Geophysical Survey as a part of a Multi-tiered Investigation in Fault Characterization and Dam Seismic Hazard Assessment – a case study from South Australia

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ABSTRACT

Fault characterisation and definition of its activity is an important task in defining the seismic hazard for dams. This is especially the case when some evidence of fault activity exists. A multidisciplinary approach (i.e. geomorphology, structural mapping in the spillway, seismic reflection and refraction, paleoseismic trenching, downhole geophysics and geotechnical boreholes) including use of lidar and bathymetry investigation have been undertaken to inform the overall dam safety and seismic hazard assessment of a dam site in South Australia. This multi-disciplinary investigative approach has led to new active strands of an active fault being recognised, which pass near the main dam and close to a proposed saddle dam, presenting challenges to the dam upgrade design and ongoing dam safety. The geophysics segment of investigation (Seismic Reflection, Seismic Refraction, and Downhole geophysics) has improved understanding of seismic risk and assisted in developing the dam upgrade design.

Keywords: Geomorphologic analysis, seismic refraction tomography, seismic reflection, paleoseismic trenching seismic hazard assessment

1 INTRODUCTION

As a part of a comprehensive safety review and upgrade design of a dam in South Australia, the geophysical seismic refraction and reflection survey, together with more comprehensive investigations on a nearby fault were undertaken. The techniques used in the geophysical survey were:

- Seismic Refraction Tomography (SRT); and
- Two Dimensional (2D) Seismic Reflection (SR).

The aim of the investigation was to provide information to assist in characterising geological hazards and mapping the location and extent of the closest neotectonic features. The investigation was performed to aid seismic structural assessment of the dam with respect to the seismic loading. The results of the geophysical survey were used as an input into a refined Seismic Hazard Assessment for the Dam.

2 GEOPHYSICAL SURVEY METHODS

2.1 Seismic refraction tomography (SRT) method

The seismic refraction tomography method is based on the measurement of the travel time of seismic waves (typically P waves) refracted, diffracted and transformed at the interfaces between different velocity subsurface layers (Gebrande and Miller 1985). Seismic energy is provided by a source ('shot') located on the surface. For shallow applications this normally comprises a hammer and plate, weight drop or small explosive charge (explosives in a borehole or a blank shotgun cartridge). Energy radiates out from the shot point, either travelling directly through the upper layer (direct arrivals), or travelling down to and then laterally along higher velocity layers (refracted arrivals) before returning to the surface. The energy is detected on the surface using a linear array (or spread) of geophones spaced at regular intervals. Shots are deployed at and beyond both ends of the geophone spread in order to acquire refracted energy as first arrivals at each geophone position.

The final output comprises a velocity model of the subsurface. The overarching purpose of seismic refraction tomography surveys is to map the changes in the seismic velocity of the subsurface both laterally and vertically. Seismic velocities are related to rock hardness, elasticity, moisture content, and weathering (Milsom 2003). When correlated with borehole logs or other directly observed data, the seismic velocity models:

- Allow the interpolation of strata between boreholes;
- Provide estimates of geotechnical parameters (e.g. stiffness); and
- Highlight zones of anomalous velocities which may be related to geological structures (faults, dykes, etc.).

The SRT survey objective was to map the seismic velocity profile of the subsurface. The SRT technique is very applicable to zones of sub-surface weathering where the weathering profile consists of a gradient rather than step changes. SRT is also applicable in areas where fault or shear zones have resulted in weathering due to fluid flow.

2.2 2D seismic reflection (SR) method

The purpose of 2D SR surveys is to map differences in acoustic impedance that result in the reflection of the surface seismic source generated energy. The 2D SR sections image the thickness and spatial distribution of major lithological boundaries and highlight structures such as faults (Sheriff and Geldart 1995).

The main objectives of the 2D Seismic Reflection Survey were:

- Fault confirmation/detection; and
- Fault spatial definition.

3 SCOPE OF WORKS

The geophysical investigation described throughout the paper comprised of eight seismic refraction lines and one seismic reflection line. The line geophone spacing, receiver number, length and some survey parameters are presented in Table 1.

Position of the seismic lines (both the SRT and SR) were determined based on geomorphological analyses of the high resolution Lidar data and the initial interpretation of the traces of the nearby fault.

