Lessons Learned From Failure of High Embankment Excavation Slopes at Culvert Replacement Sites in Alberta

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ABSTRACT

During the construction boom of the 1950's, new agricultural and resource lands were developed throughout Alberta. In response to these developments new roads and bridges, including large culverts, were constructed to provide access. Many of the large culverts are no longer viable to maintain and have reached the end of their useful life. Replacement of large culverts, in particular those buried below high embankment fills, is becoming commonplace in Alberta. Many of these new structures have been designed and constructed with little, if any, geotechnical input. This practice places significant construction risks upon the Contractor, and can be a contributing factor to geotechnical failures during construction. The geotechnical problems are related to the failure of excavation cut slopes, and embankment slopes and natural valley slopes where excavation spoils are temporarily stockpiled. This paper discusses three culvert replacement projects in Northern Alberta. A commentary on the design process and lack of significant geotechnical input and the associated consequence is presented. The paper concludes with general recommendations for geotechnical investigation requirements, a discussion of cost/benefits and geotechnical risk management.

RÉSUMÉ

Durant la boom de construction des années 50, de nouvelles terres agricoles et avec ressources naturelles furent developés en Alberta. En réponse à ces développements, de nouvelles routes et ponts, incluant de grands ponceaux furent construites pour données de l'accès. Plusieurs de ces ponceaux ne sont maintenant plus viable à maintenir, et ont atteint la fin de leurs vies utiles. Le remplacement des grands ponceaux, particulièrement ceux qui sont enterré sous des banquettes très haut devient de plus en plus commun en Alberta. Plusieurs de ces nouvelles structures ont été conceptionés et construites sans ou avec peu de consultation géotechnique. Cette pratique met plus de risque sur l'entrepreneur, et peut contribuer aux faillites géotechniques durant la construction. Les problèmes géotechniques sont lies à la faillite des pentes d'excavation coupées, les pentes de banquette et les pentes naturelles de vallées où les déblais d'excavation sont temporairement mis. Ce rapport discute de trois projets de remplacement de ponceaux dans le Nord de l'Alberta. Un commentaire sur le processus de design et la manque de contribution géotechnique et la conséquence associe est présenté. Ce rapport est conclut avec des recommandations générales pour les exigences d'une investigation géotechnique, et en plus une discussion des coûts/avantages et la gestion des risques géotechniques.

1. INTRODUCTION

During the post-World War II construction boom new agricultural and resource lands were developed throughout Alberta, with a significant push into the northwest portion, Peace Region, of the province. In response to this development, new roads and bridges, including large culverts, were constructed to provide access. Many of the large culverts are no longer viable to maintain and have reached the end of their useful life. Replacement of large culverts, in particular those buried below high embankment fills, is becoming commonplace.

Most of the old structures were designed and constructed with little, if any, geotechnical input. Regrettably, many of the new structures are also being designed and reconstructed with little, if any, geotechnical input. This practice places significant construction risks upon the Contractor, and can be a contributing factor to geotechnical failures during construction. These failures are related to excavated cut slope instability, or valley slope instability resulting from inappropriate placement of excavation spoil stockpiles. Several recent failures have prompted a review of risk management practices related to these culvert replacement projects.

This paper discusses three culvert replacement projects in Northern Alberta. A brief overview of the common issues at each of the sites is provided. For emphasis an historical review is provided of the Hamelin Creek site, which details almost 40 years of construction and maintenance problems at the site. A commentary on the design process and geotechnical input and the associated consequence is presented. A companion paper in these proceedings details recent events, investigation and remedial work undertaken at the Hamelin Creek site.

The paper concludes with general recommendations for geotechnical investigation requirements, a discussion of cost/benefits and geotechnical risk management.

2. BACKGROUND

2.1 Design and Construction Philosophy

For highway projects in Alberta, culverts were historically installed by Alberta Transportation, or by Local Road Authorities using their own forces or were constructed by day labour. This approach permitted flexibility of design and construction, and produced an experienced 'pool' of labour being able to handle the design and construction work. Over the years a series of Standard Drawings and Specification were developed, and typically this system of experienced in-house designers and construction crews familiar with the 'standards' worked fairly well.

