A case history of modeling and monitoring of ground movements adjacent to an oil sands mine pit slope

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ABSTRACT
Deformation modeling for an area adjacent to a planned mine pit slope at Shell Canada Energy's Athabasca Oil Sands Project was performed in order to predict the extent and magnitude of mining-induced ground movements. The location of new plant facilities close to the pit crest and sensitive to foundation movements created the need for detailed attention to predicting and monitoring pit slope performance. The hypothesized ground movement mechanism was the development of a progressive failure along a weak layer or layers in the McMurray Formation deposits exposed in the pit slope upon stress relief during mining. The deformation modeling was performed using the finite difference software FLAC, with the model geometry based on the planned pit slope excavation sequence and profile. The soil/rock properties for the model were based on the available geological and geotechnical information, case histories of other large excavations into the McMurray Formation and estimated in-situ horizontal stresses.

The actual ground movements adjacent to the pit slope were monitored during the initial years of mining and the pre-mining numerical analysis was revised and calibrated prior the construction of new plant facilities even closer to the pit slope. The revised analyses showed that additional movements would occur during the remainder of mining, the timing of which would overlap with the construction of the new plant facilities. Therefore, an expanded monitoring program was undertaken to help manage the risk of ground movement to the plant facilities. The further monitoring showed that additional ground movement did occur, but with magnitudes and extents that were less than predicted by the revised model.

RÉSUMÉ
Une modélisation des déformations anticipées pour un secteur situé à proximité d'un futur talus de la mine Athabasca Oil Sands de Shell Canada Energy a été entreprise afin the prévoir l'ampleur des mouvements de terrain induits par les activités minières. L'emplacement retenu pour les installations, près du sommet du talus, et la sensibilité des fondations aux mouvements de terrain ont exigés de porter une attention particulière à la prédiction et au suivi du comportement de la pente. Le mécanisme anticipé des mouvements de terrain consiste en une rupture progressive le long d'un ou plusieurs plans de faiblesse dans la formation McMurray mis à jour dans le talus créé par l'exploitation de la mine et soumis à un déchargement de contraintes dans le sol. L'analyse des déformations a été effectuée au moyen du logiciel à différences finies FLAC, en tenant compte de la géométrie anticipée lors des travaux d'excavation. Les propriétés des sols et du rocher utilisées pour la modélisation ont été établies sur la base d'informations géologiques et géotechniques disponibles, d'études de cas traitant d'excavations similaires de grande taille dans la formation McMurray et des contraintes in-situ horizontales estimées.

Les mouvements réels du terrain au sommet du talus ont été suivis dans les premières années suivant le début de l'exploitation de la mine. Les données résultantes ont été utilisées afin de calibrer et de réviser les analyses numériques pré-exploitation et ce, avant la construction de nouvelles installations implantées encore plus près du talus qu'anticipé à l'origine. Ces analyses révisées démontrent que des mouvements additionnels se produiront pendant les activités minières futures, incluant pendant la construction des nouvelles installations. En conséquence, un programme de suivi étendu a été mis en place afin de mieux gérer les risques associés aux mouvements de terrain. Les résultats de ce suivi ont démontré que des mouvements de terrain se sont en effets produits, mais que l'ampleur desdits mouvements est moindre qu'anticipé sur la base des résultats des analyses révisées.

1 INTRODUCTION

Shell Canada Energy (SCE) operates the Muskeg River Mine (MRM), an open pit oil sands mining and extraction facility, approximately 70 km north of Fort McMurray, Alberta. The location of plant facilities close to the pit crest and sensitive to foundation movements created the need for detailed attention to predicting and monitoring pit slope performance. Figures 1 and 2 illustrate the relative position of the plant facilities and the pit slope.

This paper describes the numerical analysis of potential ground movement prior to the construction of the initial plant facilities and the start of mining, ground movement monitoring during the initial years of mining, a subsequent revision of the numerical analyses using additional geological and instrumentation data available, followed by monitoring to the completion of mining adjacent to the plant site.

