3D Geological Modelling as a Tool for Evaluating Foundations – A Case Study for Lower Baker Dam, Washington State, USA

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ABSTRACT
3D geological modelling allows for detailed extrapolation of geological features into areas of the subsurface where limited information is otherwise available, resulting in an increased understanding of bedrock conditions which can be used to inform geotechnical assessments. A case study is provided for the Lower Baker Dam, Skagit County, WA, USA where Leapfrog Geo™ was utilized to construct a geological model of the dam foundation in order to identify potential abutment instability and karst-related leakage pathways. The 3D model effectively outlines a series of discrete fracture planes along which leakage is occurring, as well as kinematic interactions that have the potential to create instability within the abutments. The increased knowledge of the precise location, extent and geometry of these discontinuities provides for a more efficient and cost-effective evaluation process among the various disciplines working to mitigate these issues and stabilize the dam.

RÉSUMÉ
La modélisation géologique 3D permet d'extrapoler de manière détaillée les caractéristiques géologiques dans des zones du sous-sol où des informations limitées sont par ailleurs disponibles, ce qui permet de mieux comprendre les conditions du substrat rocheux et de les utiliser pour éclairer les évaluations géotechniques. Une étude de cas est fournie pour le barrage Lower Baker, dans le comté de Skagit, dans l'État de Washington, aux États-Unis, où Leapfrog Geo™ a été utilisé pour construire un modèle géologique de la fondation du barrage afin de déterminer l'instabilité potentielle des piliers et les voies d'écoulement associées au karst. Le modèle 3D décrit efficacement une série de plans de fracture discrets le long desquels se produisent des fuites, ainsi que des interactions cinématiques susceptibles de créer une instabilité dans les piliers. La connaissance accrue de l'emplacement, de l'étendue et de la géométrie précises de ces discontinuités permet un processus d'évaluation plus efficace et plus rentable entre les différentes disciplines travaillant à atténuer ces problèmes et à stabiliser le barrage.

1 INTRODUCTION

The Lower Baker Dam (LBD) is located at the confluence of the Baker and Skagit Rivers in northwest Washington and forms the Lake Shannon reservoir. The dam is a 285-foot-high concrete arch structure that was constructed in 1925 and is owned and operated by Puget Sound Energy (PSE) (Figure 1). The dam began leaking shortly after the reservoir was filled, with leakage emanating from several discrete locations in the bedrock along the abutment walls above the plunge pool and immediately downstream of the dam (Figure 2). PSE has made several attempts to reduce the leakage, starting with a grouting program in the 1940's; however, the effectiveness of these grout programs has not been permanent, and leakage gradually resumes over time.

PSE began a renewed effort to study the leakage and determine its impacts on the stability of the dam and rock abutments in 2012. Subsequently, PSE has pursued a more in-depth study than had been previously undertaken in order to render a longer lasting reduction in leakage. A key component of their effort has been identifying and characterizing geologic structures in the abutments that are responsible for the distribution and magnitude of leakage. As a first step in completing this effort, high-resolution geospatial data including Light Detection and Ranging (LiDAR) and bathymetry was collected over the abutments and forebay and augmented with detailed geologic

Figure 1. Overhead photo of Lower Baker Dam.

mapping and core drilling (Tetra Tech, 2013). The new geologic information was combined with the existing data set collected from construction era records (photos and mapping) and previous grouting programs over the life of the dam.

The comprehensive data package fed two modeling efforts: 1) a 3D geologic model depicting the orientations of geologic structures in the rock mass surrounding the dam, completed by Terrane Geoscience Inc. (Terrane); and 2) numerical modeling of leakage flows along interconnected sets of geologic structures, work carried out by GeoHydros LLC (GeoHydros). Modeling outputs were then used in the development of a comprehensive mitigation strategy as well as in PSE's ongoing assessment of potential failure modes (PFMs).

Figure 2. Leakage along structural pathways in the bedrock of the right abutment.

This paper describes the 3D geological modeling effort done by Terrane. The purpose of this work is to accurately characterize the structural geology of the bedrock beneath the LBD by: 1) providing the location, persistence and orientation of discontinuities that have the potential to create leakage pathways; and 2) identify critical discontinuities in the rock mass which could potentially impact abutment and foundation stability. This effort provided an opportunity to utilize a combination of new technology along with traditional geological analysis to develop a detailed 3D model of the bedrock conditions.

