of the historical investigations will reference this surface. It is usual at this point to import all relevant historical aerial imagery into the 3D geological model to assist in construction and interpretation of the 3D geological surfaces;

3. Quantification. Many investigations collect quantitative data, such as RQD, SPT's CPT's, downhole geophysics. These data can be used to quantify the geological models and provide additional interpretations of the foundation conditions beneath the dam. It is critical that this information be included into the model to produce an integrated geological model.

4. Interpretation and Validation. The interpretation and validation is an ongoing process throughout the construction of the model. Initially, this process is best undertaken by the geological modeler, who should be an experienced engineering geologist. At key points, the interpretation and validation should be undertaken by a peer-reviewer and this process should be undertaken with the geological modeler in front of the 3D geological model. Due to the complexity of data sets and geological modelling process, interpretation and validation of the data and model should be a continuous process. It is almost impossible to validate a complex 3D geological model comprising complex data sources upon completion of the model.

The construction of the 3D geological model involves considerable effort. Based on recent experiences in constructing geological models for dam safety reviews, the anticipated time allocation for the main phases of model construction are shown in Figure 1B. There is a significant degree of upfront effort (55 %) involved in the compilation and review of existing geological and geotechnical data, standardization and digitisation. This effort should not be underestimated and the success of the 3D geological model for informing the dam safety review is based on allowing adequate time for this process. Geological interpretation represents the second major input to the modelling process at 20 % and involves developing a detailed understanding of the relationships between geological structure and lithology relevant to the potential foundation failure modes.

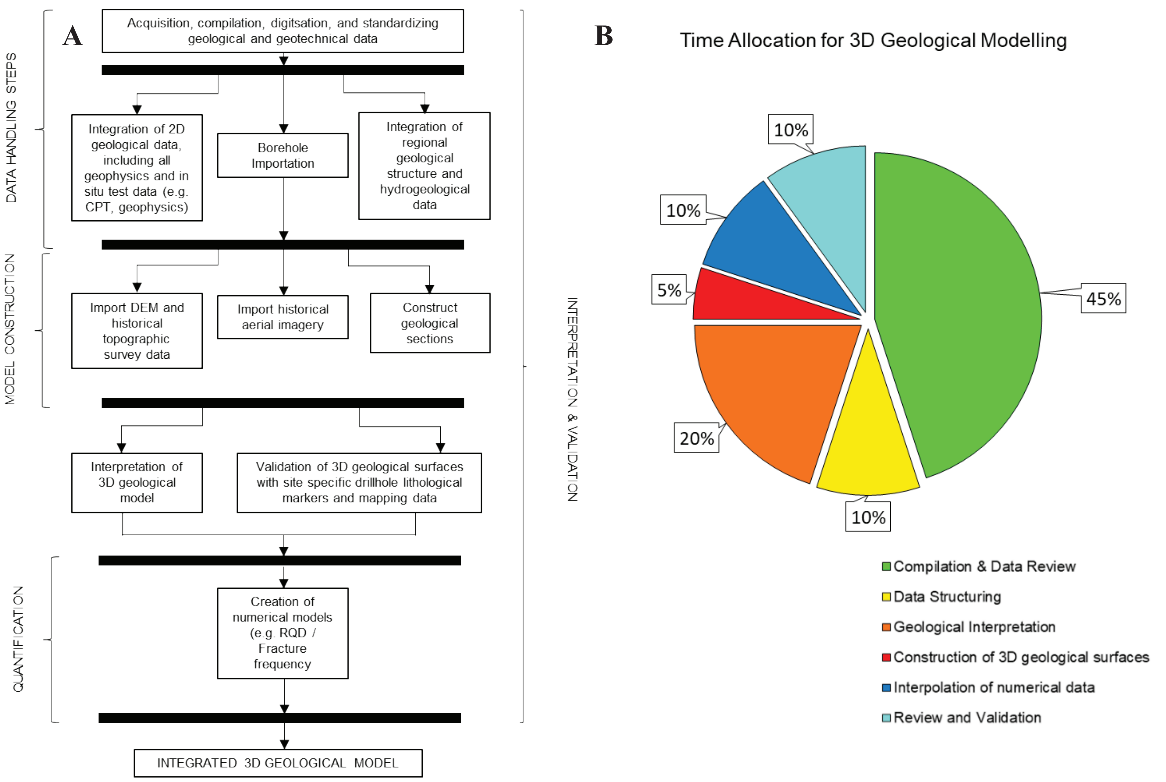


**Figure 1A** : The process of constructing a 3D geological model for the assessment of potential dam founda-tion failure modes. Adapted from Fallara et al. (2006). **Figure 1B** : Time allocation required for 3D Geologi-cal Modelling.

