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Geotechnical and geophysical investigations for a dam safety project

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ABSTRACT
Advisian was retained to undertake a dam safety review (DSR) for a client. The facility was constructed in the 1970's and very limited technical and background information was available for the facility. As such, geophysical and geotechnical investigations were carried out for the facility, including the installation of 10 vibrating wire piezometers and one slope inclinometer. Data interpreted from the two investigations were utilized to complete the dam modelling and assessment. The DSR activities followed the 2013 CDA Guidelines. Two separate DSR reports where submitted to the client, namely a report related to the liquefaction and risk analyses and a report for all the other activities.
This paper discusses the geotechnical and geophysical investigations findings and sheds light on the lessons learnt from the investigations and the finding of the DSR.

RÉSUMÉ
Advisian a été retenu pour entreprendre un examen de la sécurité des barrages (DSR) pour un client. L'installation a été construite dans les années 1970 et des renseignements techniques et de base très limitée étaient disponibles pour l'installation. À ce titre, des recherches géophysiques et géotechniques ont été effectuées pour l'installation, y compris l'installation de 10 piézomètres vibrants et d'un inclinomètre de pente. Les données interprétées à partir des deux enquêtes ont été utilisées pour compléter la modélisation et l'évaluation du barrage. Les activités du DSR ont suivi les Lignes directrices de l'ADC de 2013. Deux rapports DSR distincts que nous avons soumis au client, à savoir un rapport relatif aux analyses de liquéfaction et de risque et un rapport pour toutes les autres activités. Cet article traite des résultats des enquêtes géotechniques et géophysiques et met en lumière les leçons tirées des enquêtes et de la constatation du DSR.

1 INTRODUCTION

Advisian was retained to undertake a dam safety review (DSR) for a client. The facility was constructed in the 1970's and very limited technical and background information was available for the facility. Further, no previous DSR was completed for the facility since it was constructed in the early 1970's and no geotechnical data required to complete the DSR were available. Consequently, Advisian recommended geotechnical and geophysical investigations to capture the necessary data to complete the DSR for the dam.

The geotechnical investigation included advancement of seven (7) boreholes through the dam fill into the foundation material, with depths ranging from 11 to 20 meters (m) below ground surface. The geotechnical field program also included the installation of 10 vibrating wire piezometers in six (6) boreholes and one slope inclinometer casing in the seventh borehole. To obtain provide supplementary information on the internal dam structure and the underlying native material between boreholes, a geophysical investigation was completed using electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW) and seismic refraction methods, along 4 lines spanning 120 m to 240 m long (Figure 1). Data interpreted from the two investigations were utilized to complete the dam modelling and assessment.

The DSR activities followed the 2013 CDA Guidelines. Two separate DSR reports we submitted to the client, namely a report related to the liquefaction and risk analyses and a report for all the other activities.

This paper discusses the geotechnical and geophysical investigations findings and sheds light on the lessons learnt from the investigations and the finding of the DSR.

2 GEOPHYSICAL INVESTIGATION

2.1 Geophysical Methodology

Electrical resistivity tomography (ERT) is a technique for mapping the distribution of subsurface electrical resistivity (or its inverse conductivity) in a cross-sectional format. Resistivity data are collected through a linear array of electrodes coupled to a direct current (DC) resistivity transmitter and receiver, and an electronic switching box. Data collection is carried out in a sequential and automated fashion that takes advantage of all possible combinations of current and measure electrodes. The data are downloaded to a computer for processing and analysis. The data are inverted using a two-dimensional (2-D) finite difference or finite element inversion routine. The final product is a 2-D cross-section plotting resistivity (in ohm-m) versus depth.

Figure 1. Site Map

The seismic refraction method uses the propagation of compressional waves in the subsurface to determine the velocity structure of the ground. Seismic energy is produced by a source (e.g., sledge hammer, weight drop or dynamite), and spreads downwards and laterally through the earth. An array of receivers (geophones) measures the arrival of that energy at points on a line. Increasing vertical velocity gradients with depth will cause seismic energy to refract back to the surface. Decreasing vertical velocity gradients are rare but, where present, will bend rays away from the surface and create shadow zones that cannot be imaged. The travel path that the energy takes from each shot to each receiver can be represented by a curved ray path. Typically, seismic energy that has propagated through bedrock material will arrive with faster apparent velocities along the seismic array than seismic energy that has travelled through overburden.

