Kehiwin Lake Landslides, Hwy 41:23 Near Elk Point, Alberta: Historical Development and Remedial Measures

Tarek Abdelaziz, Donald Proudfoot
Thurber Engineering Ltd., Edmonton, Alberta, Canada
Roger Skirrow
Alberta Transportation– Geotechnical and Materials Section, Edmonton, Alberta, Canada

ABSTRACT
Highway 41 extends parallel to Kehiwin Lake, near the town of Elk Point in northeastern Alberta, Canada. Between 2001 and 2010, three rotational landslides developed progressively within a 1 km stretch of the highway. The landslides affected the highway and extended downslope to toe out into Kehiwin Lake. These landslides were monitored and remediated between 2009 and 2011. The implemented repair measures included the construction of cantilever and tied-back reinforced concrete pile walls. In late 2011, a new landslide developed to the south of the southernmost remediated landslide site. A pile wall repair is also being considered for the recent landslide site. This paper summarizes the geotechnical investigation results and repair measures, including instrumentation monitoring results at the remediated sites. A discussion of landslide risk management in relation to sunk costs is also presented.

RÉSUMÉ
L'autoroute 41 longe le bord du lac Kehiwin, près du village de Elk Point dans le nord est de la province de l'Alberta, au Canada. Entre 2001 et 2010, trois glissements de terrain rotationnels se sont développés le long d'un tronçon d'environ un kilomètre de longueur. Ces glissements de terrain ont endomagé l'autoroute avec leur pieds situés plus bas dans les limites du lac Kehiwin. Ces glissements de terrains ont été instrumentés et réparés entre 2009 et 2011. Des murs porte-à-faux sans étais et de soutènement avec anchrages furent construites afin d'atténuer les mouvements. Vers la fin de 2011, un nouveau glissement de terrain s'est développé au sud des glissements remédiés. La conception d'un autre mur de soutènement avec anchorages est présentement préconisé afin d'atténuer ce dernier glissement de terrain. Cet article présente sommairement les résultats des investigations géotechniques, les mesures mitigatives entreprises, ainsi que les données recueillies par les instruments pour les ces mêmes sites. Une discussion sur le sujet de la gestion des risques des glissement de terrain relativement aux coûts irrécupérables est également présentée.

1 INTRODUCTION

Highway 41:23 is a paved two-lane highway located about 350 km northeast of Edmonton, Alberta. The highway is aligned in a northeast-southwest direction parallel to the eastern shoreline of Kehiwin Lake, near the Town of Elk Point. Kehiwin Lake has a maximum depth of 11.6 m and a mean depth of 6.7 m. The highway was constructed in the 1960's as a sidehill cut and fill section about 20 to 45 m above lake level. A site map showing the highway location is presented in Figure 1.

Between 2001 and 2011, four rotational landslides occurred progressively on the west side slope of the highway embankment above the lake shoreline. Three of the landslides were monitored and remediated through Alberta Transportation's Geo-hazard Risk Management Program (GRMP) between 2002 and 2011. The fourth landslide site is currently under investigation.

This paper summarizes our current understanding of the repeated landslide activities along the highway, gained through several years of geotechnical investigation and monitoring, and provides details of the implemented repair measures. A discussion of landslide risk management in relation to sunk costs is also presented.

2 HISTORICAL DEVELOPMENT OF LANDSLIDES

A shaded relief plan showing approximate locations of the landslide sites is presented in Figure 2.

The first landslide (NC24) occurred in 2001 at approximate km 7.9 along the highway and was designated in Alberta Transportation's (TRANS) GRMP as NC24. The landslide was investigated and instrumented between 2002 and 2008. A cantilever concrete pile wall was constructed between February and April 2009 to stabilize the landslide site. Between July and August 2010, two new landslides developed abruptly along the highway at km 7.8, designated as NC 24A site, immediately to the south of the NC24 site and at km 8.8, designated as NC 24B, approximately 900 m to the north of the NC24 site. Both landslide sites were investigated and instrumented between October 2010 and March 2011. Remedial measures, implemented between April and August 2011, included the installation a tied-back concrete pile wall at the NC24A site and a cantilever pile wall at the NC24B site. Between July and August 2011 just as the pile wall at the NC24A was near completion, a new landslide, designated as NC24C, developed to the south of the southernmost edge of the NC24A pile wall. The new slide appears to be similar in expression to

NC24A and as such another pile wall is being considered to remediate the NC24C landslide site.

3 GENERAL DESCRIPTION OF STUDY AREA

3.1 Surface Conditions

As shown on Figure 2, the highway alignment is generally bounded on the east by a meta-stable hill slope and on the west by the Kehiwin Lake. The highway alignment is located approximately 80 to 100 m to the east of the lake shoreline. The top of hill is about 20 m above the lake shoreline at the NC24B site, and 45 m at the NC24, NC24A, and NC24C site locations.

The surface expressions of the hillside upslope of highway at the landslide sites are hummocky, suggestive of extensive historic landslide activity. Additional evidence of past landslide activity includes the presence of multiple steep scarps, extensive gullies within the slope, irregularity in the shape and texture of the slope surface, tilting trees, buried trees within the hill and along the lake shore slopes, and significant toe bulging and presence of scarps near the lake shoreline. Erosion and depositional features near the lake shoreline were also visible from the LiDAR image.

Figure 3 provides a 3D rendering image at the three adjacent landslide sites. It can be seen from the figure that three landslides developed between km 7.7 and 7.9 (NC24, NC24A, and NC 24C) are local active landslides that lie within a much larger dormant global ancient landslide that extends much further upslope of the highway and along the highway. Sites NC24 and NC24C sites are located approximately 200 m from the left and right flanks of the global landslide, which presents the possibility that additional landslides might occur outside the limits of the active landslides but within the limits of the global landslide.

3.2 Geological History

A brief discussion of the area geological setting was prepared based on available aerial photographs from 1985, 1976, and 2002; Digital Elevation Models, and published geological reports, including Fenton and Andriashek (1983), Atkinson and Lyster (2010), and Gold et al. (1983).