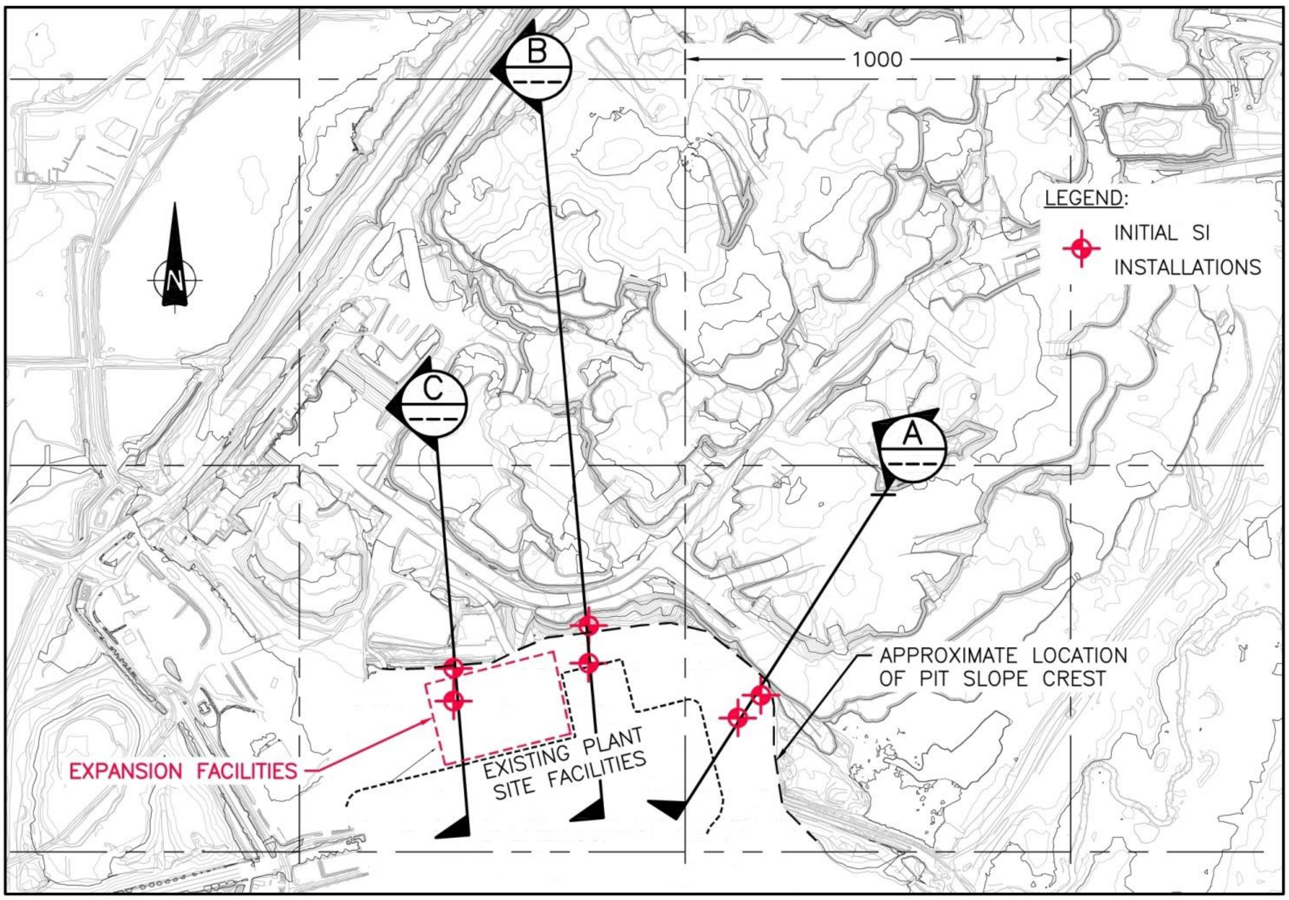

Figure 1. Site plan

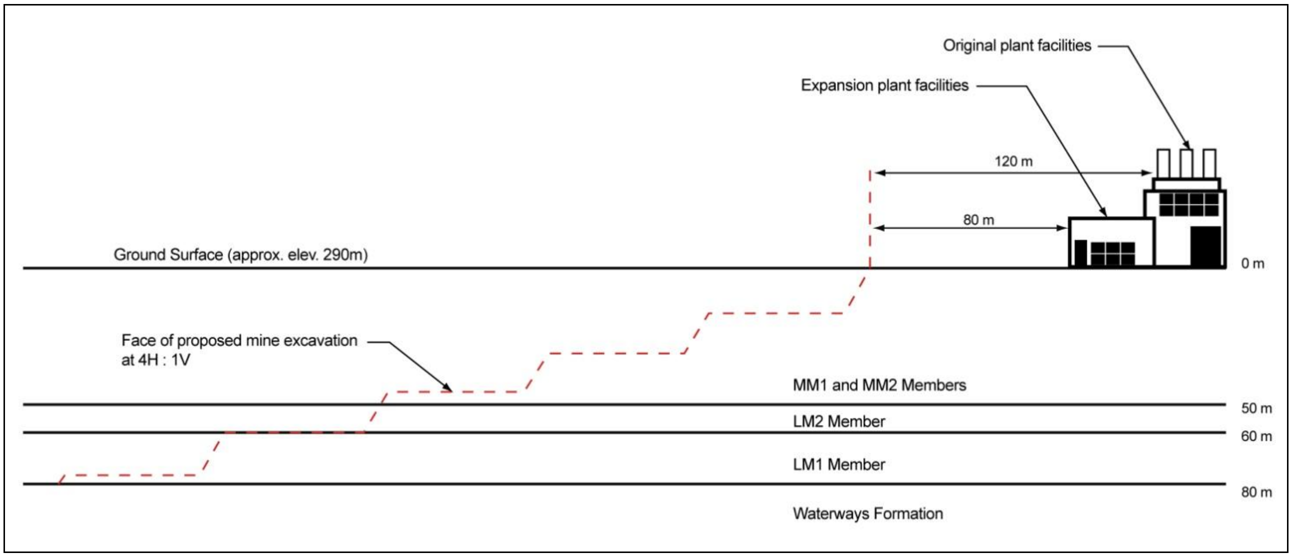

Figure 2. Schematic Cross-Section Of Plant Site and Mine Pit Slope Area

2 GEOLOGICAL CONDITIONS

The generalized geological profile in the MRM plant site and mine pit area is as follows in Table 1 (see also the schematic cross-section on Figure 2):

Table 1. Geological profile.

Depth	Stratigraphic Unit
0 to 50 m	McMurray Formation – MM2/MM1 Members (tidal and estuarine deposits)
50 to 60 m	McMurray Formation – LM2 Member (continental deposits)
60 to 80 m	McMurray Formation – LM1 Member (fluvial deposits)
Below 80 m	Waterways Formation (Devonian aged limestone)

Further description of the characteristics and properties of the McMurray and Waterways Formation deposits are found in Dusseault (1977) and Kosar (1989).