The picked travel times of the first-arriving energy can be used as input to seismic inversion software (e.g. Rayfract), which solves for the velocity model of the subsurface that best fits the observed travel times. The accuracy of each travel-time pick is determined by the frequency of the first-arriving energy and the signal-to-noise (S/N) ratio. Factors that can reduce the frequency and/or S/N ratios include soft or spongy soils, wind noise, traffic noise, and the distance between the shot and the receiver (signal strength will reduce proportionally with increasing length of the ray path). The maximum depth of investigation of a velocity model is determined by the deepest refracted ray path. As a rule, the longer the horizontal offset between a shot and a receiver, the greater the depth of penetration.

When seismic waves are generated from an active seismic source (i.e. a weight drop or sledge hammer), both surface and body waves (including compressional and shear waves) are generated, propagating in all directions. In conventional seismic methods, it is the measurement of the body wave arrival (reflection/refraction) that is of interest, whereas the surface wave arrival is generally considered to be a source of noise. A Rayleigh wave is a particular type of surface wave that travels along or near the ground surface and is characterized by relatively low velocities, low frequencies, and high amplitudes (Xia et al. 1999). Surface wave velocity is dispersive, or frequency-dependent (i.e. the sampling depth of a particular frequency component of a surface wave is directly proportional to its wavelength). Therefore, information on the shallow subsurface can be derived from measurements of low frequency components of Rayleigh waves (Park et al. 2007).

On the hand, in the multi-channel analysis of surface waves (MASW), the process for acquiring multichannel shot records is similar to that of acquiring seismic reflection shot records, utilizing an active seismic source and a linear receiver array, and collecting data in a rollalong common-midpoint (CMP) acquisition mode. Dispersion curves are extracted from each shot record using a wavefield-transformation method. The extracted dispersion curves are then inverted to obtain one-dimensional (1-D) shear wave velocity (Vs) profiles (i.e. a single 1-D profile for each shot record). Multiple profiles are then combined, resulting in a 2-D cross-section of Vs versus depth (Park et al. 2007). As Vs is also described as ‘stiffness’, sharp contrasts in Vs may indicate voids, fractures, subsidence-prone areas, or bedrock surface.

Advantages to surface-wave imaging are the ease with which the high-amplitude waves are generated (i.e. utilizing a truck-mounted weight drop or sledgehammer), and the relative insensitivity to ambient, mechanical, or electrical noise (Miller et al. 1999).

2.2 Field Work

The geophysical investigation was conducted by Advisian personnel from July 23 to July 25, 2018. The survey consisted of two seismic refraction/MASW lines and four ERT lines (Figure 1). Table 1 describes the approximate location, length, and orientation of each of the ERT and seismic lines.

Table 1. Geophysical Survey Lines

Survey Line	Location/Orientation	Length, m
ERT Line 1	NW of the dam crest/SW to NE	210
Seismic Line 1	SE of the dam crest/SW to NE	224
ERT Line 2	SE of the dam crest/SW to NE	240
Seismic Line 2	SE of the crest/SW to NE/SW to NE	240
ERT Line 3	NE of the dam across the crest/NW to SE	120
ERT Line 4	NE of the dam across the crest/SSW to NNE	120

The ERT lines were collected using the ABEM Terrameter LS system, configured into a gradient plus array, and using a minimum electrode spacing of 1.5 m. This configuration allows for data collection down to a maximum depth of approximately 20 metres below ground surface (mbgs).

The seismic lines were collected using 4.5 Hz geophones, a geophone spacing of 2 m, a shot record length of 2 seconds, and an 8 lb sledgehammer and plate as the seismic source. Seismic refraction data were processed using Rayfract, and the MASW data were processed using SurfSeis.

Positional information was collected using a Spectra Precision Epoch 50 RTK GPS system and is projected to the Universal Transverse Mercator (UTM) system Zone 12 North and referenced to the North American Datum 1983 (NAD83).