Geological modelling, which involves construction of the 3D geological surfaces accounts for a small proportion (<5%) of the effort. This process is largely automated by the 3D geological modelling software and is wholly reliant on the quality and accuracy of the input data. Review and validation are critical steps and typically represent approximately 10% of the time effort, which is distributed throughout the process of constructing the 3D geological model.

## 5. USE OF 3D GEOLOGICAL MODELS IN PRACTICE

The importance of understanding the accuracy, limitations and uncertainties associated with 3D Geological Models constructed specifically to inform Dam Safety Reviews and comprehensive risk assessments is demonstrated by a recent case study, which the Authors have been involved in. For confidentiality reasons, the dam actual dam site location cannot be revealed because the Dam Safety Review and Comprehensive Risk Assessment has yet to be completed.

The project example relates to a significant Saddle Dam structure located in Queensland, Australia. The main failure mechanism is believed to involve seepage along relict joints in the extremely to highly weathered rock sequence and through fracture zones associated with dyke intrusions.

The Saddle Dam is a zoned earthfill dam with a central clay core and an upstream clay blanket (Figure 2). A vertical chimney filter is located immediately downstream of the clay core and a downstream blanket filter zone. The filters do not extend above Full Supply Level (FSL) and do not run the full length of the embankment. Construction materials were locally sourced from borrow pits from the surrounding area, with granular materials sourced from alluvial deposits and clay core material sourced from completely weathered clay-rich rock.

The Saddle Dam has been previously assessed as having an Extreme Hazard Classification based on incremental Population at Risk (PAR) greater than 1,000.

As per state and federal guidelines the dam site has undergone several periodic dam safety reviews, which have identified credible failure mechanisms that have required quantification and associated consideration of their probability of occurrence and potential related remedial measures required.

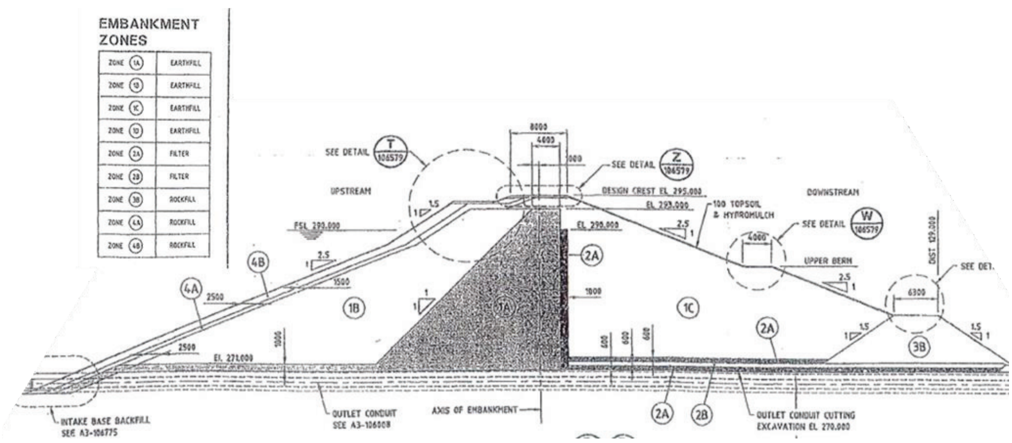


**Figure 2** : Section through Saddle Dam.

### 5.1 Geological Setting

The dam site and reservoir are predominantly situated on granodiorite rock, which has been intruded by later phase finer-grained andesite, rhyolite and micro-granite dykes.

The regional geological structure is relatively simple, with a regular pattern of dyke intrusions, which have a dominant trend of approximately 335 degrees (NW SE), with a subordinate set trending 90 degrees (E-W). Several major NW-SE trending faults are present within the vicinity of Reservoir, passing either side of the Saddle Dam.

Local geological conditions surrounding the Saddle Dam comprise deeply weathered granodiorite rocks intruded by minor andesite dykes and dyke swarms. The dykes have been intruded sub-vertically and as such were very rarely intersected by vertical boreholes undertaken during the geotechnical investigations for the Saddle Dam.

The trend of the dam inlet channel creek was noted in the original geological investigations as being controlled by the presence of a closely spaced swarm of northerly trending andesite dykes, with rare outcrops noted along the original position of the creek bed.

E-W trending vertical dykes were also noted as being common along the outlet channel, with some of these structures being thick (>10m) in gully outcrops.