During the initial analysis it was known that the thickness of the various members of the McMurray Formation varied across the plant site. In particular, the thickness of the LM2 Member was known to vary appreciably from 0 to roughly 35 m across the plant site area. Furthermore, the LM2 Member was also known to contain weak, slickensided (pre-sheared) clay layers that are generally near-horizontal to sub-horizontal (dips of 10° or less) and therefore could be significant with respect to mining-induced ground movement. However, the density of borehole data at the time did not provide a sufficient basis for a firm interpretation of the distribution and lateral continuity of such layers. Therefore, the generalized geological profile described above was used for the pre-mining analysis and it was recognized that it was a conservative interpretation of the information available at the time.

3 GEOTECHNICAL CONDITIONS

The key geotechnical conditions with respect to mining-induced ground movements are as follows.

3.1 In-Situ Stress Conditions And Stress Relief Due To Mining

The McMurray Formation is a highly overconsolidated deposit, therefore the in-situ horizontal stresses are relatively high and difficult to estimate precisely without detailed knowledge of the stress history of the soil at a particular site. The release of the in-situ horizontal stresses due to mining of the McMurray Formation was recognized to be a key factor in the initiation of any ground movements. The estimated distribution of horizontal in-situ stresses used in the pre-mining analysis was based on case histories from other oil sands projects.

3.2 Weak Layers In The McMurray Formation Deposits – Consistency

3.2.1 Tidal Clay Layers In The MM2 Member

These clay layers are relatively common and typically consist of either relatively thick layers (e.g. greater than 2 or 3 m) of Tidal Flat Mud (TFM) or Mud Flat (MF), or as thin (e.g. less than 15 mm) layers in an interbedded sand and clay Tidal Flat Mixed (TFX) sequence.

3.2.2 Clay Layers In The LM2 Member

These layers are continental marsh, coal swamp or backswamp deposits and are often slickensided (pre-sheared) and therefore have strengths that are approaching residual values. The bedding dip of these clay layers is generally between 6° and 10° however it can be as low as 2° to 6°. The distribution of slickensided layers within the LM2 Member is relatively sporadic and unpredictable and their lateral continuity is difficult to determine from borehole data. It was judged that these layers are not laterally continuous over hundreds of metres, but a specific value of the typical lateral continuity could not be reasonably assumed based on the available information. Therefore, for the purposes of the analysis a continuous, horizontal weak layer extending several hundred metres was assumed. This was recognized to be a conservative assumption.

3.3 Gas Exsolution

Gas exsolution occurs on an ongoing basis during the mining of oil sands and is characterized by softening and severe deformation within bitumen rich zones on the exposed pit face. Gas exsolution affects may also occur in areas behind the pit face that are affected by relief of in-situ stresses by adjacent mining (Morgenstern et al, 1988). Therefore, gas exsolution in bitumen-rich zones of the McMurray Formation may contribute to ground movements in the plant site area.

Gas exsolution effects were incorporated into the pre-mining analysis, with a key assumption that gas exsolution would occur only within a 25 m thick interval of rich oil sand between 54.7 and 80 m depth, i.e. below the assumed LM2 Member weak layer.

4 HYPOTHESIZED GROUND MOVEMENT MECHANISM

It was hypothesized that movement of the ground below the pit slope and the MRM base plant could occur due to the relief of in-situ horizontal stresses in the ground during mining of the McMurray Formation deposits adjacent to the plant site. This could lead to the development of a progressive failure along a weak layer or layers in the McMurray Formation deposits exposed in the pit slope face adjacent to the plant site, resulting in localized yielding and movement along a thin band of soil (referred to as a “shear band”) and propagation of the “shear band” back from the pit slope face and underneath the plant site. In essence, the soil above the weak layer would elastically rebound horizontally towards the pit slope by sliding on the slippery weak layer, resulting in further progressive strain-weakening of the weak layer. The horizontal displacement profile would be characterized by a stepped shape, with large and discrete differential displacement across the weak layer and relatively uniform displacement in the material above it. The elastic rebound of the material above the weak layer would also result in movement at ground surface and at shallow depth within the plant site area. This hypothesized mechanism of ground movement was supported by some of the case histories from other oil sands projects (McKenna and Shelbourn (1995), and unpublished data from another operating oil sands mine) and from excavations in overconsolidated clay shale (Burland et al (1977)). This ground movement mechanism is horizontal elastic rebound on a slippery layer and is significantly different from localized pit slope instability that is managed through the benching of the mine pit slope and which typically exhibits a significant vertical component to the movement.

It was recognized that overconsolidated clays and clay shales in the LM2 Member would be particularly susceptible to progressive failure during mining. These layers are known to have low residual strengths and likely naturally exist at a stress state that is near the yield strength of the soil due to the high in-situ horizontal stresses. The bedding orientation and lateral continuity of weak layers would control the degree to which any shear band due to progressive failure could propagate back from the pit slope face.

The combination of in-situ horizontal stress and the elastic properties of the material above the weak layer were hypothesized to be a key factor controlling the magnitude of deformation under the plant site. The previously-noted uncertainty in the horizontal in-situ stress conditions therefore resulted in uncertainty in the magnitude of predicted movements and this was addressed via a parametric analysis for the distribution of horizontal in-situ stresses.