2 GEOLOGICAL SETTING

An integral component to accurately characterizing the bedrock conditions of any site is understanding the geologic units and deformation history of the area. Different rock units have different material properties that affect the way they respond to stress fields. The way a rock deforms as a result of these stresses is recorded in the structural geology of the rock mass. Therefore, detailed knowledge of the tectonic history of the area is a useful predictor of the faulting and fracturing that can be expected in any given rock mass.

At LBD, the underlying geology is comprised of interbedded limestone and shale, with lesser calcareous sandstone, polymictic conglomerate and volcaniclastic units belonging to the Chilliwack Group (Tabor et al., 2003). Chilliwack Group rocks range from Silurian to Permian in age and represent lithified remnants of a deep oceanic fan complex along an island arc system. The rocks have undergone at least three phases of deformation, including: 1) Pre-mid Cretaceous assembly of terranes (volcanic island arcs, oceanic arcs, etc.) onto the western margin of the North American craton (D1); 2) Mid- to Late-Cretaceous crustal thickening through thrusting, pluton emplacement and volcanism (D2); and 3) Eocene extensional tectonism, including faulting and plutonism (D3)(Tabor et al. 2003). These major orogenic events were followed by continued continental magmatic arc development (i.e. volcanic activity) in the Oligocene through Holocene, and eventually by several periods of glaciation throughout the Quaternary Period.

A key takeaway from the geologic history of the LBD site is that the rocks have undergone multiple episodes of faulting and folding that have impacted the overall integrity of the rock mass. Additionally, they are predominantly limestone which is subject to karstification under the right geologic conditions. Accurately assessing the bedrock conditions of the site must account for both of these factors.

3 3D GEOLOGICAL MODEL DEVELOPMENT

3.1 Model Inputs

Construction of the 3D geological model utilized a combination of available data compiled over 90 years of the life of the dam as well as newly acquired sources. The model incorporates high resolution LiDAR and bathymetry scan data with mapping and borehole data from new drilling and previous grouting programs to identify key geological features and increase understanding on how those features relate to leakage and abutment stability (Figure 3).

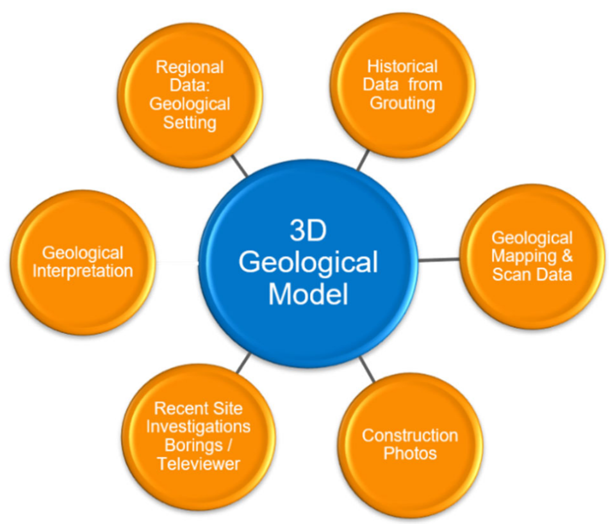

Figure 3. Summary of site-specific model inputs.

3.1.1 Geo-Spatial Data

Terrestrial LiDAR scans were completed of the dam abutments and plunge pool at the onset of the project (Tetra Tech, 2016). The resulting dense point cloud was filtered to remove vegetation and produce a high-resolution bare earth digital elevation model (DEM) of the site. As the dam is operational and restricted by its operating permits, the reservoir could not be drained as part of the current investigation. As a result, a BlueView side-scan sonar by remote operated vehicle was employed to collect bathymetry information for the abutment walls and forebay floor in the reservoir.

The LiDAR and bathymetry point clouds were merged to create a single high DEM that formed the upper boundary of the 3D geological model. The resolution of the DEM was sufficient to identify important geological lineaments as well as carry-out virtual geological mapping of exposed bedrock in both abutments (Figure 4). Mapping from the DEM allowed for the collection of a large amount of accurate structural geology information that would have otherwise been inaccessible due to the near-vertical canyon walls and reservoir.