A system of northeast and eastward-flowing channels had established prior to the last glaciation in Alberta. The pre-glacial topography mainly consisted of northeast-trending valleys separated by broad uplands. One of these valleys, a small tributary to the pre-glacial Beverly Valley, was identified within the study area. During each ice advance, the northeast drainage system was dammed, resulting in the formation of periglacial lakes. The lakes were developed in the valleys and depressions, and drainage was diverted to the south. Ice marginal lakes developed as the ice front retreated downslope. Steep-walled valleys were cut where meltwater flowed from one Lake Basin to the next; here flow was channelled southward along the ice margin, and where drainage was re-established in drift- filled segments of the pre-glacial valleys, which were filled up with lacustrine and glacial deposits.

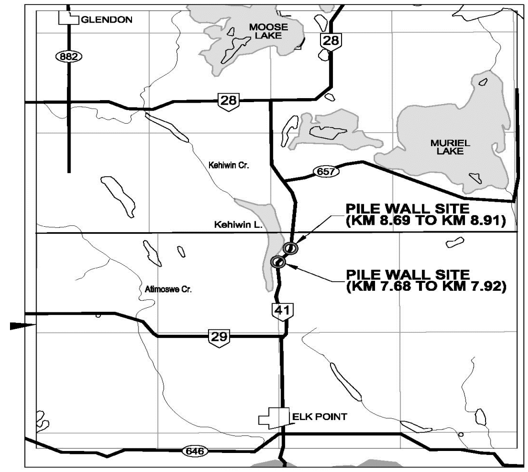


Figure 1. Site location map (N.T.S)

The last phase of glaciation was marked by massive ice thrusting, resulting in formation of large ice thrust moraines and glacitectonic ridges, consisting of pre-existing sediments, bedrock and/or drift. According to Fenton and Andriashek (1983), the study area in the vicinity of the landslide sites is where two large ice lobes met (i.e. the Primrose Lobe advancing from northeast and the Lac la Biche Lobe advancing from northwest). Extensive Ice thrusting occurred at the study area, resulting in intensive fracturing of the near surface bedrock, and transport of bedrock blocks to constitute part of the complex ice thrust moraines and ridges.

Kehiwin Lake is contained in a geologically young meltwater channel that partially follows the alignment of a pre-glacial buried valley. In the vicinity of the landslide sites, the lake appeared to have shifted its thalweg from the buried valley, indicating repeated fracturing, deformations, erosions and weathering at the study area.

3.3 Surficial and Bedrock Units

The surficial geology map, published by Fenton and Andriashek (1983) and presented in Figure 4, reveals three major surficial deposits in this area: moraine, colluvium, alluvium and lacustrine deposits. The uplands are mainly covered by glacial deposits (Stagnant and Thrust Moraine). In general, the moraine mainly consisted of clayey-sand till inter-bedded with either stratified sediment or glacially incorporated beds of older till and inter-bedded lenses of sand and silt. The Stagnant Moraine unit to the east of the Kehiwin Lake is underlain by the Thrust Moraine. The Stagnant Moraine had formed after the ice advance ceased and typically has a chaotic structure, whereas the Thrust Moraine had formed as a result of the ice thrust processes, and typically contains blocks of weathered and re-worked bedrock.