5 PRE-MINING NUMERICAL ANALYSIS

A numerical analysis for the development of shear band propagation and ground movements below the base plant site was performed using the finite difference software FLAC. The basis and key assumptions for the numerical analysis were developed from the information available prior to mining and were chosen to reflect a conservative but potentially realistic set of assumptions based on existing data, the planned mine pit slope profile and the experience and judgment of the project team. Key assumptions were as follows:

- The simplified geological profile illustrated on Figure 2 was used. A key assumption in this interpretation was the presence of a thin, weak LM2 Member unit between 54 and 54.7 m depth that was continuous across the width of the modeled area. This profile was known to be a geotechnically conservative interpretation but a less conservative interpretation could not be supported by the data available at the time.
- The analysis was performed using a strain-softening Mohr-Coulomb plasticity model for the McMurray Formation deposits. The model permitted representation of nonlinear strain-softening behaviour based on prescribed values of the friction angle, cohesion, and dilation angle as a function of the accumulated plastic strain. An elastic model was adopted to model the response of the foundation Waterways Formation limestone.
- The K_o values were estimated to vary between 3.0 and 1.0 from ground surface to 120 m depth, respectively. This estimate was based on empirical relationships derived from strength and stress history parameters, pressuremeter and hydraulic fracture tests on other oil sands projects and back

analyses of trial excavations on other oil sands projects.

- Elastic Modulus values of 300 MPa and 150 MPa were assumed for the oil sand and LM2 Unit, respectively.
- Peak and residual friction angles of 15° and 9°, respectively, for the LM2 Member. These assumed values were based on direct shear testing results on samples of the LM2 Member. It was recognized that the relatively low residual strength of the LM2 Member was indicative of the potential for initiation of a progressive failure mechanism and shear band development and propagation.

The results of the pre-mining numerical analysis showed that a shear band, delineated by a region of plastic straining at residual strength, would develop in the assumed weak LM2 Member layer (54 to 54.7 m depth) and propagate back from the pit slope face until the end of the pit excavation.

The horizontal and vertical displacements at ground surface resulting from the ground movements at depth that were predicted by the numerical analysis varied with set-back distance from the pit slope crest and with the depth of the mine pit excavation. In summary:

- Between 500 and 950 mm of horizontal movement at the ground surface was predicted for the area within 100 m of the pit slope crest and up to 80 mm of vertical settlement in the same area.
- The predicted horizontal and vertical movements at the ground surface reduced with increasing set-back distance from the pit slope crest and tapered off to zero at a set-back distance of between 500 and 600 m.
- Of note, the model predicted that the largest increments of ground movement would start during mining of the lowermost portion of the MM1 Member approximately 10 m above the top of the LM2 Member and would continue through the mining of the LM2 Member. Only minor movements were predicted to occur during the mining of the material below the LM2 Member.

A parametric assessment was performed to assess the impact of uncertainty in some of the input parameters to the predicted ground movements from the numerical analysis. The parametric assessment showed that the following parameters had a significant impact on the magnitude of the predicted ground movements:

- The detailed geological profile in the McMurray Formation deposits underlying the pit slope and plant site area, namely the presence, orientation and continuity of weak layers in the deposits. This profile had implications on the potential distance for "shear bands" to propagate back from the pit slope and beneath the plant site. A more precise characterization of the presence, continuity and orientation of the weak layers was not considered to be practical due to the natural variability in the McMurray Formation deposits.
- The actual horizontal in-situ stresses within the McMurray Formation. This had implications on the magnitude of stress-relief effects due to mining that would drive the formation and propagation of shear bands. All other parameters being unchanged, a high KO value resulted in greater mining-induced horizontal displacement.
- The actual residual strength of the LM2 Member deposits, if different from the 9° that was used in the analysis. This would affect the amount of localized yielding along the weak layer in the model, and therefore the degree to which the "shear band" would propagate back from the mining face and the resulting horizontal movement of the soil above the weak layer.
- Elastic modulus of the oil sand and LM2 Member deposits. All other parameters being unchanged, a low elastic modulus in the soil above the weak layer resulted in greater mining-induced horizontal displacement.

The numerical analysis showed that gas exsolution would have negligible impact on displacements and strains at the ground surface behind the pit slope crest.

Three options were identified for managing the risk of mining-induced ground movement to the plant site facilities:

- Establishing a sufficient set back of the base plant structures from the pit slope crest so that the surface displacements/strains predicted by the numerical analysis would be within the acceptable limits for the structures in question.
- Designing the base plant structures to accommodate the predicted ground surface displacements and strains.
- Implementing a monitoring program for ground movement as part of an "observational approach" to manage the risk to ground movement to the base plant structures.

After reviewing the results of the pre-mining assessment, the project owner selected a 120 m set-back for the plant site facilities and a ground movement monitoring program was implemented.

6 MONITORING DURING INITIAL YEARS OF MINING, AND SUBSEQUENT REVISED ANALYSIS

A series of slope inclinometers (SI's) were installed at selected locations along and adjacent to the pit slope crest in the plant site area in order to monitor for ground movement during mining, along with piezometers. Figure 1 shows the locations of the SI's that were installed, along with the three instrumented section lines (Sections A, B and C) through the plant site area that the layout of the instruments formed. The instruments were typically read monthly to bi-monthly up to late 2006. The SI data up to May 2006 showed movement in two of the six inclinometers that were installed. The profile of horizontal movement was consistent with the hypothesized shear-band mechanism represented above and is described as follows:

- On Section B, an SI set-back approximately 10 m from the pit slope crest showed up to approximately 100 mm of cumulative movement towards the mine pit from October 2003 to May

2006. The movement occurred above 37 m depth and with discrete movement zones at 28 and 37 m depth. Both of these movement zones showed approximately 40 to 45 mm of displacement and were within weak layers in the MM2 Member. As of May 2006 the accumulated movement had deformed the SI casing to the point where the reading probe could not pass below approximately 35 m depth. A nearby SI located approximately 100 m back from the pit slope crest did not show any movement up to May 2006.