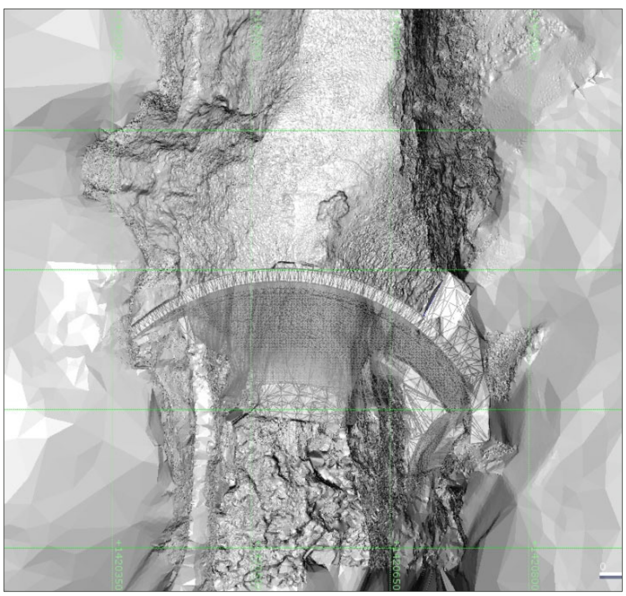

Figure 4. Plan view of LBD showing combined geospatial data (LiDAR and bathymetry). High-resolution DEM surfaces provide detail not achievable with aerial imagery.

3.1.2 Exploration Borings

Historical grout programs focused on intersecting leakage pathways in the immediate vicinity of the dam, generally <100 ft from the rock/concrete interface. As a result, existing borings were limited to a small radius around the dam and provided very little insight into the geology of the abutments and foundation. Early surface geological investigations indicated a strong possibility that the area of influence for leakage pathways originated and extended well outside the previous boring area. A total of eighteen borings were completed by PSE between 2015 and 2018 to collect information on rock type, structures and identify the key factors that determine leakage pathway development further into the abutments.

3.1.3 Televiewer Data

An important factor in 3D modelling is to determine the orientation of geologic structure in order to extrapolate them between borings or surface data points. At LBD, measurement of subsurface structures was achieved through downhole televiewer surveys on each boring using both optical and acoustic sensors. The resulting logs provide precise information on the location, orientation, aperture and infill characteristics of each discontinuity encountered (Figure 5). Interpretation of the televiewer logging also provides information on lithology, included bedding orientations and stratigraphic sequencing, and structures.

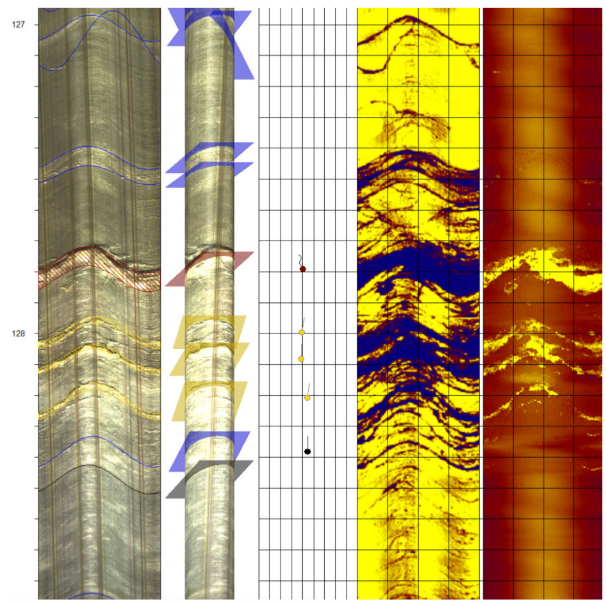

Figure 5. Example optical (left) and acoustic (right) televiewer log from 2015 boring at LBD. 3D image (2nd from left) shows orientations of geologic structures as planes determined from the logging.

3.1.4 Historical Photographs

The placement of the dam structure and full reservoir severely limit the amount of surface geologic information that can be collected. At LBD, a vast database of photographs taken during the construction of the dam between 1924 and 1925 aided in interpreting important geologic features in these areas. Despite the obvious limitations of using 2D images to interpret geology, the photographs provide extensive documentation of the excavated, pre-construction rock surface of the area currently under cover by either concrete or water. Although not an exact indicator of location or orientation, the photographs allowed for the identification of geological features that would have been otherwise obscured (Figure 6).