2.3 Results of the Geophysical Survey

ERT, Seismic Refraction, and MASW Line 1 is presented in Figure 2. The MASW results generally indicate a three-layer S-wave velocity model. The upper, slowest layer extends from ground surface to approximately 10 mbgs, has S-wave velocities ranging from approximately 150 to 200 m/s, and has been interpreted as the Dam fill material. The middle layer extends from approximately 10 mbgs to approximately 40 mbgs, has S-wave velocities ranging from approximately 200 to 400 m/s, and has been interpreted to be native ground. The bottom layer extends from approximately 40 mbgs to the base of the cross-sections, has S-wave velocities ranging from approximately 500 to 700 m/s, and has been interpreted as weathered bedrock.

On either side of the interpreted Dam fill, a range of S-wave velocities from 175 to 225 m/s was recorded; these zones have been interpreted as the Dam abutments. The Dam fill appears to be fairly homogeneous, with no localized zones of low S-wave velocities that may indicate anomalously low shear strength within the Dam fill.

ERT Lines 1 and 2 indicate areas of relatively lower resistivity values, which are interpreted as the Dam fill material bounded on either side by the Dam abutments (Figure 2). It is important to note, however, that the differences in resistivity within the interpreted Dam fill are fairly subtle, suggesting that the differences in resistivity are likely more attributable to differences in moisture content as opposed to soil composition. As a result, the base of the Dam fill has been interpreted based on the MASW results as the S-wave velocity is indicative of the level of soil compaction.

A dome shaped anomaly was recorded on each ERT cross-section, consistent with metal interference (e.g., the dark blue anomaly shown in the upper panel of Figure 2). These anomalies have been interpreted to be the metal drain pipe located within the Dam; the interpreted location of the pipe has been drawn on the Basemap (Figure 1).

The P-wave velocity cross-sections indicate a gradual increase in soil density with depth. Within the Dam, the P-wave velocities appear to be relatively slower than the Dam abutments, consistent with the ERT results. P-wave velocities recorded within the Dam are approximately 500 to 1,000 m/s; velocities within the native ground are approximately 1,500 to 2,500 m/s; velocities within the abutment are approximately 500 to 1,500 m/s. The 2,500 m/s P-wave velocity contour has been interpreted as the approximate upper boundary of a weathered bedrock layer., It appears this layer is dipping slightly to the southwest.

Figure 3 shows a "zoomed in" version of the results of ERT Line 2 with the interpreted soil layers noted on the Figure. Within the interpreted Dam fill, a layer of relatively higher resistivity values was recorded in the near surface atop a layer of relatively lower resistivity values. These differences in resistivity have been interpreted as differences in moisture content within the soil layers, where the zones of relatively higher resistivity are interpreted to have less moisture content than the areas of relatively lower resistivity.

