

GEOTECHNICAL ASSESSMENT OF THE ALAMEDA DAM

JOSEPH QUINN, P.GEOL. ASSOCIATE, ENGINEERING GEOLOGIST, KLOHN CRIPPEN BERGER LTD., CALGARY, ALBERTA, CANADA

BILL CHIN, P.ENG, PRINCIPAL, SENIOR GEOTECHNICAL ENGINEER, KLOHN CRIPPEN BERGER LTD., CALGARY, ALBERTA, CANADA

MARK PERNITO, GEOTECHNICAL CONSULTANT, KLOHN CRIPPEN BERGER LTD., CALGARY, ALBERTA, CANADA

JODY SCAMMELL, P.ENG, ENGINEER SPECIALIST, WATER SECURITY AGENCY, MOOSE JAW, SASKATCHEWAN, CANADA

ABSTRACT:

Alameda Dam, which is owned by the Water Security Agency (WSA), is a 42 m high and 1250 m long earth dam located in southeastern Saskatchewan. The dam is founded on 30 m of glacial till overlying high plasticity clay shale bedrock. During its construction in the 1990s, unexpected displacements occurred in the clay shale, which resulted in halting construction for 18 months to facilitate a review of the design. The dam was completed by adding stabilizing berms, and by constructing the remainder of the dam in controlled stages.

In the spring of 2011, the reservoir was surcharged above its full supply level (FSL) of El. 562 m in order to decrease downstream flood flows resulting from high runoff. Concerns regarding the stability of the dam were raised when the displacements in the

clay shale increased during reservoir surcharging. An interim stability analysis indicated that the factor of safety of the dam was significantly less than normally acceptable levels.

In response to the concerns, the Water Security Agency expedited a comprehensive stability evaluation of the Alameda Dam, which consisted of additional site investigations, 2D and 3D limit equilibrium analyses, and advanced 2D and 3D deformation modeling (FLAC). This paper describes the assessment methodology, and presents the main results and conclusions of the stability evaluation.

RÉSUMÉ

Le Barrage d'Alameda est un barrage en terre de 42 m de haut et 1250 m de long situé au sud-est de la province de la Saskatchewan. La fondation du barrage repose à 30 m dans le till

glaciaire sus-jacent un soubassement de schistes argileux d'une plasticité élevée. Pendant sa construction dans les années 1990, des mouvements inattendus se sont produits dans le schiste argileux, forçant l'arrêt des travaux de construction pendant 18 mois pour permettre une révision de sa structure. Le barrage a été complété en y ajoutant des berms de stabilité, et en construisant le reste du barrage par phases contrôlées.

Pendant le printemps de l'année 2011, le réservoir a été surchargé par rapport à son niveau de retenue (NDR) de 562 m d'élévation, dans le but de réduire les crues en aval émanant des forts ruissellements. Des préoccupations ont été soulevées au sujet de la stabilité du barrage lorsque des mouvements du schiste argileux ont augmenté pendant la surcharge du réservoir. Une analyse intérimaire

de la stabilité a indiqué que le coefficient de sécurité du barrage était considérablement inférieur aux niveaux acceptables.

Pour répondre à ces préoccupations, l'Agence de la Sécurité des Eaux a conduit une évaluation accélérée et exhaustive de la stabilité du Barrage d'Alameda, qui consistait en des évaluations supplémentaires du site, l'analyse d'équilibre limite en 2D et 3D et la modélisation avancée de déformation 2D et 3D (FLAC). Cet article décrit la méthodologie d'évaluation, et présente les résultats principaux et les conclusions de l'évaluation de la stabilité.

1 INTRODUCTION

The Alameda Dam is located on Moose Mountain Creek about 4 km east of the town of Alameda in southeast Saskatchewan (Figure 1). It impounds the Alameda Reservoir, which is about 23 km long at FSL (El. 562 m). The Maximum Allowable Flood Level (MAFL) is El. 567 m. The project was developed to provide flood control for residents downstream in Saskatchewan and North Dakota, and to ensure a more reliable water source for municipal, domestic, irrigation and recreational use in the Saskatchewan portion of the basin. The dam was constructed between 1991 and 1995, and has a maximum height of 42 m, a crest width of 11 m, and a crest length of about 1250 m. The top of the dam is at El. 568.5 m providing a free-board of 6.5 m and 1.5 m at FSL and MAFL respectively.

The dam is constructed of glacial till obtained from local borrow sources, with a central inclined chimney drain



Figure 2: General Arrangement Plan

connected to a horizontal drainage blanket beneath the downstream shell. The upstream and downstream slopes of the dam are 3H:1V and are buttressed with stabilizing berms. Appurtenant structures include a six-gate reinforced concrete chute spillway and stilling basin, and a horseshoe-shaped concrete low level outlet. A general arrangement plan and a typical cross section of the dam are shown in Figures 2 and 3, respectively.

The dam is founded on a shallow silt and silty gravel layer underlain by glacial till over high plasticity clay shale bedrock at a depth of about 30 m below the riverbed. A detailed description of the site geology and foundation conditions is provided by Mittal and Rahman (2000). As

described by Mittal and Rahman (2000), the presence of the clay shale of the Ravenscrag Formation had a profound influence on the design, construction and completion of the project. In particular, higher-than-expected pore pressures in the glacial till and clay shale foundation, together with unexpected shear displacements in the clay shale, resulted in halting construction for 18 months to allow time for a review of the dam design. Subsequent completion of the dam to its ultimate crest elevation was made possible by incorporating upstream and downstream stabilizing berms, and by raising the remainder of the dam in controlled incremental stage using the Observational Method (Peck, 1969). At the end of construction, the maximum settlement in the