Figure 6. Example of construction photo from 1925 showing the bedrock immediately upstream of the dam in the left abutment in what is now the reservoir. Note the presence of an irregular sub-horizontal fault in the centre of the image (white arrows).

3.2 Methodology

For the construction of the model, Terrane utilized Leapfrog Geo™ software, an implicit geological modeling software designed for use in mineral exploration and mining. The use of a software specifically designed for subsurface modelling allows for the entire historical database to be incorporated into a completely digital dataset that is easily visualized in 3D space and real-world coordinates extracted.

Construction of the model applied the following process:

1. Structural lineament analysis using the high-resolution DEM surface and available regional LiDAR surface (http://lidarportal.dnr.wa.gov/) to gain an understanding of the overall structural regime, deformational history and geologic setting of the area.
2. Geological data was compiled from all investigation reports and added to a digital database suitable for importing into the Leapfrog software. This includes information from drilling and grouting reports, as well as mapping traverses from both abutments and the forebay.
3. Surficial geological features, such as bedding planes, joint sets and faults were mapped using the virtual 3D surfaces created from the recently acquired high density LiDAR scan data. The location (x, y, z), dip and dip direction of each feature identified was recorded in a digital database.
4. The subsurface geology was modelled using data collected during the 2015-2018 drill programs, including lithology, alteration, structure. This was supplemented by the information gleaned from available 1982/1983 core collected by Shannon & Wilson and borehole records from 1934 and 1960 drill programs.
5. In areas not covered by LiDAR scan data or previous drilling, historical construction photos were examined to identify any prominent geological features. The features were then incorporated into the model using locations and orientations estimated from photos and refined using the new drill results where available.
6. Surface features were ground-truthed through geological mapping of accessible areas.

All available data were combined to form a single fault model which identifies major fault features and the generalized stratigraphy of each fault block. The geology of areas with no information was interpolated based on the expected geology established from the geological understanding of the area and sound geological principles.

4 MODELLING RESULTS

4.1 Structural Geology Model

The 3D modeling was effective in producing a comprehensive framework of the structural geology proximal to the dam. This information was then used in the analysis to identify the stratigraphic and structural factors affecting leakage pathways and potential block instability in the dam foundation. The key findings in this regard are the identification of discrete fault occurrences and highly fractured zones along with feature orientations, timing relationships, and stratigraphy of each individual fault block.

A total of 23 discrete fault structures were identified and modelled based on examination of available geologic data. These faults fall into six broad tectonostratigraphic categories (Table 1). The modeled faults do not represent an absolute list of all faults in the area, but rather represent the discontinuities where notable structural offsets exist, or where significant degradation of the rock has occurred along a discontinuity plane or zone.

Fault modelling revealed that two principal shears divide the Baker River Canyon into three discrete structural domains, comprising a West, Centre, and East block (Figure 7). SH1 occurs at the base of the western canyon wall, whereas SH2 bisects the left abutment at an oblique angle before daylighting in the forebay upstream of the dam. The principal shears are the manifestation of the second deformation episode (D2) and are largely responsible for the current geometry of the Baker River Canyon which hosts the LBD. Together with the offset remnants of the D1 fold/thrust episode, these faults create the framework, around which the stratigraphic model is constructed.

Table 1. Dominant fault sets.

Fault Set	Movement	Timing	Avg. Dip (°)	Avg. Dip Direction (°)
Thrust	Reverse	D1	45	89
Thrust Flat	Reverse (bedding-parallel)	D1	32	81
Master Joints	N/A	D1	24	260
Principal Shear	Oblique strike-slip	D2	81	255
R' Shear	Right-lateral, oblique	D2	64	139
P Shear	Oblique, dip-slip	D2	53	146

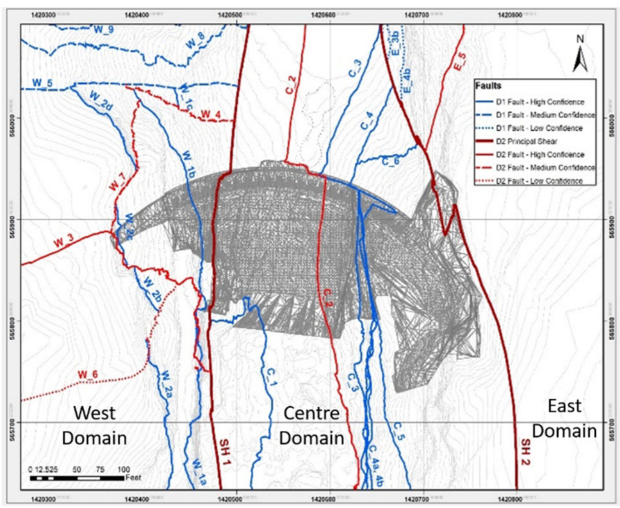

Figure 7. Plan map showing the surface expression of modelled faults and two principal shear zones (SH1 and SH2) that divide the area into three structural domains.