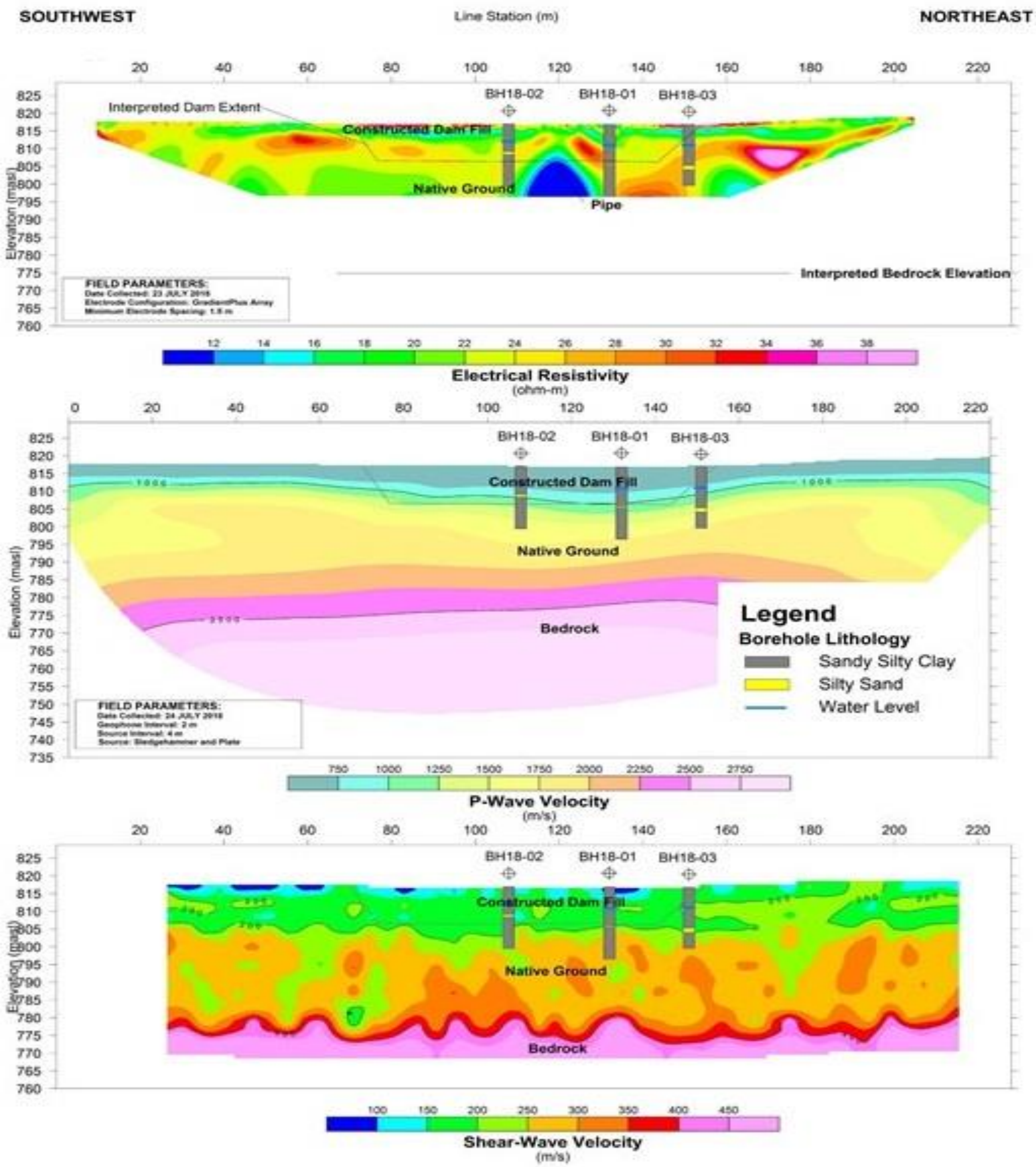

Figure 2. ERT, seismic refraction and MASW Line 1

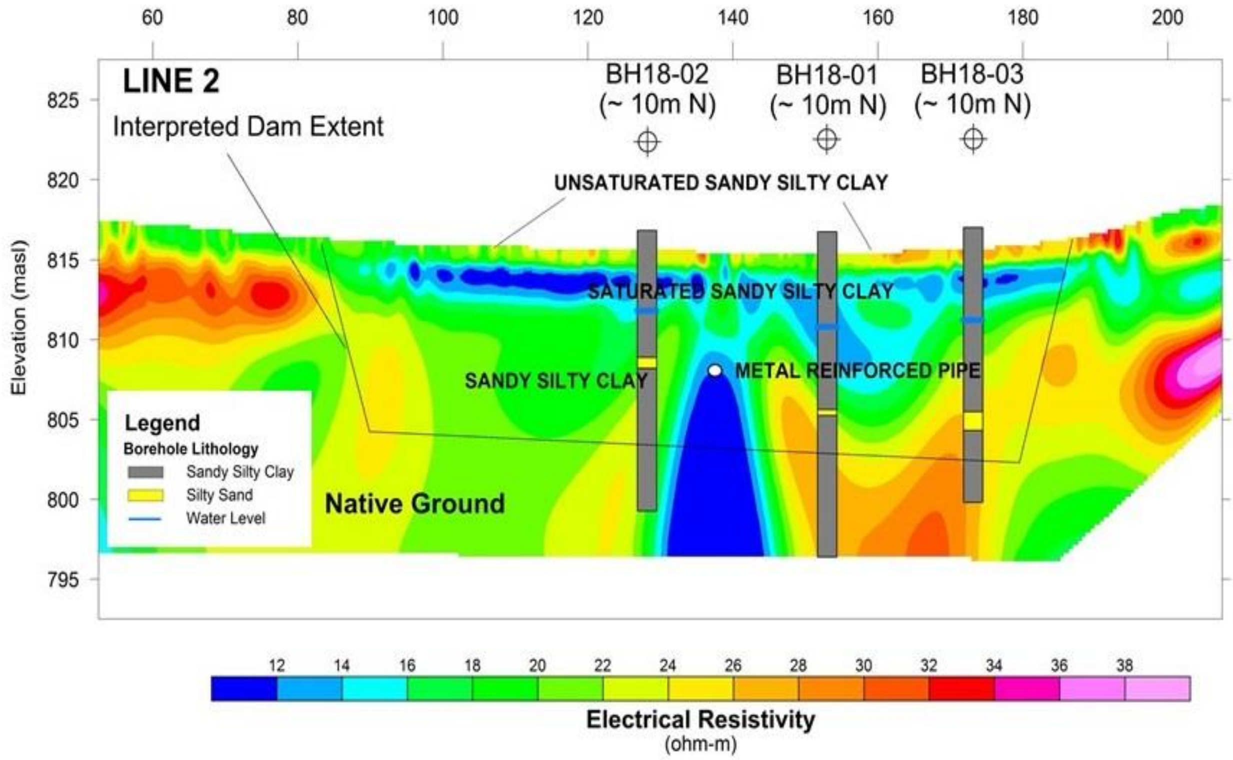

Figure 3. Zoom of cross-section for ERT Line 2

3 GEOTECHNICAL INVESTIGATION

3.1 Geotechnical Investigation

The preliminary results from the 2018 Advisian geophysical survey were utilized to confirm the borehole locations. And, prior to the initiation of the geotechnical investigation program, all underground utilities within the vicinity of the Dam were identified and marked in the field, and clearance was received from all registered utilities owners prior to the commencement of ground disturbance.

The geotechnical investigation included drilling of seven (7) boreholes. Three (3) boreholes were drilled at the crest of the Dam (BH18-01, BH18-02 and BH18-03), two (2) boreholes located approximately mid slope of the downstream face of Dam (BH18-06 and BH18-07), and two (2) boreholes near the downstream toe of the Dam (BH18-04 and BH18-05. Drilling was conducted using a track mounted R214 drilling rig. The solid stem auger method was employed for borehole drilling. All site works were supervised by an Advisian Site Supervisor.

Standard Penetration Tests (SPTs) were performed during drilling to interpret the general consistency or density of the soil units encountered.