Since the mid 1990's bridge culvert design has been outsourced to consultants and construction of bridge culverts has been done by contractors. Department staff involvement now essentially entails project initiation, design review, fiscal project management, and development of standards and specification. Standard drawings and specifications and the associated disclaimers are now used with little regard to site conditions.

For most culvert replacement sites this design process is acceptable. However, this procedure has reduced the perceived need for site specific geotechnical investigation. Predictably, there have been a few recent projects, which have experienced slope stability problems, resulting in construction delays and contractor claims. These issues eventually trace back to the design process and the adequacy of site specific information. In these cases the embankment sideslopes outside of the zone of excavation are generally not at issue provided excavation spoils are not stockpiled in sensitive locations. The geotechnical problems are related to the failure of excavation cut slopes, and failure of embankment slopes and natural valley slopes where excavation spoils are temporarily stockpiled.

2.2 Current Geotechnical Investigation Requirements

Alberta Transportation has issued requirements for geotechnical investigations, as provided in Chapter 7 of *Alberta Transportation, Engineering Consultant Guidelines for highway and Bridge Projects, Volume 1 Design and Tender*, 2002. Requirements are provided for investigation of new culvert sites, however an apparent 'loophole' may be present regarding the interpretation and application of these requirements to existing culvert sites.

An underlying issue, which will not be dealt with in this paper, is the undervaluing of the contribution of geotechnical engineering to the success of projects, in this case projects that involve deep excavations. Most culvert projects are designed by a prime consultant with input from a geotechnical sub-consultant. For whatever reason the prime consultant in many instances limits the scope of work and input of the geotechnical sub-consultant, usually as a cost-trimming exercise. In such a case the contribution of the geotechnical sub-consultant to the project is often limited to provision of a few shallow boreholes and some comments on the anticipated culvert foundation conditions. Often there are not sufficient hours allotted to the geotechnical consultant for attendance at project meetings where geotechnical issues are being discussed.

3. RISK ASSESSMENT

A review of culvert data was undertaken to help determine the nature, severity and prevalence of risk associated with culvert replacement projects. A simplified reference framework was developed to group risk factors, and the nature of the problem. This was followed with a parametric stability analysis to screen high risk sites to help determine the severity of the risk. Finally a review of the department bridge culvert database was undertaken to help assess the prevalence of the risk.

3.1 Simplified Risk Assessment Framework

A risk matrix was developed to group risk elements and simplify the assessment. Most of the culvert installations at risk had little, if any, geotechnical information available. The risks typically associated with differing soil conditions between boreholes, inadequate sampling, lab testing or poor quality geotechnical investigations was therefore aggregated into a "site knowledge" risk factor. The resulting risk matrix is presented in Chart 1.

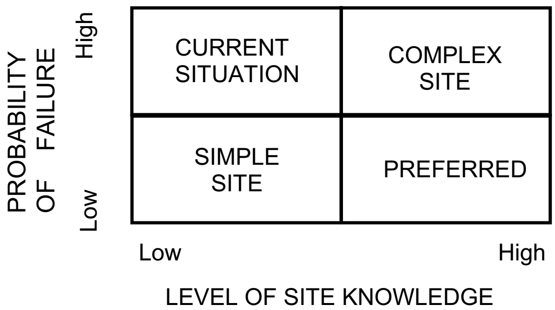

Chart 1: Risk Matrix

The risk framework identified the current situation as one of a relatively low level of site knowledge associated with a relatively high probability of failure. The preferred situation was one of a relatively high level of site knowledge associated with a relatively low probability of failure. For relatively simple sites it may be acceptable to have limited site knowledge; however for complex sites even a high level of site knowledge may be insufficient to preclude failures.

3.2 Stability Analysis

A parametric slope stability analysis of a simplified embankment cross-section profile was undertaken to provide a preliminary basis for screening of high risk sites, as an aid to gauging the severity of the problem. As shown in Figure 1, the parametric analyses used: excavation depths of 2, 5, 10 and 20 m; cut slopes angles of 1H:1V, 2H:1V and 3H:1V; embankment and foundation undrained strengths of 20 to 50 kPa.