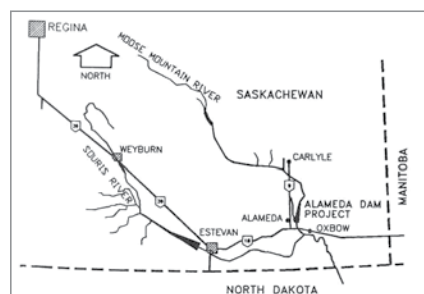


Figure 1: Project Location Plan

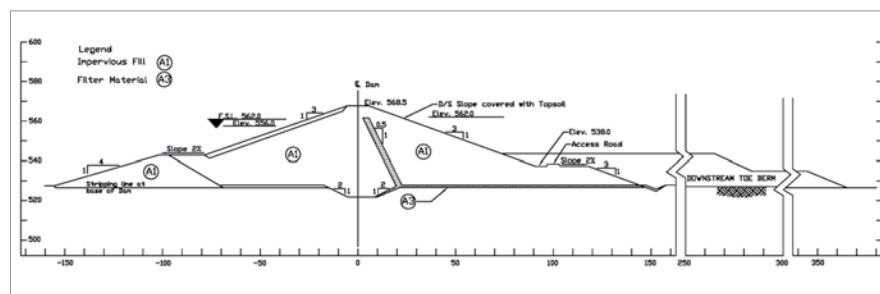


Figure 3: Typical Dam Section and Instrument Locations

foundation was about 630 mm and the maximum shear displacement in the clay shale was about 400 mm.

In the spring of 2011, there was a need to surcharge the reservoir above FSL in order to reduce downstream flood flows resulting from high run-off. The surcharge raised the reservoir level to near MAFL, which is into the designed flood zone and is part of normal flood operations. However, it was observed that the shear displacements in the clay shale increased in response to reservoir surcharging, which raised concerns regarding the stability of the dam. The results of an interim stability analysis completed in the fall of 2011 indicated that the factor of safety of the dam was significantly less than normally acceptable levels (Chin 2012).

The dam owner, the Water Security Agency (WSA) retained Klobn Crippen Berger Ltd. (KCB) in early 2012 to carry out a detailed evaluation of the dam stability. The study was designed to be carried out in phases, which enables the scope of the next phase to be optimized based on the results of the preceding phase.

The immediate near term objective was to confirm the level of safety of the dam with a 3D limit equilibrium analysis and to establish any operating restrictions that may be required during the next (2012) freshet period. The

longer term objective was to complete a comprehensive evaluation of the stability of Alameda Dam, including the potential impact(s) of ongoing foundation movements on its associated structures. The evaluation consisted of site investigations, 2D and 3D limit equilibrium analyses and advanced 2D and 3D deformation modeling (FLAC). This paper describes the assessment methodology, and highlights the key results and conclusions from the study.

2 POST-CONSTRUCTION BEHAVIOUR

An extensive instrumentation program consisting primarily of piezometers and inclinometers has been in place to monitor the behaviour of the dam. The general layouts of the instruments are shown in section on Figure 3 and in plan on Figure 4. Typical trends of selected instrument readings are shown on Figures 5, 6, 7 and 8.

As shown in Figure 5:

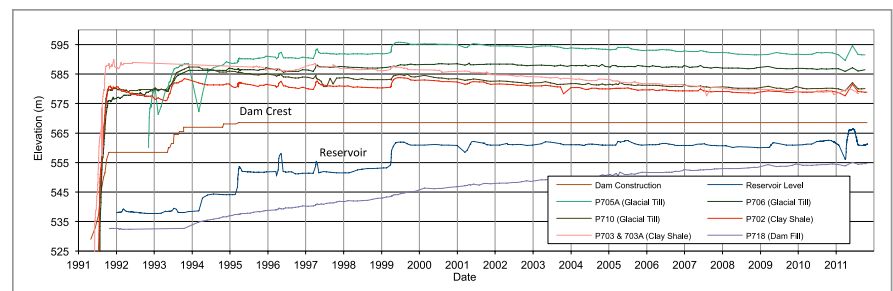


Figure 5: Typical Pore Pressure Response

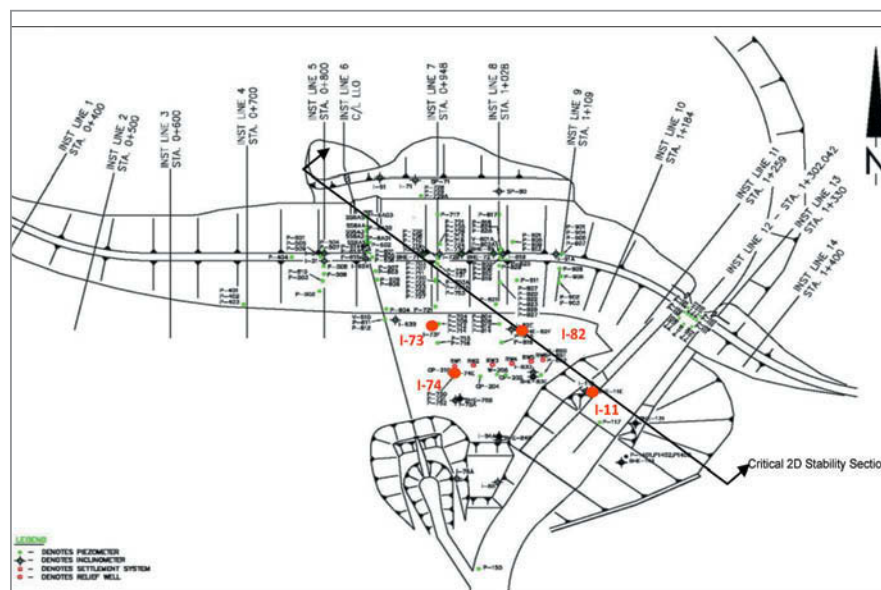


Figure 4: Instrument Layout and Critical 2D Stability Section

- Pore pressures in both the foundation glacial till (P705A, P706 and P710) and the clay shale (P702 and P703) have exhibited a slowly decreasing trend since the end of construction, indicative of ongoing dissipation. However, they have remained high even after 18+ years following the end of construction.
- Pore pressures in the foundation increased when reservoir was surcharge in 2011. The magnitude of this response attenuated rapidly in the downstream direction. (Although not shown, the response in piezometers near the downstream toe was negligible.)
- Pore pressures in the upstream zone of the dam (P718) exhibit a steadily increasing trend with time, indicative of the slow rate of saturation of the core. This slow rate of saturation is common for earthdams with wide cores after first impoundment. As shown in Figure 6:

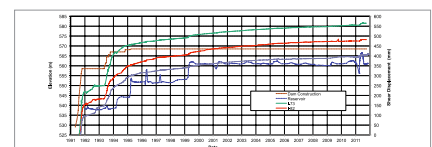


Figure 6: Typical Shear Displacements in Clay Shale

- Shear displacements in the clay shale have continued after construction at steadily decreasing rates.
- The maximum shear displacement to date, as measured at I-73, is about 570 mm.

Figure 7 shows a typical profile of cumulative movements versus depth at I-73. As shown, the horizontal movements are dominated by discrete displacements along a shear plane in the clay shale, with little to no incremental movements in the overlying glacial till or in the intact portions of the bedrock.

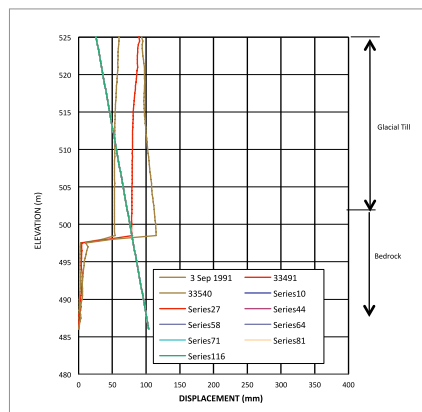


Figure 7: Typical Deformations at I-73 (Resultant of A and B Axes, 1991 to 1994)

An enlarged scale of the shear displacements recorded at I-73 in 2011 is presented on Figure 8, which clearly shows an increase in shear displacements in response to the rise in reservoir level. It was this observation which triggered the concerns regarding the stability of the dam. (Note: similar responses were also recorded in other inclinometers; however, the magnitudes of the response attenuated rapidly in the downstream direction, becoming almost negligible at inclinometers near the downstream toe.)

Of relevance to later discussions, Figure 9 highlights the fact that the directions of shear displacements vary widely across the dam footprint. They range from being nearly perpendicular

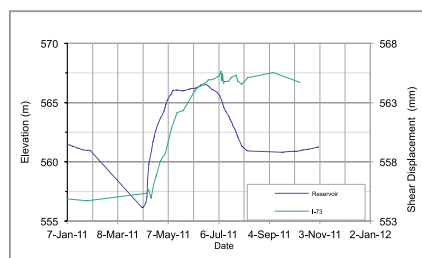


Figure 8: Typical Shear Displacement at I-73 During Reservoir Surge in Spring of 2011

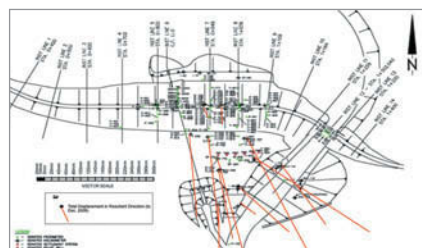


Figure 9: Direction of Shear Displacements (as of December 2008)

to the dam axis in the western portion of the dam, to a southeasterly direction that is oblique to the dam axis and nearly perpendicular to the spillway chute and stilling basin. This pattern of foundation displacements provides clear evidence that the dam performance is strongly influenced by 3-dimensional (3D) effects.

3 LIMIT EQUILIBRIUM STABILITY ANALYSES

3.1 2011 Interim Stability Analysis

Soon after the stability concerns were raised, WSA retained a consultant to promptly carry out an interim stability analysis of the dam. The analysis assumed the following:

- Material strength parameters were assumed to be similar to those used for the final design of the dam, as summarized in Table 1.
- The bottom of the failure surface was aligned coincident with an assumed continuous shear plane at approximately El. 498 m.
- Pore pressures were based on observed groundwater conditions and historical response of the piez-

as possible to reduce the risk of catastrophic dam failure and protect against potential undesirable consequences. The consultant also recommended that additional detailed analysis should be completed as quickly as possible, including an evaluation of potential remediation options that would improve the stability of the dam to meet the current CDA (2007) Guidelines.

3.2 3-D Stability Analysis

As previously discussed, evidence from instrument data suggests that the performance of the dam is strongly influenced by 3D effects, and therefore, it is reasonable to expect that these effects will play an important role in the overall stability of the dam. In order to assess these effects, 3D stability calculations were carried out using the computer program Clara/W, as follows:

- The 3D model was generated by a series of approximately parallel cross-sections along the dam alignment, which were developed based on original ground topography and available as-built surveys of the dam surface.
- The stratigraphic foundation layers were established using the same

Table 1. Assumed Material Parameters for 2011 Analysis

Material	Effective Friction Angle (degree)	Cohesion (kPa)	Unit Weight (kN/m ³)
Dam Fill	32	0	20.5
Glacial Till	30	0	21
Clay Shale (shear plane)	7 (lower bound)	0	21
	9 (upper bound)		
Intact Bedrock	40	0	20.8

ometers to previous increases in reservoir levels.