- On Section A, an SI set back approximately 18 m from the pit slope crest showed cumulative movement of approximately 60 mm including two discrete shear zones, each with roughly 1 to 2 mm of movement, in the LM2 Member starting in early 2006. The upper movement zone was at 37 m depth (near the top of the LM2 Member at this location) and the lower movement zone was at 56 m depth. There was no borehole log available for this installation so it was not possible to confirm the facies within the LM2 Member for each movement zone. A nearby SI located approximately 100 m back from the pit slope crest did not show any movement up to April 2006.

As of approximately mid-2006, mining adjacent to the plant site had generally progressed to around 40 to 50 m depth (vs. a planned final pit depth of approximately 80 m). The hypothesized ground movement mechanism was supported by the actual monitoring data, but the actual horizontal movement in the SI's was found to be significantly less than predicted by the pre-mining model. Of note, the mining of the bench just above and through the LM2 Member had not been completed as of mid-2006. This was the portion of the pit excavation that was expected to cause the largest increments of ground movement. Therefore, notwithstanding the movement data, the pre-mining model had not been fully "tested out" by comparison with monitoring data during mining through the LM2 Member.

The pre-mining analysis was revisited in 2006 due to a planned expansion of the plant site facilities that would include construction of additional structures to within 80 m of the pit slope crest between 2007 and 2009. The mining of the pit adjacent to the plant site was scheduled to be completed by the third quarter of 2009, which would result in roughly two years of overlap between the remainder of mining adjacent to the plant site and the construction of the new facilities closer to the pit crest. At the time, there was no option to accelerate the mining and/or delay the construction of the new facilities. Therefore, there was a potential for mining-induced ground movement, including the predicted peak movements during mining above and through the LM2 Member, to damage the facilities under construction as well as possibly the original facilities set further back from the pit. The completion of mining adjacent to the plant site was later rescheduled to mid-2008 due to other factors; however, this did not completely eliminate the risk to the plant facilities from mining-induced ground movement.

It was decided that the best available method to predict future mining-induced ground movement was to calibrate the deformation model to the existing mine conditions and actual horizontal movements using the updated geological and instrumentation data along with the current pit slope profile.

The pre-mining deformation model was revised and updated with the following information:

- Mine pit topography as of May 2006 and the planned end-of-year pit slope profiles for 2006 to 2009. This data was used to replace the generalized pit slope profile used in the pre-mining analysis (Figure 2) with Sections A, B and C.
- Additional geological information acquired from 2000 onwards for the mine pit and plant site area. This information was used to refine the geological profile used in the pre-mining numerical analysis to area-specific cross-sections for Sections A, B and C. The key change that resulted was the use of verified non-uniform thicknesses of and non-horizontal contacts between the various McMurray Formation members underlying the pit slope and plant site.
- Data from the SI's and piezometers that were installed and monitored during mining up to 2006.

The geological cross-sections used in the revised analysis still included a continuous weak layer extending several hundred metres back from the pit slope face. This was still recognized as very likely being a conservative assumption; however, the additional information available from the initial years of mining could not support a less conservative interpretation. Additional borehole drilling or other subsurface investigation was not planned because it was unlikely that sufficient borehole coverage could be obtained to make any definitive conclusions with respect to the continuity of weak zones in the LM2 Member.

In order to better match actual displacements, the calibration of the updated model generally required increasing the residual shear strength of the LM2 Member weak layer and decreasing the elastic modulus of the soils above the weak layer. There was no new information regarding the distribution of in-situ stresses in the McMurray Formation at the plant site, and therefore the KO profile from the original pre-mining model was not altered.

Selected results of the calibration of the deformation model are illustrated on Figures 3 and 4, as follows:

- Figure 3 shows the modeled horizontal displacements at Section B for mining up to mid-2006. The contours of the displacements illustrate the expected progressive failure mechanism with yielding and movement along the weak layer in the model.
- Figure 4 shows a comparison between the modeled horizontal displacement profile at the pit slope crest for Section B and the field measurements of horizontal displacement from the SI's installed along Section B. The modeled and measured displacement profiles are very similar, which indicates that the calibrated model was reasonably accurate for the measured ground movements up to mid-2006.