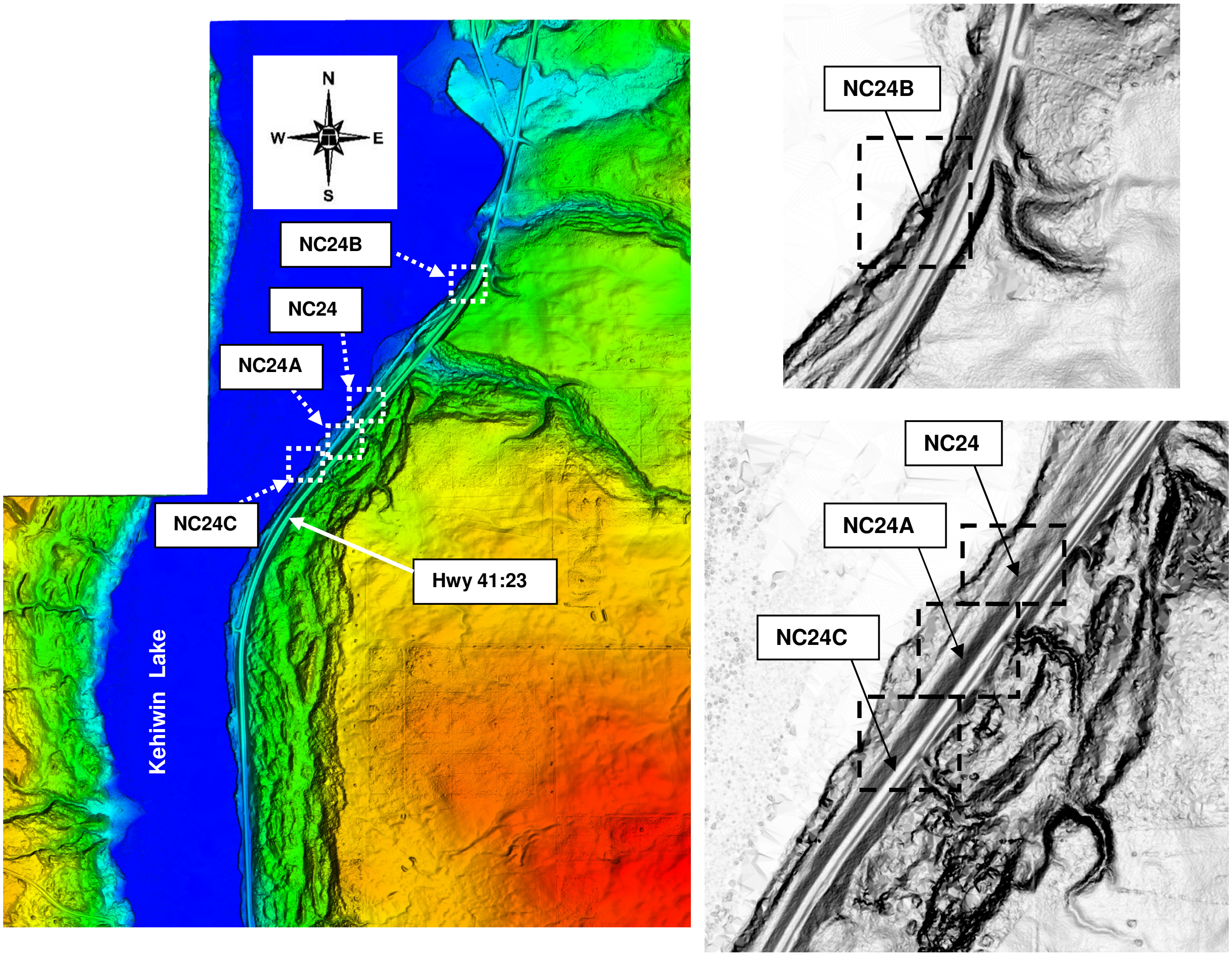


Figure 2. Shaded relief plans showing landslide locations

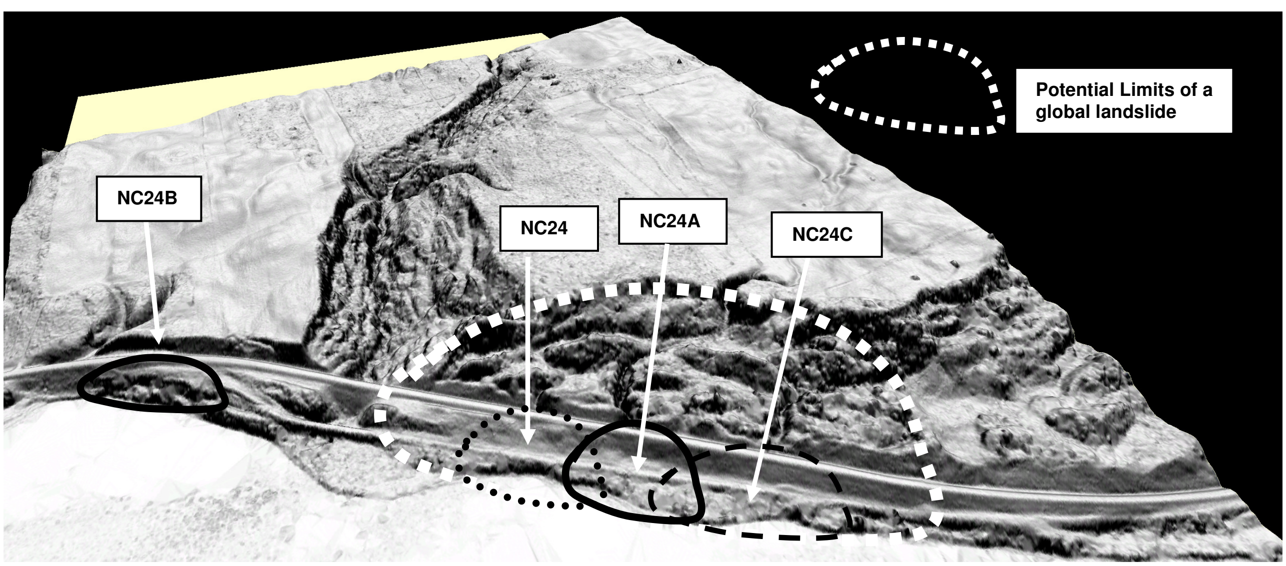


Figure 3. A 3D rendering image along the highway alignment at the landslide sites (Vertical Exaggeration is 3:1; N.T.S.)

The colluvium deposits are poorly sorted sediments that have been transported by gravity induced movement and confined to the sides and floors of valleys. The colluvium covers the hill slopes, and extends to the bottom of the hill near the shoreline of the lake.

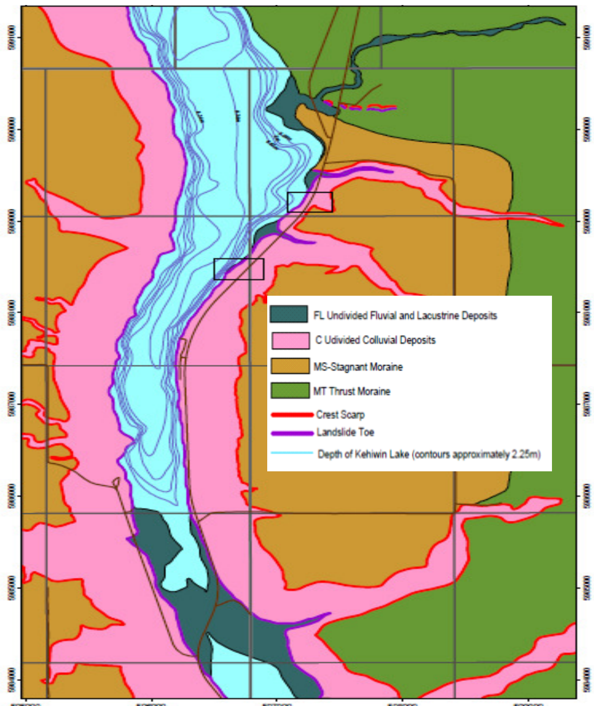


Figure 4. Surficial geology map of study area (N.T.S.)

The alluvium and lacustrine deposits formed at the edges of the Kehiwin Lake as a result of lake and fluvial erosion and deposition processes. These deposits consist mainly of silt and clay mixed with organic material.

According to the Geological Map of Alberta (1999), the study area is located at the contact of two geological bedrock formations. At the west side of the Kehiwin Lake the uppermost part of the bedrock is presented by lowermost portion of the Belly River Formation, whereas the east side of the lake consists of the uppermost portion of the Lea Park Formation. The Lea Park Formation within the study area is composed of marine medium to dark grey shale with numerous layers of calcite veined clay-ironstone concretions.