The analysis was carried out using the computer program Slope/W by Geostudio. The critical 2D section having the lowest factor of safety is aligned obliquely to the dam axis and extends into the spillway stilling basin (see Figure 4). The calculated factors of safety for the upper bound residual friction angle of 9° were 1.12 under FSL conditions and 1.0 under MAFL conditions.

On the basis of these interim results, the consultant recommended that the reservoir level should be lowered to FSL, or lower, as quickly

as possible to reduce the risk of catastrophic dam failure and protect against potential undesirable consequences. The consultant also recommended that additional detailed analysis should be completed as quickly as possible, including an evaluation of potential remediation options that would improve the stability of the dam to meet the current CDA (2007) Guidelines.

- Pore pressures were input into the model as piezometric surfaces associated with a particular foundation or embankment unit, based on piezometer data.
- The angles and locations of the back scarp (active wedge) and breakout (passive wedge) zones of the sliding mass were specified to be the same as the “optimized” 2D sliding surface.

- The sensitivity of the 3D factor of safety was assessed against the aspect ratio (i.e. ratio of the width of the sliding mass to the length of the sliding mass) and against the assumed angles of the side-slopes that form each end of the sliding mass.
- 3D analyses were carried out for a 3D model generated parallel to the critical 2D oblique section (Figure 10) and a 3D model generated perpendicular to the dam axis.

The 3D stability analysis was completed prior to the 2012 runoff to allow appropriate operation of this structure.

As shown on Figure 11, the 3D stability analysis for the oblique model shown in Figure 10 yielded a minimum 3D factor of safety of 2.0 at an aspect ratio of 0.6 to 0.75. This result indicates the significant contribution from 3D effects at this site, increasing the minimum 2D factor of safety by about 100%. This magnitude of contribution

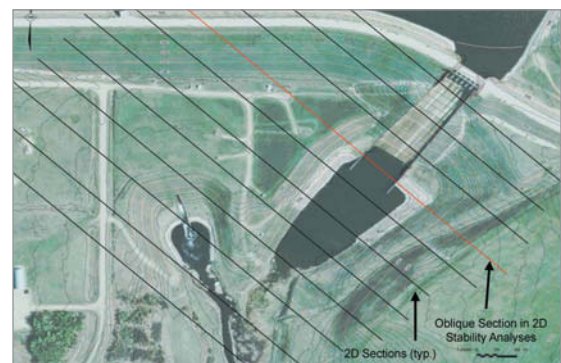


Figure 10: Oblique 2D Sections Developed for Generation of 3D Stability Model

is greater than would normally be expected based on the authors' previous experience. However, both the physical features of the dam and the pattern of foundation displacements indicated by the inclinometers would suggest that 3D methods of analyses are more representative of the actual conditions than 2D analyses.

Additional comments and observations from the 3D analyses are highlighted below:

- The 2D version of the model was checked in Clara/W against Slope/W to verify program consistency. The results were found to be very similar, with factors of safety near unity.
- The factor of safety for a 3D model generated perpendicular to the dam axis is also about 2, which is similar to the 3D oblique model.

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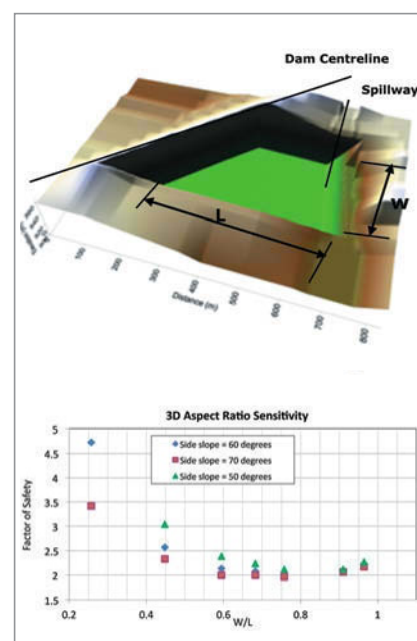


Figure 11: 3D Stability Analysis - Oblique Section

- As a broad check, a weighted average of the 2D factors of safety for each of the 2D sections was determined. This is an approximate and simplified way of simulating 3D conditions, but is conservative because it neglects the additional resistance provided at the two ends of the sliding mass. The weighted average factor of safety calculated in this manner is about 1.5.

4 STRESS DEFORMATION ANALYSIS (2D AND 3D FLAC MODELING)

4.1 Approach and Methodology

The results of the 3D stability analyses have shown that the overall stability of the Alameda Dam is satisfactory if 3D effects are invoked. Nevertheless, in view of the very low 2D factor of safety (i.e. near unity), it was considered prudent to carry out deformation modeling to provide greater insight into the key factors controlling field behaviour and to evaluate future performance. The approach was to calibrate the model

by “matching” the results to historical performance during construction using FLAC as the software platform. The calibrated model was then used to verify the limit equilibrium factors of safety and to estimate the likely patterns and magnitudes of deformations at incipient failure to provide a basis for judging acceptability of future performance.

At the outset of the project, it was acknowledged that 2D models will be limited in their inability to incorporate 3D effects. At the same time, it was also recognized that the more complex the modeling exercise, the more effort is required to properly interpret the results and to understand the relative influences of key parameter assumptions. For this study, every effort was made to achieve a reasonable balance between the simpler 2D model and the more complex 3D model.

4.2 Calibration of 2D and 3D FLAC Models

The deformation behaviour of the dam and foundation is expected to

be largely controlled by the strength and deformation properties of the glacial till overlying bedrock. Therefore, the glacial till parameters were the main focus of the FLAC calibrations. Space restrictions preclude providing a detailed description of the calibration process, but the key highlights are summarized herein.

Given the intended objective of the study, it was considered appropriate to use a linear elastic model for the dam fill, an elastic-plastic model for the shear zone in the clay shale and a hyperbolic model for the glacial till. The elastic parameters assigned to the constitutive models for the dam fill and shear zone were selected from experience. Strength parameters for the shear zone were selected for consistency with the limit equilibrium analyses. These parameters were then kept constant, while the glacial till parameters were varied for calibration with historical behaviour.