4.2 Stratigraphic Model

Modelling indicates stratigraphic relationships are highly variable between the West, Center, and East domains. There is no observed correlation between geologic units and structure in the three blocks, reflecting the offset in stratigraphy that occurred during D2 faulting which juxtaposed units of different composition and stratigraphic levels.

Establishing stratigraphic relationships in the model principally consisted of determining continuity of units across drill holes and interpolating this information into areas with known information using measured orientations from surface mapping, oriented core or televiewer data. One of the challenges in the Baker River Canyon is the dominant presence of limestone as the principal lithological unit in the abutments, making it difficult to establish continuity across holes due to the lack of stratigraphic marker units. To account for this, an effort was made during core logging to identify those units which could potentially act as marker horizons across holes and potentially the canyon walls. The results of the 3D modelling (Figures 8 and 9) provides insights into the internal deformation of the rock mass and the resulting implications for leakage and abutment stability.

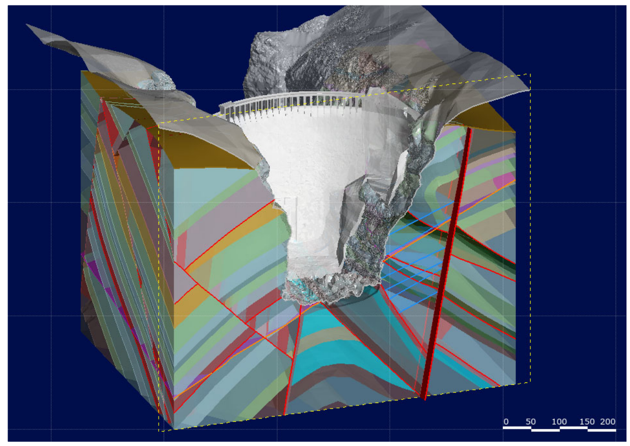

Figure 8. 3D screenshot of the combined structural and stratigraphic model of the LBD bedrock foundation. Different coloured layers represent individual unit contacts and discrete marker horizons. View looking NNE.

The right abutment is interpreted as the west-dipping limb of an anticline with movement down and to the south along principal shear SH1 during the D2 tectonic event. Lithologies observed in the right abutment are indicative of a continuous stratigraphic sequence that was originally higher up in the stratigraphic package relative to the East Block. The block which is interpreted to have moved to the west as a result of left lateral strike slip faulting during D1, and as such, exposes rocks from deeper within the stratigraphic package along with remnants of D1 thrust fabrics.

The area at the base of the dam in the Centre structural domain is coincident with the apex of a large anticlinal fold. Significant deformation occurs along the axial plane of this feature where planes of weakness and fracturing are concentrated. The fractured rock along the apex of the anticline has been eroded away and given rise to the canyon as observed today.

West-dipping master joints are interpreted to have formed during the D1 fold event, followed by a later reactivation during D2 as the East Block moved up relative to the Center Block. This later tension resulted in an opening of the existing fracture network in the left abutment resulting in an open conduit system for seepage. In the upper parts of the block in the left abutment wall, rocks exhibit strong evidence of thrust faulting in which propagation folding has occurred during movement along weakened graphitic shale layers leading to the overturned shale layers and steeply dipping limestone near the downstream crest of the dam.