4 LANDSLIDE SITES AND REMEDIAL MEASURES

4.1 NC24 Landslide

This site has a history of instability going back to 1988 when initial slumping was noted on the highway west side slope. Repairs at this site were limited to subgrade excavation and replacement in 1992 and pavement overlay in 2000. TRANS records indicated that a large landslide occurred north of NC24 and was repaired using lime columns; however, the exact site location could not be determined from the records. In 2001, instability was noted again on the west side slope of the highway. The landslide was about 140 m wide and 100 to 110 m long, and extended from the east ditch to the lake shoreline. The highway embankment west side slope was about 7 m high and inclined at 3H:1V.

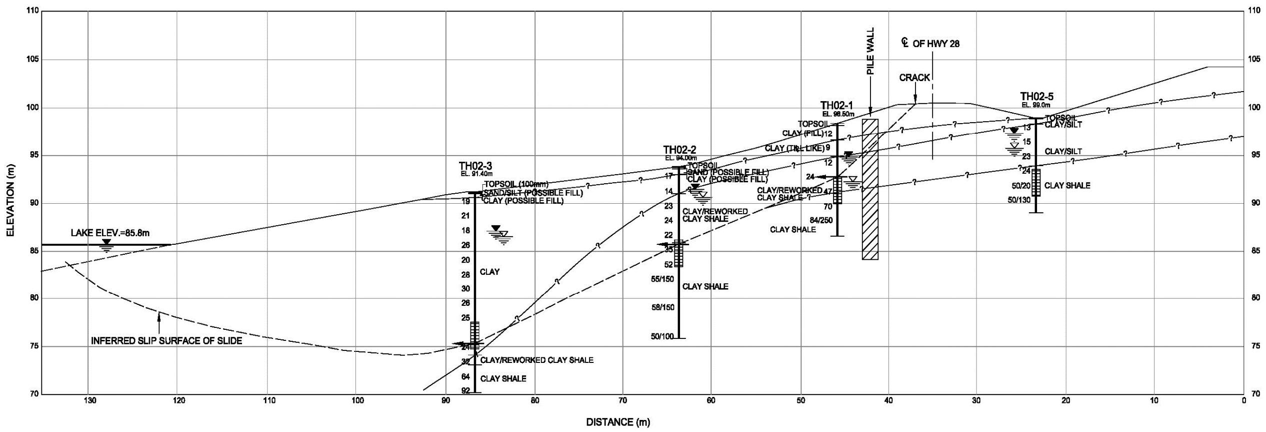
The landslide features included observations of pavement distress on both lanes, the presence of 10 to 20 mm wide longitudinal and diagonal cracks, and 10 to 20 mm local depressions along the highway surface. A total of 13 test holes, complete with slope inclinometers and standpipe piezometers, were drilled at this site in 2002. A stratigraphic cross section at the site is presented in Figure 5. The geotechnical investigation indicated that the sub-surface conditions consisted of 2 to 3 m of clay fill overlying colluvium soils. The colluvium soils consisted of a mixture of clay, clay till, re-worked clay shale, and was underlain by clay shale bedrock. The thickness of the colluvium increased from 5 m near the highway to about 17 m near the lake shoreline. The slope inclinometers showed that the slip surface was located within the high plastic re-worked clay shale formation near the top of the bedrock. The slip surface was located between 5 to 6 m depth below the top of the highway. The ground water levels within the landslide area were 1.5 to 4 m below ground surface.

Between 2002 and 2008, the site was monitored through TRANS's GMRP. The design of a cantilever concrete pile wall to retain the upper portion of the landslide mass was completed in late 2008. Figure 6 presents the layout of the pile wall. The construction of the wall was undertaken in 2009 under Alberta Transportation's Contract No. 7357/0/8, and included the construction a 145 m long cantilever reinforced concrete pile wall on the west side of the highway. The construction cost (excluding engineering fees) was $1.1 million. The pile wall consisted of 41, 1.8 m diameter and 15 m deep concrete piles with a center-to-center spacing of 3.6 m (i.e. 2 times the pile diameter).

Three slope inclinometers (SI09-1 to -3) were installed in piles #7, 18, and 29 to assess the effectiveness of the remedial measure and confirm design assumptions. Between 2009 and the 2013, the slope inclinometers indicated that the pile wall was effective in stabilizing the landslide. The pile head deflections ranged from 2 to 9 mm. For illustration purpose, the incremental and cumulative deflections versus depth plots in SI09-1 are presented in Figure 7.

4.2 NC24A and NC24B Landslides

Both landslides occurred suddenly between July and August 2010 after prolonged heavy rainfall events. At the NC24A site, the landslide occurred in August 2010 and was about 100 m wide and 140 m long, and extended from the east ditch to the lake shoreline. The highway embankment west side slope was about 9 m high and inclined at 3H:1V. The landslide at this location shifted the highway laterally towards the lake by about 200 mm and resulted in about a 150 mm drop along the highway surface. The northernmost extent of this landslide stopped about 7 m from the south end of the NC24 pile wall. The landslide movement developed rapidly over the course of several days and appeared to accelerate. It adversely