Calibration of the glacial till parameters progressed from “simple” to “complex” in the following way:



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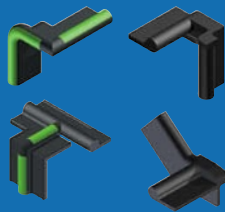
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- The starting parameters were based on data from site investigations completed as part of this study, including pressuremeters and a specialized lab program consisting of consolidated undrained triaxial compression tests, consolidated drained triaxial compression tests and consolidated undrained triaxial extension tests on glacial till samples. Model verification was established using 2D FLAC to simulate the pressuremeter and triaxial test results, and through closed-form analytical solutions to these analyses.
- The starting parameters were refined as necessary using 2D FLAC to calibrate with dam performance during the early stages of construction. Use of 2D FLAC was considered appropriate as the instrument readings indicated that 3D effects were minimal prior to construction of the stabilizing berms. For this purpose, the 2D FLAC model was generated along Instrument Line 7 (see Figure 4) where the largest movements were recorded.
- The final step involved using 3D FLAC to further refine the parameters derived from the 2D FLAC calibrations.

Dam construction was simulated by applying successive load increments, as summarized in Table 2.

Effective stress analyses were carried out for both 2D and 3D FLAC modeling. Pore pressure inputs for 2D FLAC were simplified by assigning equivalent average B-bar values determined from actual piezometer readings for each load increment. Pore pressures for 3D FLAC were determined by interpolation of actual piezometer readings using the method described by de Alencar et al (1992).

The finite difference mesh generated in 3D FLAC is shown on Figure 12. A typical cross-section from 3D FLAC, cut along Instrument Line 7, is shown on Figure 13. The “final” calibrated material parameters from 3D FLAC which provided the “best match” of the results with measured displacements at the end of construction are summarized in Table 3.

Simulation	Date	Dam Lift		Additional loadings	FLAC Calibration
Sequence		Lift No.1	Crest El. (m)		
1				Excavations: 50% spillway & 100% original LLO	Sequence 1 to 7: 2D FLAC and 3D FLAC
2	June 11, 1991	1	533.0	Excavations: 75% spillway	
3	July 16, 1991	2	537.5	Excavations: 100% spillway	
4	August 2, 1991	3	544.0		
5	September 3, 1991	4	550.0	Reservoir level filled from El. 530 to 539 m	
6	September 14, 1991	5	551.5		
7	September 30, 1991	6	556.0		
8	Oct. 1 to Nov 8, 1991	-	-	Stage 1 of downstream berm	Sequence 8 to 19: 3D FLAC only
9	October 24, 1991	7	558.5		
10	Apr. 29 to May 22, 1992	-	-	Upstream berm	
11	Aug. 29 to Oct. 14, 1992	-	-	Stage 2 of downstream berm	
12	May 21, 1993	8	560.0		
13	June 18, 1993	9	561.5		
14	July 14, 1993	10	564.5		
15	September 1, 1993	11	566.5		
16	October 15, 1993	12	567.0		
17	Spring 1994	-	-	Reservoir level filled from E. 539 to 544 m. Tailwater level in spillway & LLO stilling basin at El. 526 m.	
18	Fall 1994	-	-		
19	November 3, 1994	13	568.1		

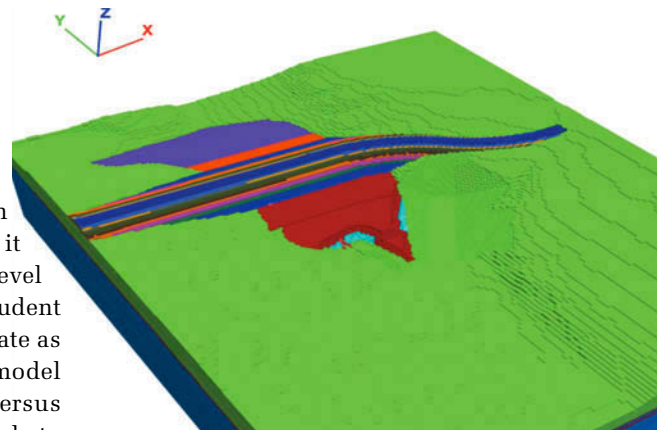


Figure 12: 3D FLAC Model

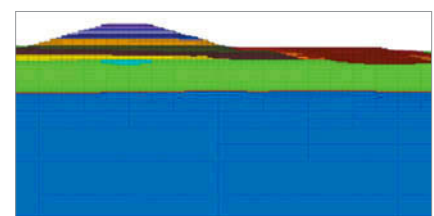


Figure 13: 2D Section from 3D FLAC Model

It is worth noting that, given the complexity of the problem, it became apparent that a certain level of practical compromise was prudent between the desire to incorporate as much detail as possible in the model to accurately reflect reality, versus limiting the amount of detail only to a level necessary to achieve a satisfactory “model equivalence”. A key learning in terms of achieving “model equivalency” in a practical way was to maintain the thickness of the shear zone constant throughout the model and to ensure that the bottom elevation of the shear zone was the same in every simulation.

Table 3. Material Parameters From 3D FLAC Calibration of Dam Construction Performance

Material Model		Parameters							
		Unit Weight	Elastic		Strength			Hyperbolic	
		(kN/m ³)	E (MPa)	n	c' (kPa)	φ' (deg.)	k (MPa)	n	Rf
Dam Fill	Linear Elastic	20.5	80	0.45	0	n/a	n/a	n/a	n/a
Glacial Till	Hyperbolic	21.0	n/a	0.40	0	30	800	0.80	0.90
Shear Zone	Elasto-Plastic	20.8	45	0.45	0	8	n/a	n/a	n/a
Clayshale	Linear Elastic	20.8	1000	0.45	0	40	n/a	n/a	n/a

Note: E = elastic modulus, n = Poisson's Ratio; c' = effective cohesion; φ' = effective friction angle; k = Young's modulus (at reference pressure) for hyperbolic model; n = modulus function for hyperbolic model; Rf = failure ratio for hyperbolic model.