Undrained - Short Term Analysis
Strengths varied from 20 - 50 kPa
Slope angle varied from 1 to 2 to 3H:1V

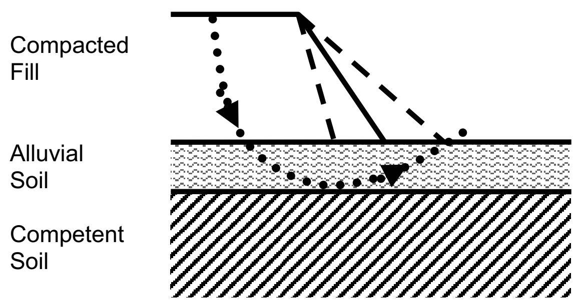

Figure 1: Parametric Slope Stability Analysis

The analysis showed that satisfactory stability conditions were present for the condition of a weak embankment overlying a weak foundation soil for burial depths less than about 6 m. A factor of safety of 1.1, based on an undrained analysis, was used as the acceptance criterion for the stability assessment. The parametric analysis was then related to the risk framework with the results shown on Chart 2.

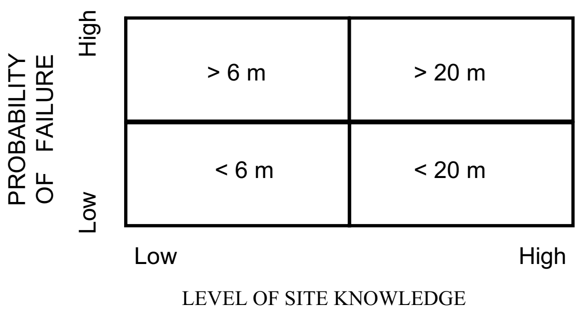

Chart 2: Risk Matrix Related to Stability Analysis

Chart 2 may be interpreted to show that for culvert burial depths of less than 6 m, only a low level of site knowledge is required in order to provide a low probability of failure. For burial depths greater than 6 m a low level of site knowledge may result in a high rate of site failure. A high level of site knowledge produces a low probability of failure for burial depths less than 20 m, while even a high level of site knowledge may be insufficient to produce a low probability of failure for very deep burial depths.

3.3 Bridge Culvert Database Analysis

Alberta Transportation maintains a detailed database of bridge culvert information. A review of existing bridge-sized culvert site data was undertaken as a part of risk management assessment in order to assess the prevalence of the problem. This data was mined, sifted and interpreted to produce some interesting conclusions.

Bridge sized culverts are defined as culverts larger than 1.5 m diameter. For the purposes of this assessment burial depth is defined as the depth of cover above the crown of the pipe plus the diameter of the pipe. This measurement reflects the minimum depth of excavation required to remove and replace the culvert. Additional sub-excavation below the culvert bottom is usually required to place a granular pad foundation for the replacement culvert.

There are 7123 bridge sized culverts below provincial highways in Alberta. Of these 1645 (23.1% of the total) have a burial depth of 6 m or more, 454 (6.4%) have a burial depth of 10 m or more, and 116 (1.6%) have a burial depth of 15 m or more. Of the 1645 pipes with burial depths greater than 6 m, 157 (2.2%) are predicted to require replacement within 5 years, 367 (5.2%) require replacement with 10 years and 575 (8.1%) within 15 years.

Of the 116 culverts buried deeper than 15 m, 12 are predicted to require replacement within 5 years, 21 within 10 years and 37 within 15 years. The rate of replacement for very deeply buried culverts is therefore slightly more than 2 per year. A similar analysis for bridge culverts with burial depths of more than 10 m and more than 6 m predicts annual replacement rates of about 10 and 38 respectively. Several culverts have burial depths in excess of 30 m with one burial depth listed at 54 m.

The prevalence of the potential problems was clearly illustrated to the department upon completion of the culvert file review.

4. CASE HISTORIES

Three case histories of culvert replacement projects were reviewed to determine policy or procedural inadequacies that might have contributed to the failures experienced at the sites. The three sites are: Highway 725 at Hamelin Creek; Highway 88 at an unnamed creek, and; Highway 22 at an unnamed creek. Each project was reviewed to determine the availability of geotechnical information, whether the available information could have helped avoid site problems, and the nature of the geotechnical investigation done for the culvert replacement project. Only the file review description for Hamelin Creek is provided in detail for brevity sake. Brief descriptions of the issues and resolution are provided for all sites.