CROSS SECTION A-A' @ STATION 0+052

Figure 5. Stratigraphic cross section along the NC24 site

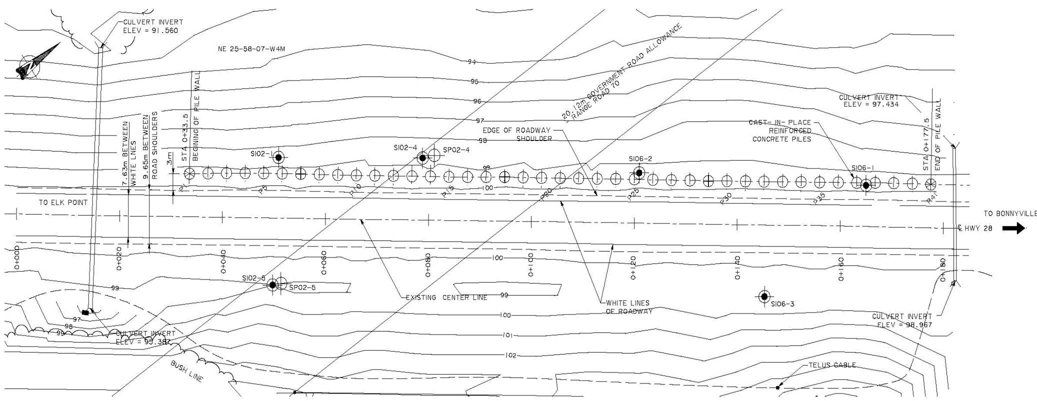


Figure 6. Site plan showing the layout of the NC24 pile wall

affected both highway lanes, and encroached into the NC24 pile wall location. Using the probability and consequence scale of geo-hazard risk associated with the GRMP this landslide site was assigned a risk level rating of 60, indicative of the urgent need to implement remedial measures to avoid potential closure of the highway.

A total of 9 test holes, complete with slope inclinometers, pneumatic and standpipe piezometers, were drilled at this site in 2010. The geotechnical investigation indicated that the sub-surface conditions at this site were very similar to the NC24 site. However, it appeared that additional fill was placed to raise the highway vertical profile at this location. The depth of movement in the slope inclinometers was within the high plastic re-worked clay shale formation near the top of the bedrock. However, the slip surface was deeper than the NC24 site and was located between 9 to 10 m depth below the top of the highway. A stratigraphic cross section at the site is provided in Figure 8.

A landslide occurred at the NC24B site in July 2010, and signs of instability were noted along the highway surface and west side slope. The highway embankment west side slope was about 2 to 3 m high and inclined at 3H:1V. The landslide head scarp cracks were located in the shoulder of the southbound lane, and extended about 15-20 m long along the outside edge of the highway white

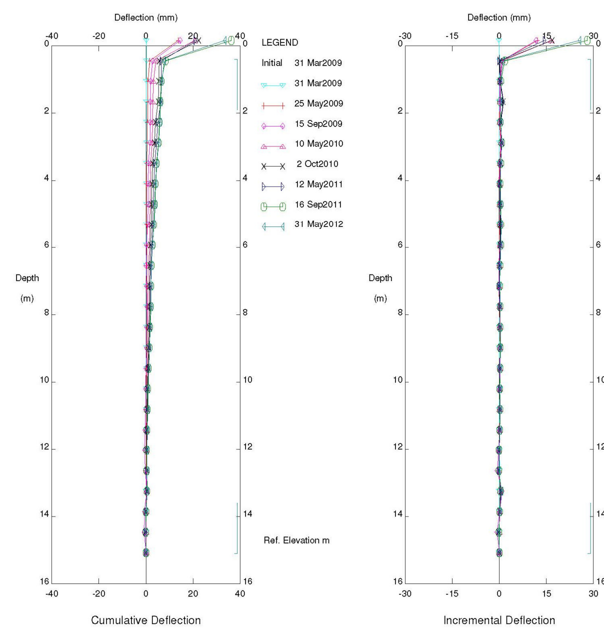


Figure 7. SI09-1: Incremental and cumulative deflections versus depth plots for NC24 pile wall