Table 1. Seismic Refraction Tomography and Seismic Reflection Traverse Statistics

Line	Geophone Spacing (m)	No of receiver stations	Receivers Frequency (Hz) / Polarization	Sampling rate (ms)	Recording length (s)	No. of seismic spreads	No. of Seismic Shots	Line Length (m)
SRT_SL-01	4	47	4.5 / Vertical	0.25	1	2	22	184
SRT_SL-02	4	24	4.5 / Vertical	0.25	1	1	11	92
SRT_SL-03	4	24	4.5 / Vertical	0.25	1	1	11	92
SRT_SL-04	4	47	4.5 / Vertical	0.25	1	2	23	184
SRT_SL-05	3, 4	185	4.5 / Vertical	0.25	1	8	98	547
SRT_SL-06	3, 4	116	4.5 / Vertical	0.25	1	5	55	414
SRT_SL-07	3, 4	116	4.5 / Vertical	0.25	1	5	55	414
SRT_SL-08	4	47	4.5 / Vertical	0.25	1	2	22	184
Total SRT						26	297	2111
Seismic Reflection Line-1	4	300	40 / Vertical	0.5	2	1	533	1196

3.1 Site Geology

The area in which the project is located corresponds to the deformed rocks of the Burra Group as indicated by the geological maps and other published literature (Parkin et al 1964).

These comprise a sequence of Late Precambrian shallow marine sedimentary rocks including siltstones and sandstones (including the “Woolshed Flat Shale”) and dolomite, now metamorphosed to low grade meta-psammites, meta-pelites and marble. Table 2 summarises the geological units present in the project region.

The rocks beneath the dam are considered by Kapetas (1993) to lie within the “Mt Bold Shear Zone (MBSZ)” and comprise the Woolshed Flat Shale, which Kapetas describes as “….an upper unit of laminated sandy or silty shale and phyllite, and a lower unit of dolomitic phyllite and thin dolomite lenses which outcrops in the eastern part of the investigation area…” The auxiliary spillway is thought to have been excavated through the younger Stonyfell Quartzite.

3.2 Seismic refraction tomography survey

3.2.1 Data acquisition

A total of 2111 m of seismic refraction lines (26 spreads and 297 seismic shots) were acquired during the survey.

3.2.2 Seismic refraction survey layout

Taking into account the targeted depth of the survey, target size, and site obstacles, an optimal seismic survey spread geometry was selected for seismic data acquisition. This consisted of 24 geophones with a seismic spread of 3 m or 4 m geophone spacing. Most of the seismic traverses were surveyed with 11 to 13 seismic shots. The acquisition parameters used included: recording sample rate – 0.25 ms; recording length – 1 s. A sledgehammer and a metal plate were used as a seismic source in the seismic refraction tomography survey.

Table 2. Geological units in the Dam Reservoir area

Group	Formation	Age	Lithology
Burra Group	Stonyfell Quartzite	Torrensian	Feldspathic quartzite, arkose, siltsone
	Woolshed Flat Shale		Laminated siltstone, phyllite and quartzite.
	Skillogalee Dolomite		Dark chert, sandstone, phyllite, grey dolomite rock
	Aldgate Sandstone		Feldspathic sandstone, arkose, conglomerate, heavy mineral laminations near base

3.3 Seismic reflection survey

3.3.1 Data acquisition

A single seismic reflection line of 1196 m in length (533 seismic shots) was acquired during the survey in the period from 12th to 16th of December 2016. Sampling rate of 0.5 ms and 2 s recording length were used as preferred recording parameters in the seismic reflection survey. A combination of explosive charges and heavy Bobcat mounted weight drop were used as proffered seismic sources in the seismic reflection survey data acquisition.

3.3.2 Seismic reflection survey layout

The seismic reflection survey setup and geometry consisted of a 300 receiver seismic system.
Seismic reflection survey has following geometrical parameters: Receiver separation was 4 m; Source separation was at 4 an 8 m for the weight drop and explosive shots respectively.
Number of shots was 533. Survey was configured to use a "split spread" seismic disposition geometry. The nominal "fold / coverage" was 75 to 150.
Pre-trigger delay of 20 ms was applied to the shot records to achieve the consistent time zero correction to be applied to the post processing. SEGY data format was used in the survey. A "total trace maximum" gain setup was used during the acquisition. The active spread consisted of 300 channels (single vertical geophones with natural frequency of 40 Hz) with the Seistronix Distributed EX-6 Seismograph System ().