4.1 Hamelin Creek, Highway 725

Hamelin Creek is a minor tributary of Peace River, located in northwestern Alberta. The site where Highway 725 crosses Hamelin Creek is located about 115 km northwest of the City of Grande Prairie, Alberta. At the crossing location the valley is about 600 m wide at the upland prairie level, 100 m wide at valley bottom level and about 60 m deep. A companion paper in these proceedings provides a more detailed description of the physical site setting.

A review of Alberta Transportation files details a site history that dates to the mid 1950's when a low level bridge was installed to replace an oil company temporary crossing. The low level structure was located about 300 downstream from the current crossing site, and provided sub standard road geometrics. Several planning studies were completed in the mid 1960's to review road relocation options. The current location was chosen in 1967.

Field observations were provided that described suspected unstable valley slope conditions. Although this comment had little relevance to the initial culvert construction, it was prophetic in relation to the reconstruction undertaken 35 years after initial construction.

Preliminary engineering and foundation test hole drilling was completed in 1967. The foundation investigation indicated a potential requirement for staged construction of the embankment fill and the use of a basal filter blanket to permit escape of excess pore water pressure. At this location there are two branches of Hamelin Creek. These branches were carried in a north culvert, 6.0 m diameter by 130 m long, and a south culvert, 3.4 m diameter by 146 m long. Both culvert pipes were structural plate corrugated metal pipe (SPCMP). Although staged construction was used, it does not appear that a basal drainage blanket was constructed. A chronology of site activity follows:

1968
Construction started. Poor embankment and culvert foundation conditions were encountered. Some portion of the unsuitable foundation material was removed.

1969
Culvert bed preparation was completed. Placement and compaction of about 7 m of embankment fill completed. Cracks were noted along both the east and west fill slopes in December 1969.

1970
Extraordinary measures taken to protect upstream inlet of culvert where settlement and deformation were noted. Sheet piling driven around the upstream inlet of the larger culvert and heavy riprap was placed in front of the sheet piling. Fill settlement problems were noted below the concrete collar of the smaller culvert inlet and in the fill over the culverts. Deformation of the culverts followed which resulted in tears along 24 plates in the smaller culvert and 10 plates in the larger culvert. Fill placement was halted to permit investigation of the movement.

1971
The investigation that following revealed that the embankment fill was place with erratic compaction effort. The solution at this time appeared to consist of installation of stiffener plates in both culverts, grouting of the voids, and placement of additional fill at a slow rate. The fill height reached about 12 m.

1972
Struts installed in the large culvert in response to deformations and cracks. Embankment fill is still moving. No additional fill placed.

1973
Struts removed and a grouted liner installed along middle half of pipe. Pre-cast concrete girders from an old bridge used to line the outlet of the culvert.

1974
Settlement of the small culvert concrete collar repaired. Fill at outlet of larger culvert restored and protected with rip-rap. No fill placed. Extra work expenditures related to culvert deformation and slide between 1969 and 1974 totaled $406,000.

1975
Some additional fill placed. Slope movement and distortion of the unlined ends of the large culvert observed. Fill placement halted.

1976
Upstream end of small culvert distorted into oval shape. Struts placed in large culvert to prevent collapse. Drift collected in large pipe due to struts, partial blockage of pipe. Slope instability around south, downstream, end of smaller pipe. Berm to be built using drift and debris collected from pipe. Deep scour hole repaired. Continued deformation of large diameter pipe observed. Pipe was jacked back into shape and cover plates welded in place to strengthen the deformed section. Small scale slides occurred, damaging beveled end of the culvert.

1977
Drift accumulated at inlet of small culvert diverts flow, creating scour of embankment slope and slope movement. Larger scale slope movement observed on slope between the culvert inlets. Repairs completed. Entire length of small culvert strutted.

1984
Segment of embankment slope failed due to scour. Top and site plates of the large culvert have collapsed downstream of the lined segment. Segment of pipe removed, replaced and extended. Inspection of material surrounding the pipe showed that backfill was not granular fill as specified, but silty clay.