The soil sampling program included collection of grab samples directly from the auger and collection of split spoon samples immediately after the SPT testing. The samples were collected at regular intervals, or as directed by the Advisian Site Supervisor. All soil samples were placed in sealed containers. The sampling program also included retrieval of Shelby tube samples. These samples are relatively undisturbed and were collected from cohesive soils using a thin-walled, open Shelby tube sampling device. The Shelby tube samples were sealed from both ends to maintain its field moisture content.

The SPT N-values are provided in Figure 4 while the natural moisture content and Atterberg limits are provided in Figure 5.

3.2 Instrumentation Installation

A total of ten (10) vibrating wire (VW) piezometers were installed in six (6) of the boreholes (BH18-01, BH18-02, BH18-03, BH18-04, BH18-05 and BH18-07). Nested VW piezometers were installed in BH18-01, BH18-02, BH18-03 and BH18-07 (two VW in each of those boreholes), to monitor groundwater condition both within the Dam body and within the native foundation soil. One (1) VW was installed in each of BH18-04 and

BH18-05 to monitor groundwater condition within the Dam foundation soil. All of the installed VW piezometers were PWS-series (porewater or pore fluid pressure designed to be embedded in earth fills) manufactured by RocTest Ltd. (Roctest) with maximum sensing pressure of 350 kPa.