5 RESULTS OF 3D FLAC MODEL

5.1 Comparison of Shear Displacements

Figure 14 provides a comparison between computed versus measured displacements at 4 inclinometers. The 4 inclinometers chosen for calibration include I-11, I-73, I-74 and I-84, and are located spatially across the dam as shown on Figure 4. Not all of these instruments were installed at the start of construction; therefore, it was necessary to adjust the displacements calculated by 3D FLAC

to coincide with the installation date of the inclinometers. As shown, the calibrated 3D FLAC model was capable of computing shear displacements that closely matched measured displacements simultaneously at 4 different inclinometer locations using one set of material parameters. The predicted magnitudes and trends of the displacements in response to dam construction are both comparable to measured displacements.

A similar outcome would not have been possible with a 2D model. In fact, in view of the variations in movement direction shown on Figure 9, one can

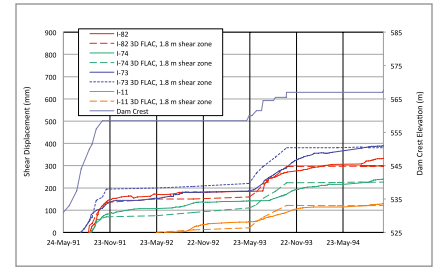


Figure 14: 3D FLAC Shear Displacements Versus Measured Shear Displacements at I-11, I-73, I-74 and I-82

imagine that a different set of material parameters will most certainly be required to match the movements at a given inclinometer depending on how the 2D FLAC model is oriented in relation to that inclinometer.

5.2 Comparison of Displacement Directions

Figure 15 compares the directions of movements computed by 3D FLAC to the actual movement directions recorded in a number of inclinometers, for the November 1994 period. As shown, the movement directions predicted by the model are less



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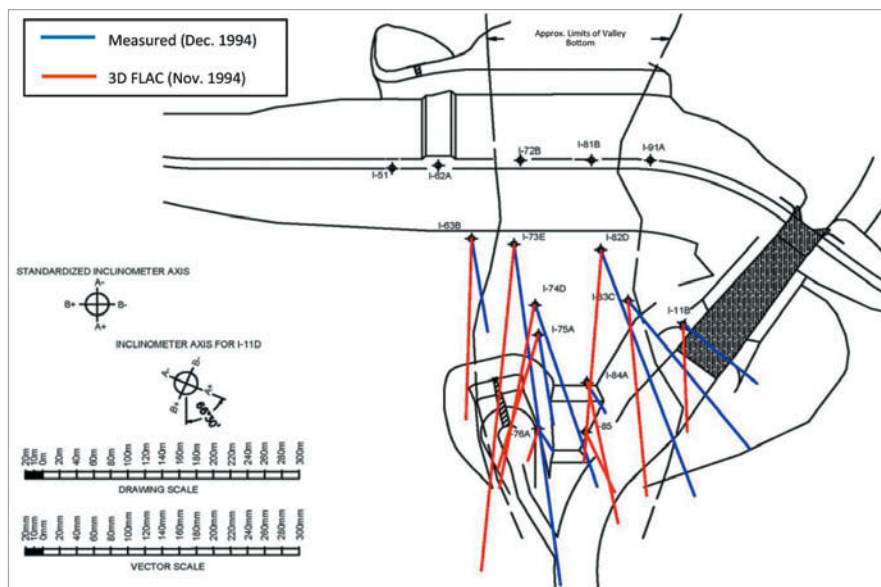


Figure 15: 3D FLAC Movement Directions Versus Actual Movement Directions

satisfactory than the magnitudes. Further interrogation of the model results will be necessary to identify the main factors impacting the computed movement directions, but this is beyond the terms of reference of the current study.

5.3 3D FLAC Factors of Safety – Conventional Strength Reduction Method

It is worth noting that 2D or 3D deformation analyses offer the additional benefit of providing an independent means of calculating the factor of safety for comparison to limit equilibrium methods. This is done in FLAC by using the Strength Reduction Method whereby, after an equilibrium state of the numerical model has been solved (for instance, the end of construction state or the post-construction state), the strength parameters are divided by a series of prescribed strength reduction factors, with the model being brought back to equilibrium after the application of each factor. The factor of safety is then determined as the strength reduction factor required to cause the model to no longer reach an equilibrium state, or from the occurrence of a distinct inflection in the plots of displacement versus strength reduction factor.

The results of the strength reduction method are presented on Figure

16 together with relative displacement contours to help illustrate the general shape of the 3D sliding mass. As shown, the equivalent factor of safety using 3D FLAC is 2.2, which is consistent with the factor of safety of 2.0 previously computed using 3D limit equilibrium method. Of interest, the apparent direction of sliding is towards the spillway providing support to the view that the critical stability section is oblique to the dam axis, consistent with the limit equilibrium calculations.

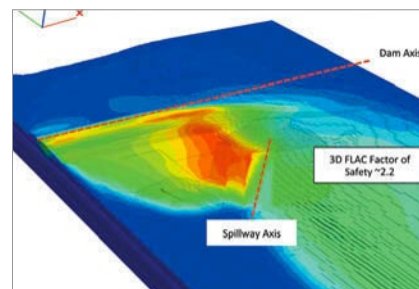


Figure 16: 3D FLAC Factor of Safety by Conventional Strength Reduction Method

5.4 3D FLAC Factors of Safety – Strength Reduction Applied to Glacial Till Only

The factor of safety determined by 3D FLAC using the conventional strength reduction method is consistent with the definition of the factor of safety in limit equilibrium methods. This allows a direct comparison of the two results as a means for independent validation. In actuality, however, it is likely that the stability of the dam and displacements in the shear zone will be controlled by the properties of the glacial till, and therefore, it is of interest to determine the factor of safety relative to the mobilized strength of the glacial till.