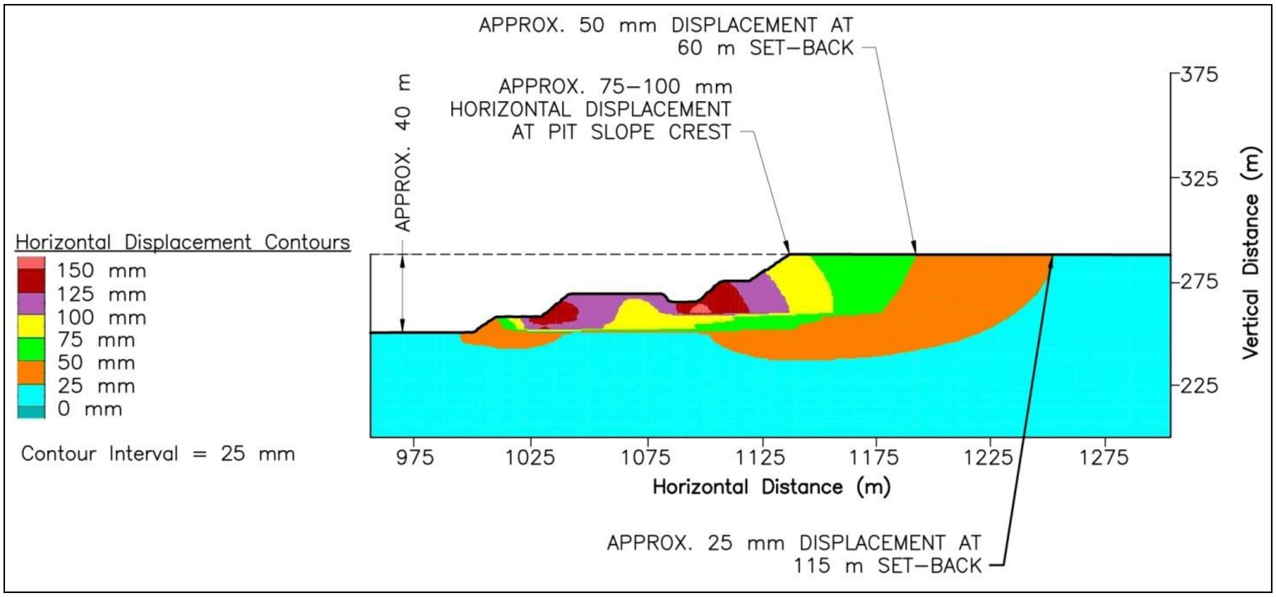

Figure 3. Section B Modeled Horizontal Displacements to Mid-2006

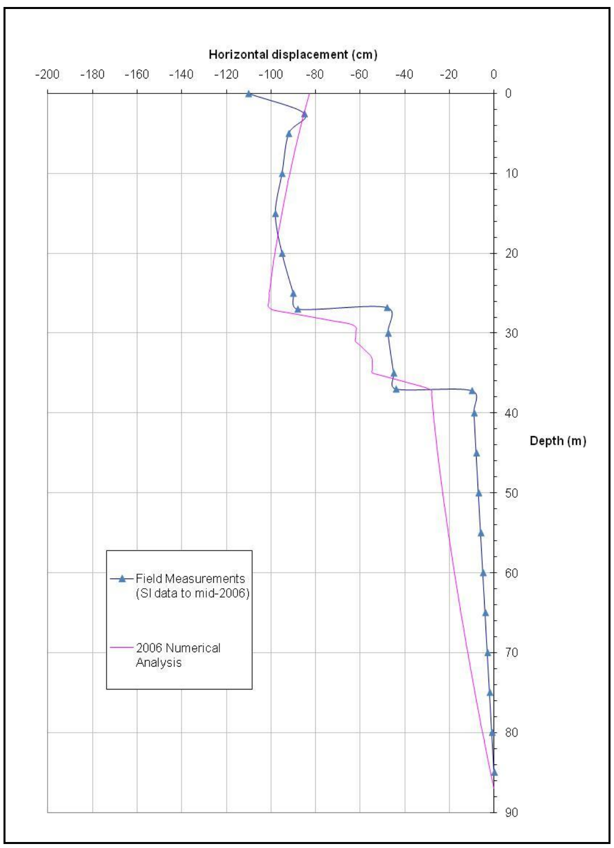

Figure 4. Section B - Horizontal Displacement Profile At Pit Slope

The revised model was then used to make updated predictions of ground movements for Sections A to C during the remainder of the mining adjacent to the plant site. The revised model showed that the magnitude of potential mining-induced ground movements for the remainder of mining adjacent to the plant site was less than predicted in the pre-mining analysis. For example, for Section B:

- The revised model predicted 180 to 320 mm of horizontal movement near the pit slope crest (vs. 500 to 950 mm estimated in the pre-mining analysis), depending on the assumed horizontal continuity of the LM2 Member weak layer which was varied from a minimum of 100 m to greater than 500 m. Figure 5 shows the predicted horizontal displacements at Section B upon the completion of mining adjacent to the plant site, for an assumed 100 m long, horizontally continuous weak layer. The calibration of the revised model to the SI data up to May 2006 suggested even lower magnitudes of movement would occur during the remainder of mining; however, these estimates were discounted slightly because as of May 2006 the mining had generally not progressed through the LM2 Member.

- The revised model also showed that between 200 and 315 m of set-back distance from the pit slope crest would be required to have 25 mm or less of horizontal movements (vs. >400 m estimated in the pre-mining analysis), again depending on the assumed horizontal continuity of the weak layer in the model. For comparison, the pre-mining analysis showed the 25 mm displacement contour at more than 400 m set-back from the crest, the existing plant facilities were as close as approximately 120 m to the crest and the new plant facilities were planned to for construction as close as 80 m to the crest. It should be noted that the "25 mm or less" displacement was not a structural tolerance criteria for the plant facilities, but was used for comparative purposes to illustrate the variation in set-back values for this displacement between different assumed continuities of weak zones in the MM and LM2 Members.