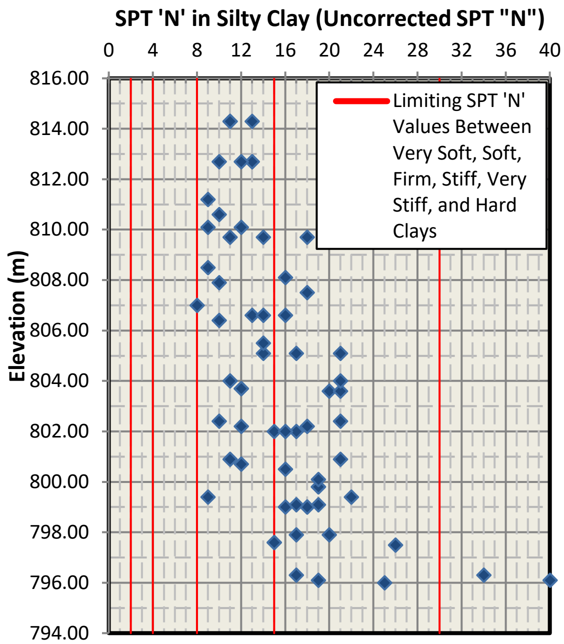

Figure 4 Standard Penetration Test (SPT) N versus Elevation

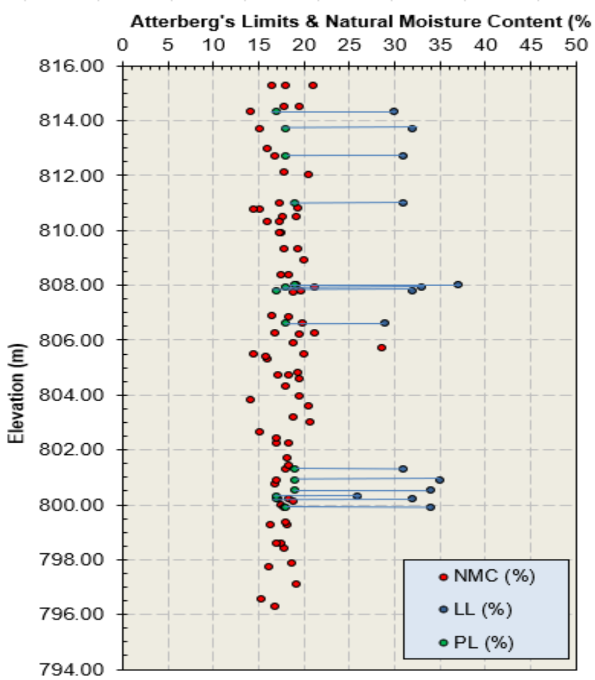

Figure 5 Natural moisture content and Atterberg limits versus Elevation

The VW piezometer sensor filters were saturated and kept under water prior to installation. The VW piezometers were installed by first securing the piezometers to 25.4 mm diameter polyvinyl chloride (PVC) pipes with sensor filter facing upward. The fixed length PVC pipe was used both as anchor and provided reference of installation depth. The VW piezometer along with the 25.4 mm diameter PVC pipe were then lowered to prescribe depths and grouted in place with bentonite cement grout.

One (1) RocTest 70mm diameter GEO-LOK type inclinometer casing was installed in BH18-06 to 14.5 mbgs.

4 DAM SAFETY REVIEW (DSR)

4.1 Background Information

The facility was constructed in the 1970's to supply water for oilfield activities. The Facility has had several owners since the time it was constructed. The facility has been through multiple owners and the current owner has little technical and/or background information available for the facility. During the preliminary review conducted Advisian obtained digital files with a scanned copy of a general layout drawing of the facility from 1970 and scanned copies of four review drawings for the spillway proposed in 1978 from Alberta Environment.

The owner is no longer withdrawing water from the reservoir created by the facility for their operations in the region. The owner also operates a water intake and pump station on a river that is currently for their operations and the excess water, if any, used to supply water to the reservoir. Pumping from the river generally occurs in the late summer and fall to raise the water level in the reservoir, if and when needed. Runoff from spring snow-melt and rainfall typically fills the reservoir and results in flow through the spillway.

The reservoir has also a recreational value to the surrounding communities, including campgrounds. Additionally, the reservoir provides aquatic habitat.

4.2 DSR Approach

Noting that the CDA (2007) Dam Guidelines have been revised with focus moving from the traditional standard-based approach to dam safety assessment to a risk-informed approach (CDA 2013 Revision). In this risk-based approach, the traditional deterministic standard-based analysis is considered as one of many considerations. A formal risk assessment provides a systematic and structured method for understanding possible outcomes, areas of importance and uncertainty, and impacts of interactions between various modes of failures. On the other hand, in the traditional approach the likelihood of hazard occurrence is explicitly addressed only for floods and earthquakes.

For the DSR, Advisian followed the 2013 Canadian Dam Association guidelines. A site reconnaissance was initially conducted by three engineers (two geotechnical

and a hydrotechnical). The site inspection covered the dam structure, the appurtenant structures and the reservoir.
Assessment of the dam was carried out by completing hydrotechnical and geotechnical analyses and the findings and recommendations were provided in the DSR report was made available to the owner.