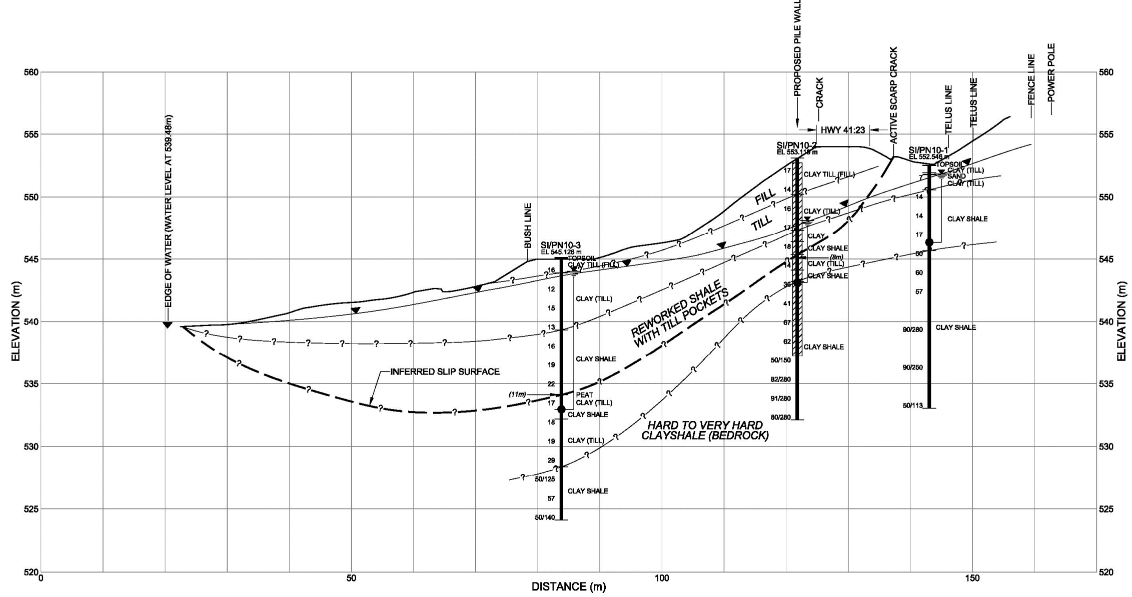


Figure 8. Stratigraphic cross section along the NC24A site

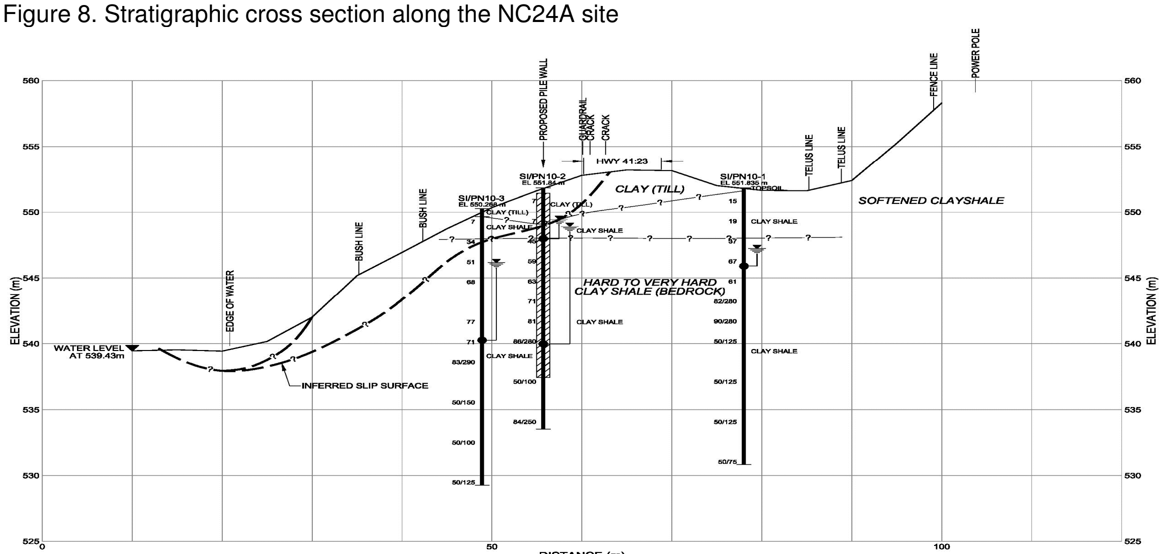


Figure 9. Stratigraphic cross section along the NC24B site

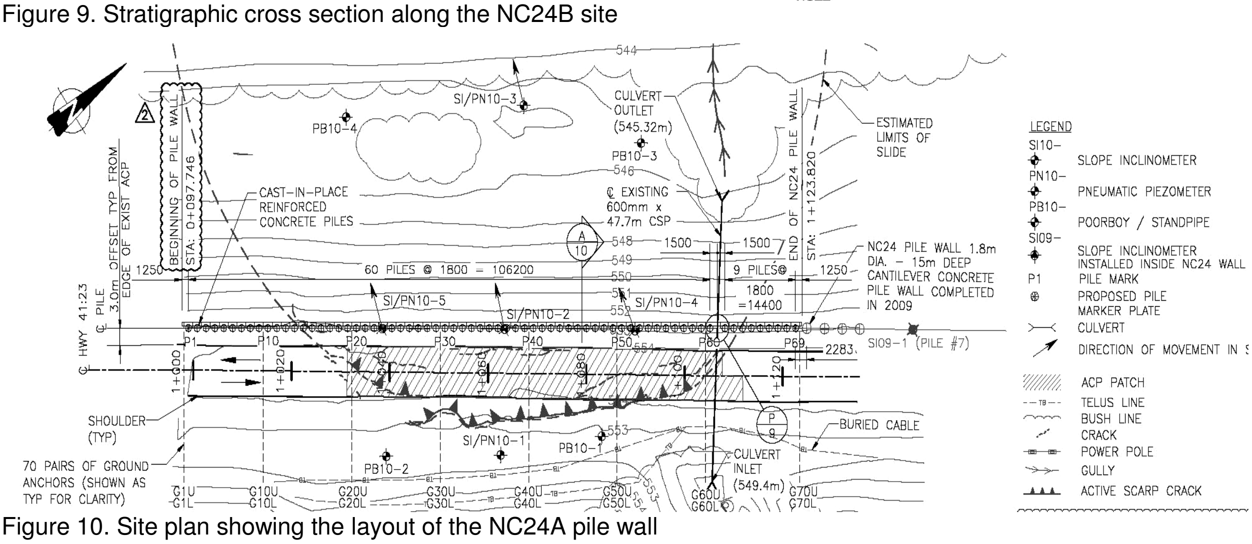


Figure 10. Site plan showing the layout of the NC24A pile wall

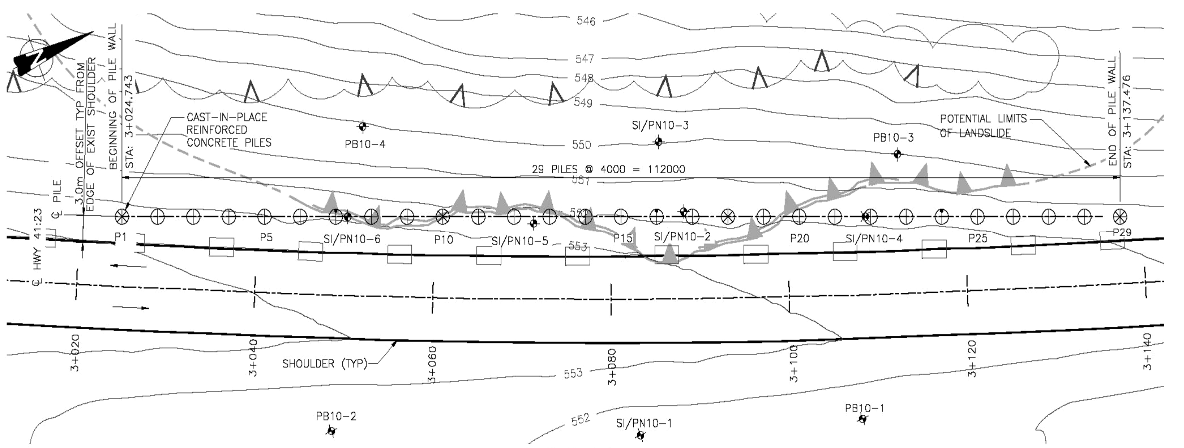


Figure 11. Site plan showing the layout of the NC24B pile wall

line. Downslope head scarp cracks were located 3.0 to 4.0 m from the edge of the pavement and were 100 m long parallel to the highway. The landslide features included appearance of 30 mm wide diagonal and longitudinal cracks with up to 25 mm drop across the crack surfaces, settlement and lateral distortion of existing guardrail for a distance of 15 to 20 m along the highway surface, and presence of multiple tension cracks within the lake shore slopes. In addition, scattered riprap was noted near the shoreline, indicating previous efforts to stabilize the lake bank slopes. At this site, the main concern was the possibility of landslide retrogression into the highway driving lanes. A total of 10 test holes, complete with slope inclinometers, pneumatic and standpipe piezometers, were drilled at this site in 2010. The geotechnical investigation indicated that the sub-surface conditions consisted of 1 m of clay fill overlying 2 to 3 m of colluvium soils, consisting of clay till, and re-worked clay shale underlain by clay shale bedrock. The bedrock appeared to be less disturbed and much shallower at this site. The slope inclinometers indicated that the slip surface was located 3 to 4 m deep below the top of the highway in the re-worked clay shale formation near the top of the bedrock. A stratigraphic cross section at the site is provided in Figure 9.

The landslide repair measures for both sites were completed between April and August 2011, and included the construction of a 127 m long tied-back concrete pile wall at the NC24A site and a 113 m long cantilever concrete pile wall at the NC24B site. The construction was undertaken under TRANS's Contract No. 11165. The construction cost was $3 million. Figures 10 and 11 show the layout of the pile walls at the NC24A and NC24B sites, respectively. Figure 10 shows the tied-back pile wall at NC24A site, which was essentially contiguous with the NC24 pile wall. The pile wall included the construction of a total of 69, 1.2 m diameter and 15 to 18 m deep concrete piles with a centre-to-centre spacing of 1.8 m, and a reinforced concrete waler along the tops of the piles. A total of 140 grouted ground anchors were installed along the wall. The anchor design loads ranged from 300 to 360 kN and the lock off loads ranged from 240 to 290 kN. The anchors had free lengths ranging from 15 to 20 m, and 10.5 to 12 m bond lengths in the clay shale bedrock. The structural element consisted of 36 mm diameter, Grade 1030 MPa, DWIDAG threaded Double