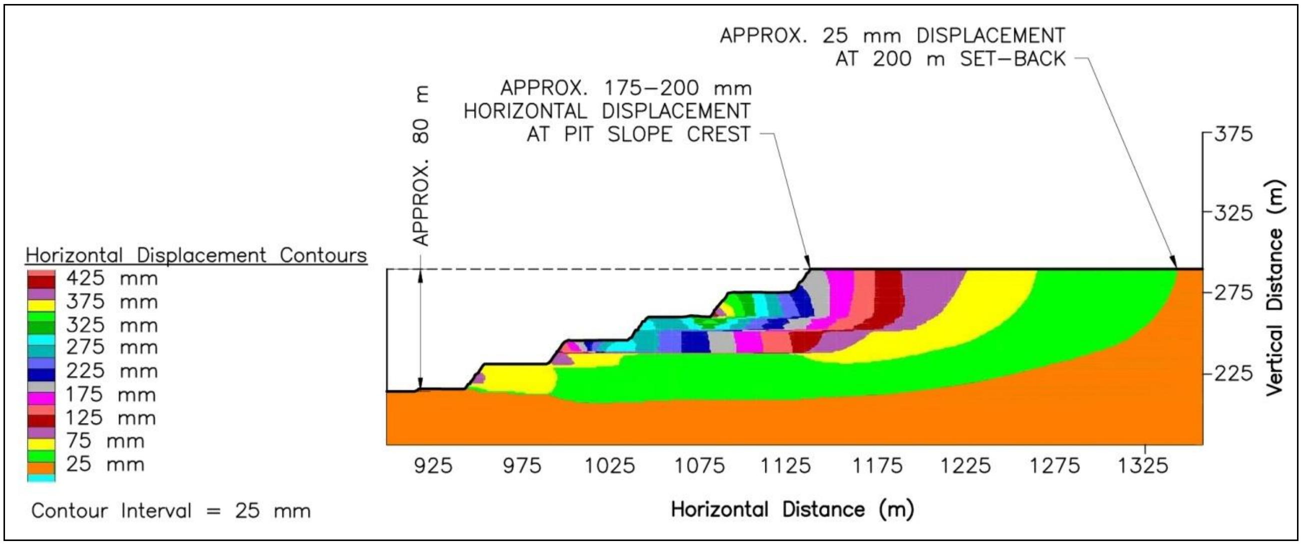

Figure 5. Section B Predicted Horizontal Displacements at Completion of Mining (Assumed 100 m Long Weak Layer)

Even though the revised estimates of ground movements were less than in the pre-mining analyses, movements greater than the reported structural tolerances of the facilities could not be ruled out at the planned 80 to 120 m set-back distances from the pit slope crest for the existing and new facilities during the remainder of mining.

7 RISK MANAGEMENT

It was decided to use the Observational Method to manage the risk to the plant facilities from ground movements during the remainder of mining adjacent to the plant site. This was to consist of:

- Installing 21 additional SI's with a layout forming eight instrumented section lines in the plant area, with SI's at the following positions:

  "First line" SI's as close as possible to the pit slope crest.

  "Third line" SI's adjacent to the existing and future plant site facilities closest to the pit slope crest.

  "Second line" SI's mid-way between the "first line" and "third line" SI's.

- Installing 33 vibrating wire piezometers at selected locations adjacent to the SI's, with the piezometer tips targeted for clay facies/zones in the MM2 and LM2 Members of the McMurray Formation.
- Developing practical mitigative measures that could be implemented immediately if required in response to detection of mining-induced ground movement below the new plant site facilities. These measures could include reducing the overall pit slope angle, buttressing the pit slope, mining in narrow panels below the plant site or other measures. It was stressed that such measures would need to be developed with input from mine planning and operations personnel to ensure their practicality and the ability to implement them without delay if required.
- Monitoring the instruments during mining, with clearly established timing and frequency of readings, timely interpretation of the data and clear lines of communication and response protocols in the event of confirmed ground movement.

8 MONITORING RESULTS TO COMPLETION OF

MINING

Monitoring was performed during the remainder of mining adjacent to the plant site from late 2006 to mid-2008. The SI's were read once per month at a minimum. Ground movement was detected in several of the "first line" SI's across the plant site, but propagated as far back as the "second line" SI's at only one location (SI's MRM07-5023 and 5024, in the east end of the plant site). The timing of the movements at this location also showed a well defined link to the start, pause and resumption of mining above and through the LM2 Member, as illustrated on Figure 6. Also, the movement at the "second line" SI (MRM07-5024) occurred essentially simultaneously with the movement at the "first line" SI (MRM07-5023) but was of a lower magnitude. This is consistent with the elastic rebound nature of the hypothesized ground movement mechanism. It also indicates that there would be little opportunity for "advance warning" of any movement propagating back to greater distances behind the pit slope face based on readings taken at the "first line" and "second line" SI's.

None of the "third line" SI's around 100 m set-back detected any movement, whereas the revised deformation model in the 2006 analysis predicted that movements would occur more than 200 m back from the pit slope crest.