4.3 Hydrotechnical Analysis

The hydrotechnical analysis included:

- Verification of hydraulic modelling inputs based on a recent survey.
- The dam reservoir water balance.
- The dam freeboard assessment.

4.4 Hydrotechnical Results

The results of the updated hydraulic model of the dam show that the maximum water level in the dam reservoir will reach 816.18 m in 100-year flood and 816.75 m during a 1,000-year flood. Given that the lowest dam crest elevation is 816.49 m, the dam will be overtopped at 1,000-year flood. Both the service spillway and emergency spillway will spill during 100-year and 1,000-year flood events.

The change in the estimated dam breach parameters because of slightly higher inflow design flood (IDF) water elevation in the reservoir will be marginal and will have negligible to no effects on the inundation mapping.

The estimated maximum water elevation including wind setup and wave runup at operating pond conditions is 814.85 m. With the dam crest elevation of 816.49 m, the available normal freeboard of the dam is approximately 1.64 m. However, the IDF maximum water elevation exceeds the dam crest elevation and the dam is overtopped. Sufficient freeboard is not available in the Dam under IDF conditions. It is required that the risk of having no freeboard at the IDF flood of the Dam be assessed.

4.5 Geotechnical Assessment

The geotechnical assessment included:

- Verification of the geological setting
- Verification of the geotechnical parameters for the assessment
- Seepage analysis
- Slope stability analysis.

4.6 Geotechnical Assessment Results

Steady state seepage analysis covered two scenarios dam, one with and the other without drainage blanket. In the case where no drainage blanket is assumed, the analysis indicates potential seepage daylighting at the downstream slope approximately five meters from the dam toe. Note that seepage was not observed during the site visit, although extensive growth of vegetation was observed toward the dam toe. Vegetation growth may indicate the presence of an elevated phreatic surface. Based on the two sets of vibrating wire piezometric data obtained immediately after the geotechnical investigation in the two boreholes near the dam toe, the inferred phreatic surface appears to exist approximately 1.1 to 2.3 mbgs within approximately a 4 m wide section of the slope parallel to the toe of the dam (bounded by the waterfront on the downstream). While in the case where a drainage blanket is assumed no issues with seepage are reported.

Results obtained from the transient seepage analysis for the two scenarios, i.e. with and without a blanket drain, after 30 days period (a 30-day period is assumed as the maximum period during which the reservoir level is assumed to be at the 100-year flood level). In both scenarios, given the flow properties of the soils encountered the seepage results indicate no significant pore pressure build up near the downstream end of the dam in response to the upstream elevation of the reservoir level.

Results of the slope stability assessment indicated adequate factor of safeties under both static and pseudo-static conditions, for the scenario with drainage blanket. The results for the scenario without a drainage blanket indicated inadequate factor of safety under drained static and pseudo-static conditions resulting from seepage along the downstream slope and stressed the need to maintain proper drainage conditions.

Results of the slope stability assessment indicated adequate factor of safety for the undrained conditions during the seismic loading within the dam body. Based on our observations during the site visit, and our interpretation of the piezometric data obtained, Advisian considers the scenario with no drainage blanket to represent a hypothetical worst case.

Therefore, the stability of the downstream slope is unaffected by the 100-year flood event.

5 CONCLUSIONS AND LESSONS LEARNT

The geophysical and geotechnical investigations shed some light on the dam facility and provided the data necessary for completing the dam safety review for the facility. The followings conclusions and lessons learnt are

- The dam is in a safe condition and operated safely for a 100-year flood. However, the 1000-year flood will overtop the dam and the associated risks should be assessed in accordance to the CDA 2013 Guidelines.
- The surveillance program is, generally, adequate following the implementation of a dam inspection checklist, which was recently designed by Advisian and implemented for the facility, to detect possible safety problems.
- Documentation for many activities is lacking However, little effort will be needed to prepare the required documentation.
- Combining the geophysical and geotechnical investigation can provide insight on the information obtained for the DSR.

- It is prudent to engage professional disciplines (at least geotechnical and hydrotechnical) prior to the purchase of a facility.

6 REFERENCES

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