Corrosion Protection bars. Prior to the installation of the production anchors, a total of 4 pre-production anchors were installed and tested to confirm the design loads. Proof testing was undertaken for all production anchors and performance tests were carried out on eight anchors to confirm the creep and strength characteristics of the anchorage system. After the proof and performance loading tests were completed, the anchors were locked off at the specified lock-off loads. Lift-off tests were carried out immediately after locking off the anchors to confirm load losses due to seating effects. Four slope inclinometers (SI11-1 to SI11-4) were installed in piles P9, P27, P45, and P60 to measure the pile wall deflection. Vibrating wire load cells were also installed in ten of the anchors for long term monitoring of the anchor loads. Between 2011 and the 2013, SI011-1 to SI011-3 have shown that the pile wall deflected laterally by -1.5 to -10 mm (i.e. pile wall deflected towards the highway, in response to locking off the anchors). For illustration purpose, the incremental and cumulative deflections versus depth plots in SI11-3 are presented in Figure 12. Figure 13 shows the variation of anchor loads with time for the NC24A pile wall. It should be noted that VC1708 and VC1710 anchors were locked off at 240 kN, whereas the remaining anchors were locked off at 290 kN. The anchor lock-off loads dropped by 13 to 28 % and it should be noted that the majority of the load losses occurred during construction. The reduction in the anchor loads can be attributed to the non-simultaneous locking of anchors and re-distribution of loads along the wall. It is of interest to note that the decline in anchor loads was not accompanied by any ground movements and therefore the performance was considered acceptable as long as the current and future load losses did not reduce the anchor loads below that required for maintaining the stability of the retaining structure.

The depth of movement was shallower and the quality of the bedrock was better at the NC24B site than either the NC24 or NC24A sites. Although other mitigation options were possible at this site, the contractual advantages to maintaining a consistent mitigation design predicated the use of a pile wall at NC24B. The pile wall at this site included the construction of a total of 29, 1.5 m diameter and 10 m deep concrete piles with a center-to-center spacing of 4 m (i.e. 3 times the pile diameter). Three slope inclinometers labelled SI011-1 to -3 were installed in piles 7, 16, and 24 to assess the effectiveness of the remedial measure and confirm design assumptions. The slope inclinometers did not show any discernible movements, indicating that the remedial measure has been effective in stabilizing the landslide.

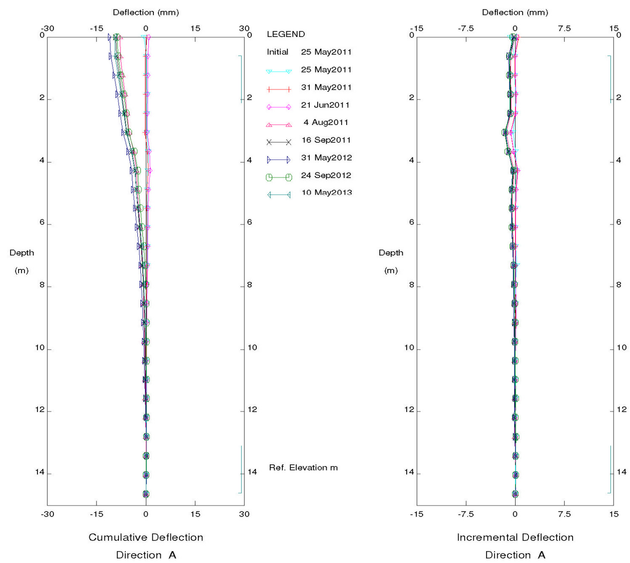


Figure12. SI11-3: Incremental and cumulative deflections versus depth plots for NC24A pile wall.