### 5.2 Weathering

One of the most important aspects of the granodiorite rock mass beneath the Saddle Dam is that it is extremely weathered. The Extremely Weathered (XW) rock mass has been decomposed to a low to medium plasticity clay with a low proportion (<25 %) of sand and is approximately 1 m thick across the site. The XW to HW rock mass has been weathered to a very low strength (<2 MPa), which extends to a depth of approximately 6 m below the pre construction ground surface. Slightly to unweathered, massive granodiorite, with associated dykes occurs at depths greater than 10 m. Even within the slightly weathered rock mass, more highly weathered seams can occur, and these are often infilled with sandy clay and represent the potential for higher rock mass permeabilities.

### 5.3 Groundwater

Preliminary geotechnical investigations indicated static groundwater levels within 3 m of pre-construction ground surface. Pre-construction groundwater seepages were noted to both the east and west of the Saddle Dam. During construction, groundwater seepages within test pits and outlet channel excavations occurred along open joints in the extremely to-highly weathered granodiorite rock mass. The persistence of these structures could not be verified during the current assessment of geological and geotechnical data.

### 5.4 3D Geological Model Construction

A number of pre- and post-construction geotechnical investigations were undertaken over the dam footprint and beyond the downstream toe, with the latter campaigns associated with trying to identify the leakage paths and potential liquefaction potential associated with loose granular foundation materials below the dam.

As part of a 20-year dam safety review, an integrated 3D geological model of the dam foundation was generated for the purpose of trying to confirm the potential leakage pathways. All 3D geological modelling was undertaken using Leapfrog Works 3.0.3.

As part of the acquisition, review, compilation, digitisation and standardization of geological and geotechnical data, the following information was used to construct the geological model:

- Published regional geological maps and unpublished construction phase maps of the local geology;
- Historical aerial photography;
- Current topographic surface was generated from recent post-construction LiDAR derived DEM;
- The pre-construction topographic surface was generated by digitizing the original survey contours and a DEM generated from the contours;
- Pre- and post-construction site-specific drillholes and test pits;
- Pre-construction 2D geological sections generated from the original ground investigations;
- Pre-construction 2D seismic velocity profiles;
- Post-construction electrical resistivity method (ERM) surveys;
- Construction phase photographs of the dam foundation and outlet channel, often without sufficient reference to accurately confirm actual location or view.

Of notable absence from the data sources available was dam foundation geological mapping (which was apparently never undertaken), and during the dam safety review process integration/viewing of historic recovered rock cores was limited by the fact that most of the core boxes of interest could not be found.

Although the exact location of the construction phase photography could not be confirmed, careful review of the images by an experienced engineering geologist did reveal important geological details not apparent from the original geological reporting and drillhole data:

1. Evidence for continuous discontinuities which transmit groundwater in the outlet channel excavation;
2. Persistent lateral shears at the edge of dyke intrusions had potential to transmit groundwater; and
3. Dykes appeared to be highly fractured and resulting in groundwater seepage into outlet channel excavation.

Due to the lack of foundation mapping and given most drillholes were vertical and relatively shallow, terminating within the weathered rock sequence, very little information on the nature and orientation of the dyke structures was available. Only indirect evidence from geophysical ERM surveys was available to assist in construction of the geological model.

During development of the 3D Geological Model, there was significant uncertainty regarding the extent of post-construction cut/fill placed across the dam site. For the current dam safety review, this was significant because the depth to extremely to highly weathered rock was important due to the potential leakage pathway through open relict joints in the dam foundation. Using the pre-construction DEM developed from digitizing the original topographic survey and the current LiDAR-derived DEM, estimates of the cut/fill volumes were able to be made.

Combining all available information into a single integrated geological model, allowed are more comprehensive assessment of the complex geology of the site to be made (Figure 3).