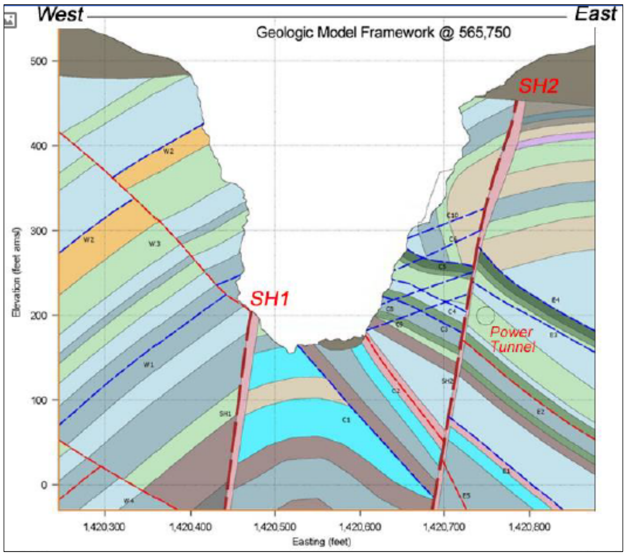

Figure 9. Example of a 2D vertical cross-section through the Baker River Canyon showing major faults (dashed red and blue) and lithological contacts.

The structural block defined as the left abutment east of SH2 displays similar characteristics to the canyon wall in the Center Block, indicating that SH2 bisects the strongly sheared rock mass. The block exhibits evidence of thrust faulting in which, at least, the upper parts have likely undergone propagation folding during movement along weakened graphitic shale layers leading to the observed variability in bedding. The East Block is interpreted to have moved up and to the north an unknown distance along the SH2 shear during regional strike-slip faulting.

Examination of the geology based on modelling has determined that the rock mass in both abutments and the canyon floor have been affected by an extensive network of faulting and fracturing as a result of the two different styles of deformation that have occurred over the geological history of the region. This deformation has likely led to the formation of structural pathways from which leakage is occurring, and possible areas of instability in the abutments.

5 MODEL APPLICATIONS

Each of the major discontinuities identified in the bedrock foundation at LBD presents a potential zone of weakness along which instability can occur or a pathway along which leakage from the reservoir can occur. By knowing the precise location and orientation of each of these geologic features, a more effective targeting strategy can take place for assessing and mitigating the PFMs. The following sections provide working examples of where outputs from the 3D model tie directly into evaluating the PFMs at LBD. In addition to the examples noted below, outputs from the 3D geological model are also being used in ongoing performance-based testing and analysis of the foundation interaction and effects, and in determining seepage reduction alternatives by targeting known pathways.

5.1 3D Numeric Groundwater Flow Modelling

The hydro-stratigraphic framework surrounding the LBD was determined to be directly linked to permeable zones along faults and fractures associated with bedding-parallel and normal faults and fractures as well as canyon-parallel shear zones (Terrane, 2018). Primary permeability in the rocks is very low as indicated by more than 100 Packer tests performed during the recent borings (Kincaid et al., 2018). By contrast, leakage from the reservoir into the plunge pool occurs under very high pressure along subsets of the fault/shear and highly fractured zones that connect to discrete intake points in the forebay to discharge points in the plunge pool. Therefore, permeability within the rocks surrounding the dam is controlled by variably permeable fractures set within a nearly uniform body of essentially very low permeability rock (Kincaid,et al., 2018).

Preferential pathways were characterized through an expansive dye tracing effort, including 20 at the bottom of the reservoir in the forebay and 69 in packer-test zones in boreholes drilled in the abutments (GeoHydros, 2016). The groundwater flow modelling is calibrated to heads measured from vibrating wire piezometers, flow rates and velocities, and travel times (Figure 10). The LBD leakage model is considered a reliable predictor of: 1) The distribution of piezometric heads throughout the rock mass surrounding the dam; 2) The localization of high flow zones; and 3), The rates of flow through those zones.

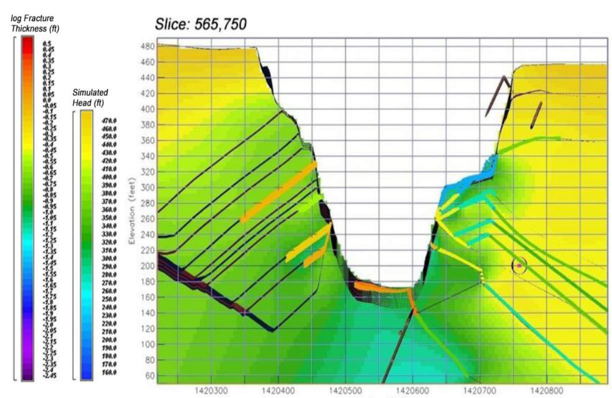

Figure 10. Example of a 2D vertical cross-section through the groundwater model showing the simulated heads with respect to the discrete fractures established through 3D modelling.