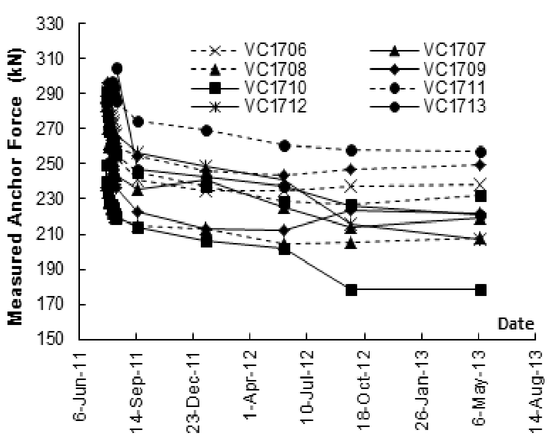


Figure 13. Variation of anchor loads with time for the NC24A wall

4.3 NC24C Landslide

The NC24C landslide occurred in late July 2011 at approximately the same time as the NC24A pile wall was nearing completion. The landslide resulted in pavement distress along the highway that was consistent with the initial surface expression of the landslides at NC24 and NC24A sites. It is expected that this site will continue to deteriorate in a manner consistent with that observed at the adjacent sites. The pavement distress extends for a distance of about 170 m to the south of the south end of the NC24A pile wall. A total of thirteen test holes, complete with slope inclinometers, pneumatic and standpipe piezometers, were drilled at this site between November and December 2011. The geotechnical investigation indicated that the sub-surface conditions at this site were very similar to the NC24 and NC24A sites. The depth of movement in the slope inclinometers installed along the west side of the highway was about 9 to 10 m below the highway, and hence it is expected that a tied-back concrete pile wall similar to the one installed at the NC24A site will be required to stabilize the landslide. However, the length of the pile wall will be determined based on the instrumentation results. During this phase of investigation, additional slope inclinometers were installed further to the south of the distressed area to determine if movements are taking place to the south of this site. Considering a similar repair measure to the NC24A site, the construction cost of a 200 to 350 m long pile wall could be in the range of $3 to 5 million.

5 LANDSLIDES MECHANISM AND RISK MANAGEMENT

5.1 Landslides Mechanism

The geotechnical investigations indicted the Kehiwin Lake hillside has slumped extensively in the past. In addition, there is evidence to suggest that wave action of the lake eroded its shoreline over time and caused repeated episodes of slope failures. These slope failures have resulted in the current meta-stable hillside conditions which appear to be destabilized by extended periods of rainfall. It is likely that the construction of the highway embankment fill could have resulted in very slow creep movements along pre-sheared surfaces within the landslide terrain. These movements could have been aggravated at random locations along the highway in response to the loss of lateral support downslope of the highway location due to the progressive erosion of the toe of ancient landslides by the wave action of the lake.

5.2 Landslides Risk Management

TRANS initiated the Geo-hazard Risk Management Program (GRMP) to aide in prioritizing the landslides repair work in a rational and defensible manner. The program aims at monitoring and repairing active landslide sites along highways based on available budget allowance and objectively assigned risk level factors. A discussion of the specifics of the GRMP is beyond the scope of this paper. Details are available at the Alberta Transportation website at: http://www.transportation.alberta.ca/Content/docType372/Production/refmatprsite.pdf

Although Highway 41:23 was constructed in the 1960's on a landslide terrain, there was no evidence of slope instability along the highway for almost 4 decades. However, over the last decade four landslides have occurred progressively and seemingly randomly along the highway. Based on the history of this highway, additional landslides may take place in the future at areas that are currently considered to be stable. It is challenging to predict the likelihood of future occurrence of landslides and when such landslides might be expected to occur. The landslide risk management strategy along this highway included monitoring and repairing of local landslides using pile walls. The alternative approach would be a major highway re-alignment into a more stable terrain well upslope of the current highway alignment. This option was assessed as part of the engineering assessment done for NC24 prior to the occurrence of NC24A, B or C. Preliminary assessment of this option at that time indicated that the realignment cost could be in the range of $15 to $20 million, but this option would have no progressive or future costs associated with it. At the time there was no awareness of the future landslide remediation costs and the realignment option was discarded based on costs. As the landslides at NC24A, NC24B and finally NC24C occurred, the realignment option was revisited for discussion purposes. With sunk and current repair costs now approaching $8 million, there is still considerable allowable future costs before the realignment option costs would be reached. The support for a realignment option will however decrease as more and more funds are spent on localized landslide repairs along Kehiwin Lake. At this time it is unlikely that a realignment option will ever be pursued, excepting the unlikely reactivation of the global dormant landslide that would fully encompass NC24, NC24A and NC24C.

One approach to the analysis of progressive and sunk costs is to combine the future realignment cost and the total of already expended landslide repair costs in relation to the costs of repairing the most recent landslide and likely future landslide or maintenance costs. NC24C will cost between $3 and 5 million, while based on LiDAR imaging one might assess future landslides to total another $3 to 5 million for a maximum of $10 million, The realignment option and current landslide costs total $24 million, well in excess of the $6 to 10 million required to repair local landslides. Using this approach it is highly unlikely a realignment option will be implemented. An additional advantage of repairing the local landslides is the ability to stagger available funds over a number of years to repair future landslides at this location

6 SUMMARY AND CONCLUSIONS

This paper provided a summary of existing landslides along highway 41:23, implemented remedial measures to stabilize the landslide movements, instrumentation monitoring results, and risk management strategy to deal with current and possible future landslides in this area.

Based on the existing information, the following conclusions are drawn:

1- Periodic occurrence of landslides over the last decade was attributed to several factors, including construction of the highway alignment within the toe of an ancient landslide, placement of fill to build the highway, and progressive erosion of the toe of the ancient landslide.
2- Pile walls have been effective remedial measures to stabilize each of the local landslide sites.
3- Based on the history of the road, periodic sliding is likely to occur at unknown presently stable locations along this highway. As these instabilities occur, failures and successes associated with remedial measures at other locations along the road will be used to guide new designs. As new techniques or options arise, these will be used where appropriate as well.
4- Care must be taken when implementing a repair measure to ensure that nearby slides are not aggravated or reactivated as has happened within the study area.

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