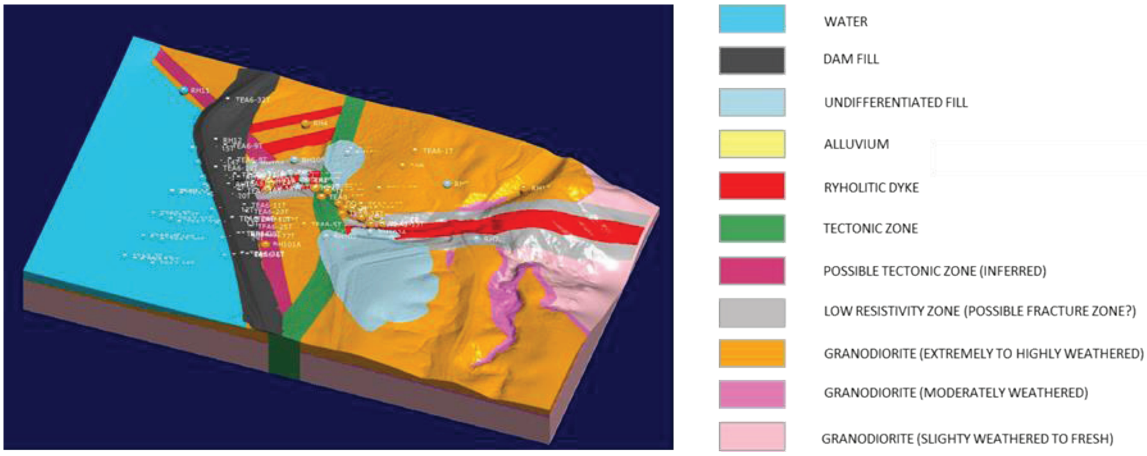


**Figure 3** : Integrated 3D Geological model of the Saddle Dam site.

## 6. MODEL RELIABILITY

Within a 3D model it is very difficult to quantify the statistical variability and uncertainty associated with an interpreted surface given the spatial distribution of data points. While there are statistical techniques which exist, they rely on large data sets which are often more appropriate to mining investigations where large amounts of data come from a relatively restricted area.

In order to adequately manage both geological and geotechnical risks associated with the input data, a qualitative scheme has been developed (based on dam projects) which aims to capture the relative reliability of the input data used to construct the 3D geological model (Table 1).

**Table 1** : Geological / Geotechnical classification of the reliability of 3D Geological Models for Dam Safety Reviews (Adapted from Haile, 2004).

| Data Type | Requirements |
|---|---|
| Implied | • No site-specific geotechnical data necessary or available.<br>• The geological model has a low level of reliability.<br>• Variability or uncertainty in the geological model could have a significant impact on the reliability of the Dam Safety Review and Risk Assessment through influencing conditional probabilities. |
| Qualified | • Project-specific data are broadly representative of the main geological units and inferred geotechnical domains, although local variability or continuity cannot be adequately accounted for.<br>• The geological model has a moderate level of reliability.<br>• Variability or uncertainty in the geological model could have a moderate impact on the reliability of the Dam Safety Review and Risk Assessment through influencing conditional probabilities. |
| Justified | • Project-specific data are of sufficient spatial distribution (density) to identify geotechnical domains and to demonstrate continuity and variability of geological and geotechnical properties within each domain.<br>• The geological model has a high level of reliability.<br>• Variability or uncertainty in the geological model unlikely to impact the reliability of the Dam Safety Review and Risk Assessment through influencing conditional probabilities. |
| Verified | • Site-specific data are derived from the local in situ rock mass. All geological boundaries have been mapped in the field upon exposure during construction.<br>• Geological model is based on foundation mapping and direct observation of in situ foundation conditions. Geological model is based on foundation mapping.<br>• Variability or uncertainty in the geological model unlikely to adversely impact the reliability of the Dam Safety Review and Risk Assessment through influencing conditional probabilities. |

An example (based on the aforementioned Saddle Dam) of how this qualitative scheme was applied to assess the reliability of the 3D Geological Model for the Dam Safety Review and Risk Assessment is summarized in Table 2.

**Table 2** : Implementation of qualitative assessment of 3D Geological Model reliability for the purpose of Dam Safety Review.