5.2 Kinematic Analysis

The 3D structural model provides mechanism by which the kinematic interactions between individual discontinuities can be assessed to determine potential slope stability issues. Examination of the faults modelled at LBD determined that several faults have the potential to interact with the master joint set in the left abutment to create a wedge (Figure 11). Geometries exported from the model were used to carry out a kinematic analysis on each of the potential removable blocks identified to determine the appropriate remediation effort required (Shannon & Wilson, 2019).

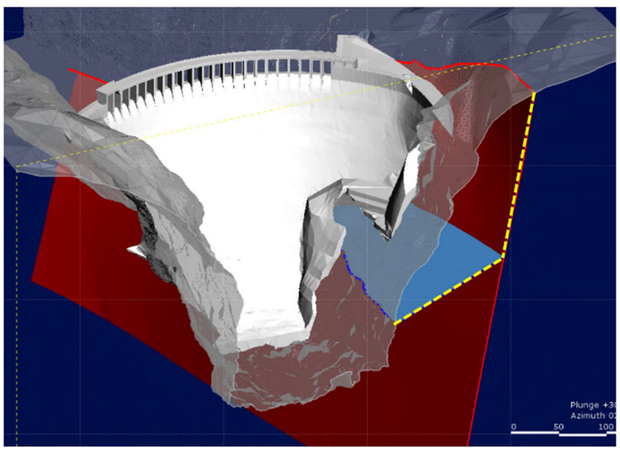

Figure 11. Example of a 2D vertical cross-section through the Baker River Canyon showing major shear zone SH2 (red) potentially forming a kinematically admissible plane shear block (yellow dash) with the Master Joint Set (blue) in the left abutment.

5.3 Rock Mass Characterization

The 3D modelling environment is also an important tool for the interpolation of rock properties throughout a specific area of interest. At LBD, changes in the rock mass deformation modulus were modelled using established geologic structure and lithologic boundaries to identify zones of weakness in the bedrock that were then used in analyzing erosion potential due to both over-topping and along internal flowpaths. The resulting block model provides a precise indication of where modulus values are interpreted to reach an established critical threshold (Figure 12).

6 DISCUSSION

Modern 3D geological modelling allows for detailed extrapolation of geological features into areas of the subsurface where limited information is otherwise available, resulting in an increased understanding of bedrock conditions which can be used to inform geotechnical assessments.

The work at Lower Baker Dam has shown that high-resolution point cloud data/DEM can be used to accurately map the geology of otherwise inaccessible areas. Similarly, down-hole tools, such as the optical and acoustic televiewer systems can provide a more accurate method of measuring the location and orientation of geologic features and extrapolating them between known data points, all of which results in a much higher degree of accuracy when evaluating the geology of a site.

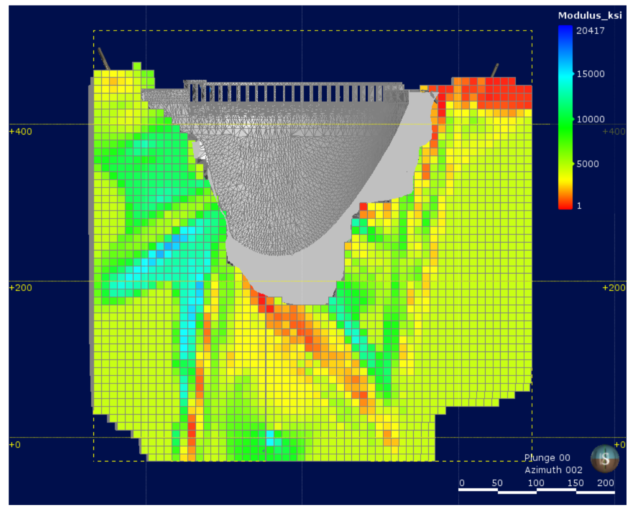

Figure 12. Example of a 2D vertical cross-section through an interpolated block model of rock mass deformation modulus values illustrating different rock strengths.

The use of digital sources, combined with existing historical and project data, for 3D geological interpretation make for a cost-effective method of determining subsurface conditions and allow for ease of data transfer between the multi-disciplinary teams often working on such large-scale infrastructure projects.

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