3.3.3 Seismic Source Characteristics

The Bobcat Clark type drop hammer attachment (873 kg) mounted to the T300 Bobcat machine with a metal striker plate was used as one of the seismic sources in the seismic reflection survey (Figure 2).

4 SEISMIC DATA PROCESSING

4.1 Seismic refraction tomography data processing

Seismic refraction tomography data was firstly exported into the "Seg2" standard seismic format. The first arrival times were then picked and the initial seismic velocity models created using a smoothed Delta t-V method (Rohdewald 2011).

Figure 1. EX-6 Distributed Exploration Seismograph with battery and cables

Unlike many refraction analysis methods Delta t-V method does not require the interactive assignment of travel times to hypothetical and mathematically idealized refractors. Sorting travel times by common midpoint (CMP) instead of common shots, averages out the effects of dipping layers on travel times. The travel time field is smoothed naturally by stacking CMP-sorted travel time curves over a few adjacent CMP's. Then each CMP curve is independently inverted with the 1D Delta t-V method.
The constant velocity gradient assumption means that seismic rays follow circular arc segments inside each layer modelled. As a consequence, rays can be reconstructed and analytically treated. The method automatically detects systematic time delays on CMP curves and translates these delays into "velocity inversions". Estimated velocities and layer thicknesses are corrected for the inferred velocity inversions. To obtain a 1D initial model without artefacts, the horizontally averaged velocity vs. depth model was extended laterally along the profile. The initial velocity model was then inverted using the true 2D Wavepath Eikonal Travel time (WET) inversion algorithm (Schuster and Quintus-Bosz 1993). The method is capable of imaging the velocity distribution in complex geological environments with increased weathering and presence of "inverted velocity" features. The resulting velocity models were refined with increased number of WET iterations. Number of iterations was set to achieve the optimum fit between the picked and modelled travel times. The resulting velocity models are presented in Figure 4.

Figure 2. Bobcat T300 with the drophammer and striker plate attachment in operation

4.2 Seismic reflection data processing

The seismic reflection data were firstly exported into the SEGY standard seismic digital format. The records were then filtered for the seismic noise and background removal. The data was then treated for the refraction statics (Hatherly et al 1994). This process involves removal of negative influence that the weathering layer has on the alignment of seismic reflectors with depth. Usually, for this purpose the seismic refraction first arrival picks can be utilised. Due to the difference in travel time arrivals from the source to the receivers along the seismic line, the reflectors appear "curved". To align the reflector curvature, a process called "constant velocity stack analysis" is undertaken on data (Figure 3).

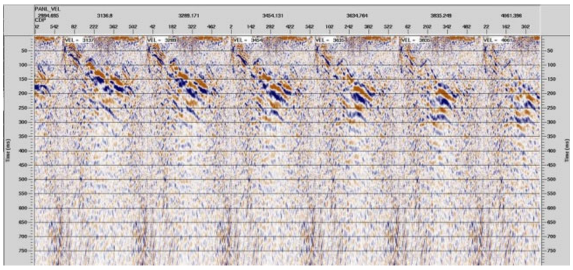

Figure 3. Constant velocity stack analysis (surface) – CVA

A set of different stacking velocities is analysed at separate panels and so called "normal moveouts" (NMO) correction appropriate for the offsets of the seismic traces being examined as a function of arrival time and the coherence between the traces to be stacked. Such a set of velocity panels shows weather increasing or decreasing the velocity will enhance individual events. As a result of the process, when the correct stacking velocity is selected, the seismic events / reflectors (Figure 3) appear flattened.
Subsequently, the seismic reflection data is subjected to the process called "Common Depth Point" (CDP) "stacking". The procedure involves "summing / sorting" of the seismic signal amplitudes for common depth points along the line. For this purpose, and to increase signal to noise ratio, considerable data redundancy (overlapping / seismic fold) is inbuilt into data (Sheriff and Geldart 1995).
The pre stack processing was mainly focused on suppression of the background noise (Urosevic et al 1992). The resulting seismic reflection line stack image is shown in Figure 5.