| Data Type | Reliability Assessment | Comments |
|---|---|---|
| Topography | Verified | • Pre-Construction topographic surveys dated 1988 have been digitised and uploaded into the Geological Model. This was to compare elevation differences between the pre-construction topography with 2009 LiDAR survey to understand Fill Levels.<br>• 2009 LiDAR survey forms the elevation surface on which the 3D geological model has been based. |
| Stratigraphic / Lithological boundaries | Qualified | • Major lithologies on site comprise granodiorite intruded by andesitic dykes.<br>• Granodiorite was proven in all sub-surface boreholes.<br>• Andesitic dykes were under-represented in the borehole data because all holes were vertical which reduces the likelihood of intersecting vertical geological features. It is impossible to model dyke distribution across the site from borehole data alone.<br>• Presence of dykes in the 3D model inferred wholly from geophysical investigations and not confirmed through physical drilling across the site. Only BH104 confirmed the presence of an andesite dyke in an area in which geophysics suggested.<br>• No geological mapping data exists which confirms the variability of the stratigraphic / lithological boundaries within the dam foundation.<br>• Alluvial / Colluvial sequence was not included in the model due to variability and because it was likely stripped from beneath the dam foundation during construction. |
| Weathering / alteration | Justified | • Major weathering sequence established from borehole data.<br>• Locally deeper weathering in the vicinity of the dykes intrusions caused by increased fracturing and alteration of the host rock has not been modelled because this was not possible from the borehole data alone.<br>• Minor alteration was observed in the 2016 series boreholes, but this could not be correlated to intrusive zones. |
| Relict Joint presence & nature within XW rock sequences of the dam foundation | Qualified | • Existence of relict joints with significant water flows were identified through construction of the Outlet Channel within extremely and highly weathered rock sequences<br>• There is a lack of physical evidence of the nature and extent of relict joints within the extremely weathered rock sequences forming the dam foundation<br>• Jacobs's experience with similar igneous weathering profiles suggests that such features will be present within the dam foundation stratigraphy |
| Major Structural features | Qualified | • Major structural geological features within the Saddle Dam site consist of andesitic dyke intrusions (either as single structures or anastomosing swarms). The locations of these have been inferred only from the 2016 geophysical investigations and have not been physically proven either from mapping or subsurface investigations.<br>• Dykes inferred from geophysical investigations appear to follow the regional structural trend (NW-SE to NNW-SSE) with a minor E-W trend.<br>• No clear evidence from borehole data exists in relation to the extent of the fracture zones associated with dyke intrusions could be gained. This is related to the density of the drilling and the fact most historical boreholes did not progress far enough into slightly weathered to fresh rock. |

All 3D geological models formulated have various degrees of accuracy coupled with associated levels of uncertainty. The level of uncertainty may be a combination of the type and amount of data sources, as well as their individual accuracy and spatial distribution, and of course the level of experience of the modeler undertaking the task and the degree of relevant quality assurance applied.

In practice, very few of the data sources used for model generation can be verified with a high degree of certainty, therefore the choice of what data is valid and useful, and what data should be discounted, falls on the modeler and hence he/she's level of experience is a key factor.

At the present time a number of general statements can be made regarding the general reliability of overall 3D geological models:

- Model interpretation is based on existing geological information, which has generally not been independently verified during the development of the 3D geological model;
- The degree of uncertainty increases away from known investigations and interpretative sections as surfaces are interpolated between points with little or no data; and
- Output 2D sections are simply a representation of the complex 3D geometry of geological surfaces.

Successful management of geological/geotechnical risks or uncertainties for sensitive structures, such as dams, is fundamental in their appropriate design and ultimately in their adequate performance over time. Communicating these risks to other engineering disciplines, governing or regulatory bodies, stakeholder and community groups, as well as of course Clients, needs to be done in an appropriate and successful approach. It is suggested that such a valid approach should follow a three-stage framework:

- Assess the applicability and level of certainty of each data source availability as inputs to the geological model;
- Formulate the model and undertake a relevant and credible quality assurance approach to verify its findings; and
- Present the model and its inherent uncertainties in a meaningful way to stakeholders (this would be by documentation and visually).

Unlike 2D geological models, the level of scrutiny required for 3D models is significantly greater. Often the geological models developed for the design of sensitive structures, such as dams (where the consequence of failure is usually extreme). In addition, the models are increasingly used to provide input directly into geotechnical design, as input into BIM federated models or other engineering disciplines, where the level of required accuracy may be much greater.

## 7. CONCLUSIONS

3D geological models are key aspects in determining associated ground risks for existing or new dams. Relevant application of geological first principles is essential in formulating these models. Model generation must be undertaken and reviewed by suitably experienced personnel covering both the aspects of the software used and the intrinsic nature of ground engineering associated with dams.

Without presenting the uncertainties of 3D geological models in a meaningful manner to stakeholders, individuals/companies may run significant risks in providing perceived advantageous or disadvantageous of ground conditions that ultimately may be lead to costly and time consuming construction delays &/or safety risks, and possibly litigations and reputational risks.

It is recommended that a Geological Model Report be provided with all generated 3D geological models. In addition to this documentation, it is essential that either animation/video files of the model be provided that can be run with typically available computer applications, and that the modeler actually presents the model using the software package utilized setting out the key components and the areas of uncertainty.

As previously mentioned the presentation of the geological model, and its uncertainties, may be essential in highlighting to other engineering disciplines & Clients the accuracy in federated models such as BIM, which are increasingly utilised for infrastructure projects. For example, dam, structural or mechanical & electrical engineers in a 3D environment can provide proposed construction details down to a mm scale, whereas 3D geological models may be accurate only to 10's of m's.

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