This was determined by applying a series of prescribed strength reduction factors to the glacial till only, while keeping the strengths of the other

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materials unchanged. This method of calculation yielded a factor of safety of 3.6 against a potential failure that is triggered by yielding of the glacial till.

5.5 Calculated Shear Displacements and Glacial Till Shear Strains at Incipient Failure

Additional insight regarding the stability of the dam can be provided through a review of the theoretical magnitudes of shear displacement in the clay shale, and the shear strains in the glacial till, at the point of incipient failure.

The magnitude of displacements that could theoretically develop at incipient failure for I-11, I-73, I-74 and I-82 are presented on Figures 17. The results computed using the conventional strength reduction method and the “till-only” reduction method are both included, and range between 1000 mm and 3000 mm. These “failure” displacements are about 3 to 10 times greater than the actual displacements measured to date.

Shear strains that could theoretically develop in the glacial till, within the region of the passive wedge, at incipient failure are shown on Figure 18. As shown, the shear strains range from 7% to 15%, which are close to or greater than the minimum “failure” shear strain measured at peak deviator stress in consolidated undrained triaxial tests on glacial till samples.

Figure 19 plots the shear displacements versus the reduction in glacial

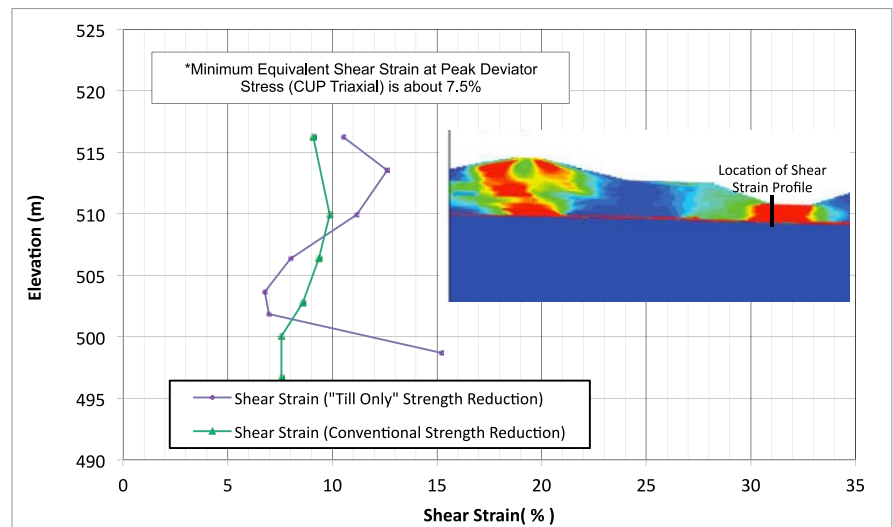


Figure 18: Theoretical Shear Strains in Glacial Till Near Downstream Toe of Dam, at Incipient Failure

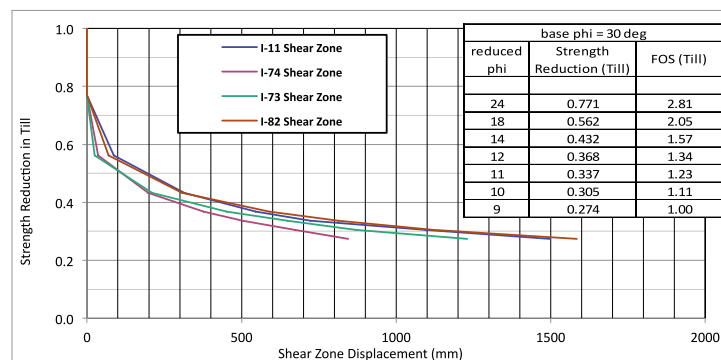


Figure 19: 3D FLAC – Shear Displacement Versus Till Strength Reduction Factor

till strength. The results indicate an expected trend whereby the incremental rate of shear displacements begins to increase more rapidly as the glacial till strength reduction factor (or factor of safety) decreases.

Table 4 presents a comparison between the shear displacements and glacial till shear strains, as computed by 3D FLAC at the point of incipient failure of the dam, and the actual displacements and shear strains measured to date. The comparison is made near the toe of the critical oblique section where I-11 is located. It is evident by this comparison that there is significant reserve strength remaining in the glacial till.

6 CONCLUSIONS AND COMMENTS

Concerns were raised regarding the stability of the dam when displacements along the clay shale shear plane increased in response to surcharging of the reservoir in the spring of 2011. Conventional 2D limit equilibrium analysis completed at that time indicated that the factor of safety of the dam was significantly below normally acceptable levels. Assuming a residual