5 GEOPHYSICAL SURVEY RESULTS

The geophysical survey results are presented by SRT results (P-wave velocity models) and SR results (CDP stack - time section image). Both SRT results and SR results are presented in Figure 4 and Figure 5 respectively.

5.1 SRT Survey Results

5.1.1 General notes

The results of the seismic refraction tomography inversion for the survey seismic lines are presented as coloured velocity models in Figure 4. The figures contain the P-wave seismic velocity tomography models with a location inset map to the right indicating the relative positions of the lines in the survey area. For each velocity tomogram shown on the left, the relevant survey line is shown with the black arrow. In the tomography velocity models, different seismic velocity values are presented with the appropriate colour range starting from 'colder' or blue colour representing lower velocities to the more intense "warmer" colour ranges (yellow, red, white) representing higher velocities. More intense (i.e. "warmer") colours represent a corresponding increase in material density and velocity (seismic impedance). The seismic survey results are generally described in this paper proceeding from west to east across the subject site. The interpretation in this section of the paper is limited to drawing the reader's attention to the presence of major anomalies and correlating the modelled velocities with test pits and borehole logs.

5.1.2 General velocity trends along the seismic refraction tomography profiles

The typical P-wave velocity model is generally comprised of three horizontal layers. The depth to the boundary between the uppermost layer and the second layer, and the second and third layer is variable. *Table 3* shows the range of P-wave velocities for each layer.

5.2 2D Seismic Reflection survey results

Seismic Reflection Line SRL-1 was located near the centre of the survey area and oriented NW to SE.
The stacked reflection image for SRL-1 is displayed in Figure 5. The figures show major reflectors and structures along the line. Generally, reflection seismic data undergoes a process called time – depth conversion which shifts seismic events in space and time to the location where the event occurred in the sub- surface (Sheriff and Geldart 1995). If this process is not undertaken, seismic events are located as a function of acoustic wave travel time rather than being displayed as a function of depth. The reflection stacks presented in this paper have only undergone pre-stack processing (i.e. trace filtering, gain enhancement and stacking have been applied).
Time – depth conversion, which requires detailed control of acoustic velocities, has not been applied, so the vertical scale in Figure 5 is displayed in milliseconds (ms), representing the two – way – travel time of seismic waves from the source to the reflector and back. These additional refinement steps may be undertaken as a separate exercise if more detailed borehole and laboratory data is available to constrain the seismic properties of the lithology in the project area. From the SR time section presented in Figure 5 the following can be concluded:

- The location of the main fault may be inferred as a SE dipping structure originating at chainage 400 m. This has been marked in red solid line on Figure 5.

Note that the dip of this structure is apparent dip and not to be relied on due to no depth conversion of the data and the line not intersecting the fault at 90 degrees.