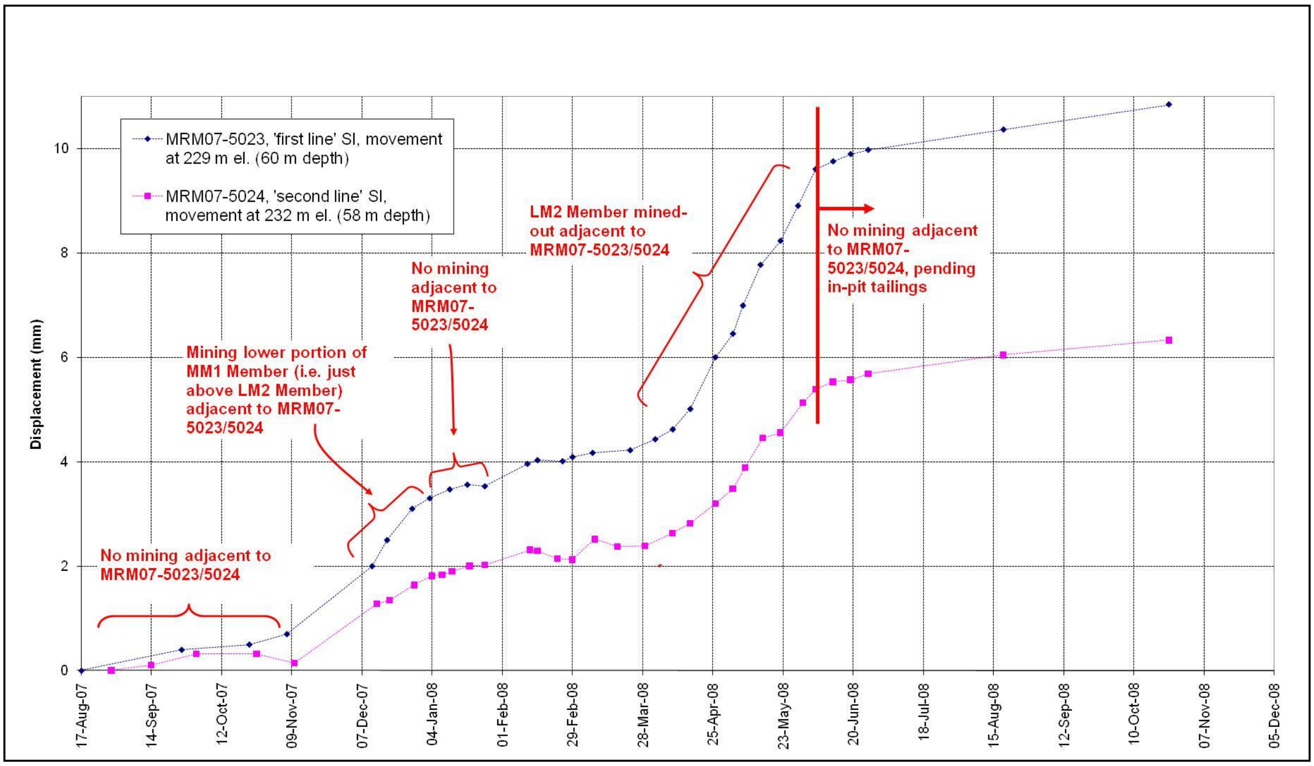

Figure 6 - MRM07-5023 and MRM07-5024, Displacement vs. Time Data For Movement Zones

The mining adjacent to the plant site was completed around mid-2008, without any ground movement confirmed at any of the "third line" SI's when the mining adjacent to the SI's reached final depth. There was little basis to expect initiation of ground movement during the period after mining and before the pit slope adjacent to the plant site was eventually buttressed by in-pit tailings deposition planned to start in late 2008/early 2009.

Of note, the final pit slope angles adjacent to the plant site generally varied between 2.5H:1V and 2.7H:1V, with limited areas at inclinations as steep as 2.1H:1V and as gentle as 3.5H:1V. This is generally slightly steeper than the 2.9H:1V to 3H:1V inclinations used in the 2006 deformation analysis, based on the mine plan information available at that time.

9 CONCLUSIONS

The main conclusions drawn from the interpretation of the ground movement data are first, that mining-induced ground movement consistent with the hypothesized "shear-band propagation" movement mechanism was detected during the monitoring program, and second, the propagation distance of the movement back from the pit slope face and the magnitudes of the measured ground movement were both less than predicted by the pre-mining and 2006 revised numerical analyses despite the as-mined pit slope profiles being slightly steeper than planned and modeled.

Movement was detected at seven of the eight "first line" SI's, but was detected at the "second line" SI (roughly 50 m back from the pit slope crest) at only one of the instrumented section lines. None of the "third line" SI's that were typically 100 m back from the pit slope crest detected any movement. This indicates that the maximum propagation distance was between approximately 50 and 100 m from the pit slope crest, and at only one of the seven instrumented section lines where mining-induced ground movement was detected.

The 2006 numerical analysis generally showed greater than 180 mm of horizontal movement within 100 m of the pit slope crest. The largest measured movement was at the "first line" SI on Section B, where approximately 100 mm of cumulative movement (including two discrete shear zones in the MM2 Member each having approximately 40 to 45 mm of displacement) was measured prior to the SI becoming deformed to the point where the reading probe could not pass through the SI casing. Therefore, the total amount of movement was likely higher. The other locations where movement was measured in the "first line" SI's showed 10 mm of movement or less, and the one "second line" SI that detected movement showed approximately 6 mm of movement.

The monitoring data indicated that, for the MRM plant site, the continuity of weak layers and/or the effects of the relief of the in-situ horizontal stresses upon mining were less than expected based on the numerical analysis. This could be due to lower in-situ horizontal stresses than estimated and used in the model and/or more favourable geological conditions than the (recognized) conservative assumptions used in the model (e.g. fewer, relatively discontinuous and perhaps more competent weak layers than assumed based on the available information). It is also possible that the lower than predicted movements may have been partly due to the residual strength of the weak and pre-sheared layers being higher than estimated based on available data; however, this is judged to be less likely than the other factors noted above.

Further deformation modeling could be done to back-analyse the measured ground movement and further revise the material properties used in the deformation model for the base plant and Area 250 area. The model could be calibrated by varying the material parameters or the constitutive model to better match the measured ground movements. However, ground movement predictions from such a model could be misleading for other sites where the orientation and continuity of weak layers are not known with any more certainty. A further refined model would not necessarily provide a basis for applying less conservative set-back distances to other sites.

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