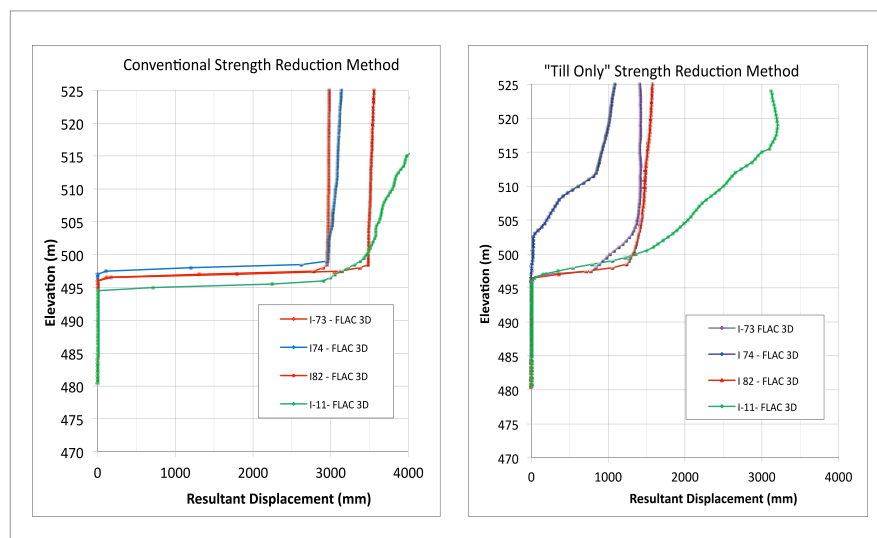
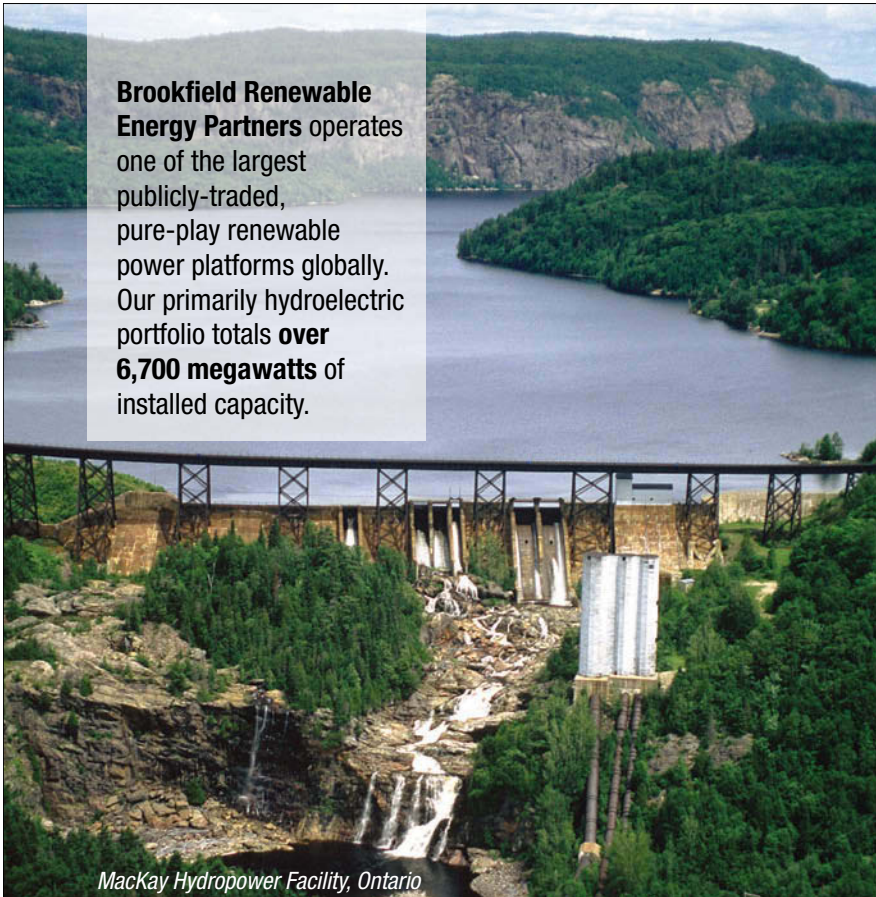


Figure 17: Theoretical Shear Displacements at Incipient Failure

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friction angle of 9 degrees in the clay shale shear plane, the calculated factors of safety were reported to be 1.12 at FSL and 1.0 at MAFL conditions.

Based on the detailed evaluations completed since then, it is apparent that the stability and performance of the dam is strongly influenced by 3D effects. These contributions are significant, increasing the factor of safety to 2.0 when 3D effects are invoked (i.e. approximately doubling the 2D factor of safety).

The completion of advanced deformation modeling using FLAC as the software platform provided further insight into the key factors controlling field behaviour, which would otherwise not have been achieved through limit equilibrium methods only. Because of the site conditions, 2D FLAC was not capable of replicating the 3-dimensional aspects of field behaviour and it was necessary to use 3D FLAC for the majority of the analysis. Nevertheless, every effort was made to achieve a reasonable balance between the simpler 2D model and the more complex (and time-consuming) 3D model.

The results of the 3D FLAC modeling were extremely valuable to the project on several fronts. Firstly, the modeling work provided a means to independently verify the appropriateness of, and therefore provide greater confidence in, the 3D limit equilibrium results. This additional support was considered prudent since the contribution of 3D effects to overall stability at this site is much greater than normally expected based on the

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Table 4: Displacements and Shear Strain Comparisons

3D FLAC Strength Reduction Method	3D Factor of Safety	Computed Shear Displacement Near Toe of Oblique Section At Incipient Failure	Current Shear Displacement at Inclinator I-11	Computed Shear Strain in Till Near Toe of Oblique Section at Incipient Failure	Current Maximum Shear Strain in Glacial Till in I-11	Average Failure Shear Strain of Till at Peak Deviator Stress (Triaxial Test)
Conventional	2.2	3000 mm	235 mm	7 to 10%	<2%	~7%
Till Only	3.6 (on Till Strength)	1500 mm	235 mm	7 to 15%	<2%	~7%

authors' experience. One of the most important aspects of the deformation modeling was to provide significant insight into the possible mechanisms and deformation trends that might be expected if the dam is near the point of incipient failure. It is clear from these insights that the deformations to date are well within acceptable levels and that the glacial till overlying the bedrock has ample reserve strength to maintain stability of the dam in the long term.

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