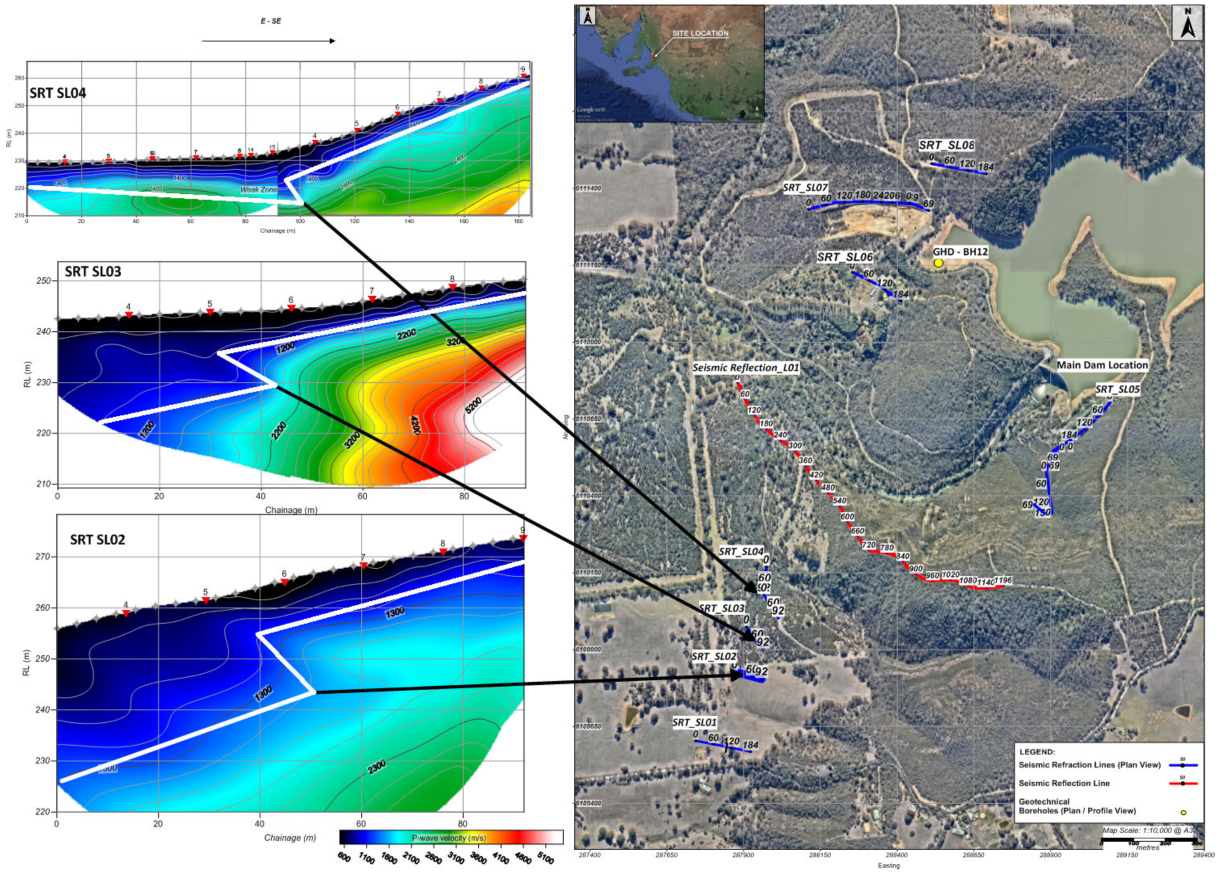

Figure 4. Seismic Refraction Tomography (SRT) Results (SRT SL 02, SL 03 and SL 04 upwards respectively)

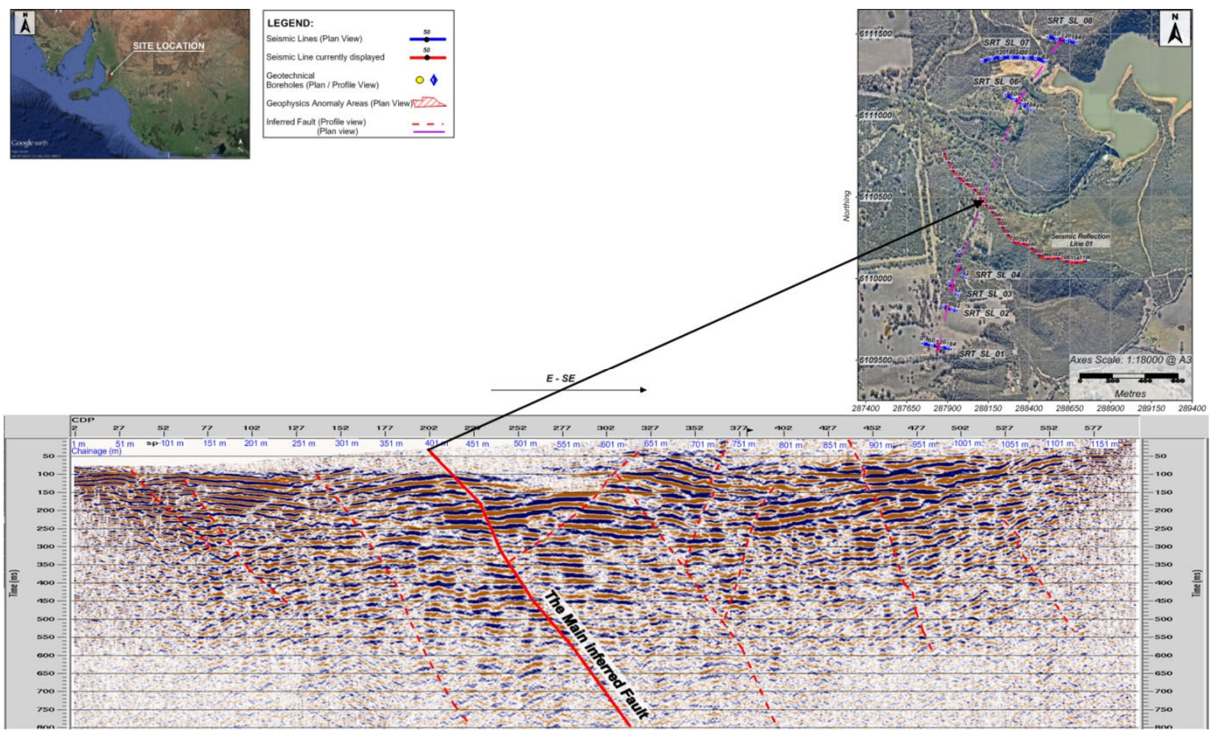

Figure 5. Seismic Reflection (SR) Results (the black arrow indicates the location of the fault traces on the inset map)

Table 3. P-wave velocity trends vs site geology

Layer	P-wave velocity (m/s)		Geology	Conceptual Interpretation
	Minimum	Maximum		
1	600	1400	Unconsolidated soils and sand. Zones of deeper weathered material.	This layer has the lowest velocity range (600 to 1400 m/s). The velocity varies laterally and with depth. At the lower range of velocities, below 700 m/s, these velocities are generally inferred to be unconsolidated sand and residual soils. The velocity range is also within the range seen in stiff clays ranging from medium to very stiff material which is expected in the project area in the weathered unit. Higher velocity ranges 700 to 1400 m/s, may relate to extremely or highly weathered sedimentary rocks.
2	1400	3200	Increasing weathering results in a decrease in velocity. This range is typical for strongly weathered rock.	Layer 2 shows the greatest lateral and vertical variation. These velocities relate inversely to the degree of weathering in formations.
3	>3200		Slightly weathered or fresh basement.	The depth to layer three is variable along the alignment. The material is likely associated with slightly weathered or fresh bedrock.

6 CONCLUSIONS

Geophysical investigation results indicated anomalous features that can be associated with the geological structures – faults. These features generally are presented by inverted velocity zones (weak zones) or an abrupt change of velocity on P-wave velocity models and by the discontinuity of the layering on the seismic reflection stack image. Below is a summary of these features observed on the seismic lines:

- Sharp change of velocity is modelled on Seismic Line SRT SL02 P-wave velocity model (Figure 4);
- Lower velocity zone (weak zone) is observed in the first half of Seismic Line SRT SL03 (Figure 4);

Lower velocity zone (weak zone) is observed in the middle of Seismic Line SRT SL 04 (Figure 4);

- The location of the nearby main Fault may be inferred as a SE dipping structure originating at chainage 400 m on the Seismic reflection section. This has been marked in solid red line on Figure 5.

The Fault inferred alignment in the vicinity of the dam based on the interpretation of the geophysical seismic anomalies is presented by a magenta line in Figure 6. Findings of the seismic refraction tomography and seismic reflection survey were then used to fine tune locations of the paleoseismic trenches. Three paleoseismic trenches were excavated at the approximate locations of the SRT SL02, SL03 and SL04 (Figure 6) and samples taken for dating and further analysis of the fault activity (i.e. average long term slip rates). This data, together with the more accurate location and geometry of the fault as defined by the geophyscis data, was subsequently used in the updated site specific seismic hazard and fault displacement hazard analyses.

Additional angled geotechnical borehole (GHD-BH12) drilled in the zone of the saddle dam indicated relatively large sheared zone at the location inferred from the geophysical survey further confirming the location of the fault trace. This relatively wide broken zone was also imaged using downhole geophysics (acoustic and optical televiewer) survey. The geophysics results were incorporated into a 3D geological model of the dam site (Macklin et al 2019).

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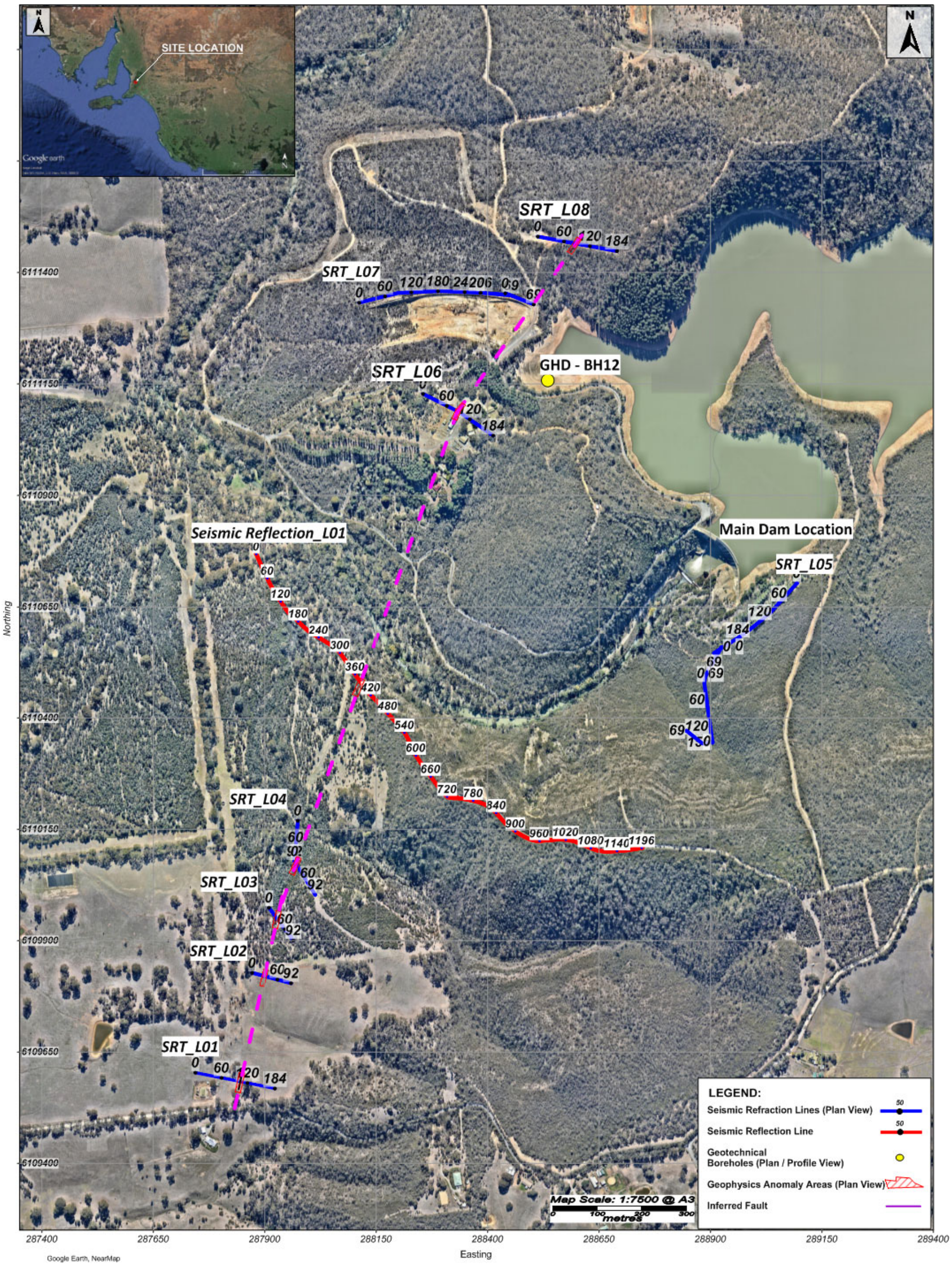

Figure 6. Interpreted fault Trace based on the Geophysics Survey results