1985
Shotcrete repair and strengthening of large culvert done. 175 mm thick layer of steel fibre reinforced shotcrete applied at cost of $35,000. Within 2 months cracks were observed in the shotcrete repair.

1989
Preliminary estimate of a 5 m increase in fill required to bring the crossing up to applicable highway geometric standards.

1990
Note to file discussed anticipated problems related to placement of extra fill. Struts washed out from large culvert. Struts replaced. Minor maintenance issues from 1990-2000.

The design for the new culvert was done in 2000. the two culverts are to be replaced with a concrete arch pipe with a rise of 6.2 m, a span of 10.0 m and 129 m invert length of pre-cast or cast-in-place concrete for estimated cost of $4.1 million. The new design includes an increase in fill height of about 5 m.

A companion paper provides details related to site problems during the construction of the new culvert. The final cost of the replacement culvert, including the extra work done to mitigate geotechnical problems, was about $8.4 million.

4.2 Watercourse Culvert, Highway 88

This project involved the replacement of an 88.5 m long 1800 mm diameter culvert with a 96.3 m long 3050 mm diameter culvert at the base of a 16 m high embankment. The site is located about 4 km west of Fort Vermillion, in northern Alberta. Based on a review of department files it does not appear that a geotechnical investigation of any sort was undertaken for the design of the original or replacement culvert structures. The records also contain no mention of geotechnical concerns prior to the culvert replacement project.

The excavation done for the culvert replacement followed the excavation profile shown on the Department standard drawing S-1418-93 “Installation of Large Steel Pipes”. This drawing shows an excavation using 1H:1V sideslopes and a minimum undercut below the culvert base of 0.6 m. One small-scale failure occurred on the east cut slope during excavation. This slide was followed by a large-scale failure that involved the entire west excavation slope, as shown on Figure 2. The exposed cut slopes were further flattened to stable slopes. An additional slide occurred during fill placement that damaged the new culvert.

Work was shut down for several weeks while the situation was evaluated, geotechnical investigations were completed, and obligations and contractual issues were resolved. The slide was attributed to a artesian groundwater conditions that saturated the lower portion of the embankment fill, and the presence of weak foundation soils; conditions which would have been identified during a geotechnical investigation during the culvert design process.

The original contract price for the culvert replacement was approximately $631,000. The final costs totaled $1,652,000. The extra costs was related to the additional engineering and construction effort required to mitigate the sequence of slope instabilities The additional costs were split between engineering costs, about $66,000, and construction activities, about $955,000.

4.3 Watercourse Culvert, Highway 22

This project involved the replacement of an 88.5 m long 1800 mm diameter culvert with a 96.3 m long 3050 mm diameter culvert at the base of a 13 m high embankment. The site is located about 0.5 km south of Drayton Valley, in west central Alberta. Based on a review of department files it does not appear that a geotechnical investigation of any sort was undertaken for the design of the original or replacement culvert structures. The records also contain no mention of geotechnical concerns prior to the culvert replacement project.

The excavation done for the culvert replacement followed the excavation lines shown on the Department standard drawing S-1418-93 “Installation of Large Steel Pipes”. This drawing shows an excavation using 1H:1V sideslopes and a minimum undercut below the culvert base of 0.6 m. A failure of one of the excavation slopes occurred shortly after the contractor had completed the main excavation and was working on the culvert undercut. Work was shut down for several weeks while the situation was evaluated, geotechnical investigations were completed, and obligations and contractual issues were resolved. The slide was attributed to a weak foundation and wet embankment fill materials; conditions which would have been identified during a geotechnical investigation during the culvert design process.

The contract price for the culvert replacement was approximately $467,000. The final costs totaled $973,000. Apart from the cost overrun, the work was delayed for several weeks, resulting in significant inconvenience for highway users.

4.4 File Review Summary

Three project files were reviewed. One file, Hamelin Creek, provided an abundance of information that clearly illustrated historic geotechnical related problems. Based on a review of this file one would expect to encounter geotechnical problem with the proposed culvert replacement project. A review of the Hamelin Creek files should have alerted the design consultant to the need for site specific geotechnical information and that the site was geotechnically problematic.

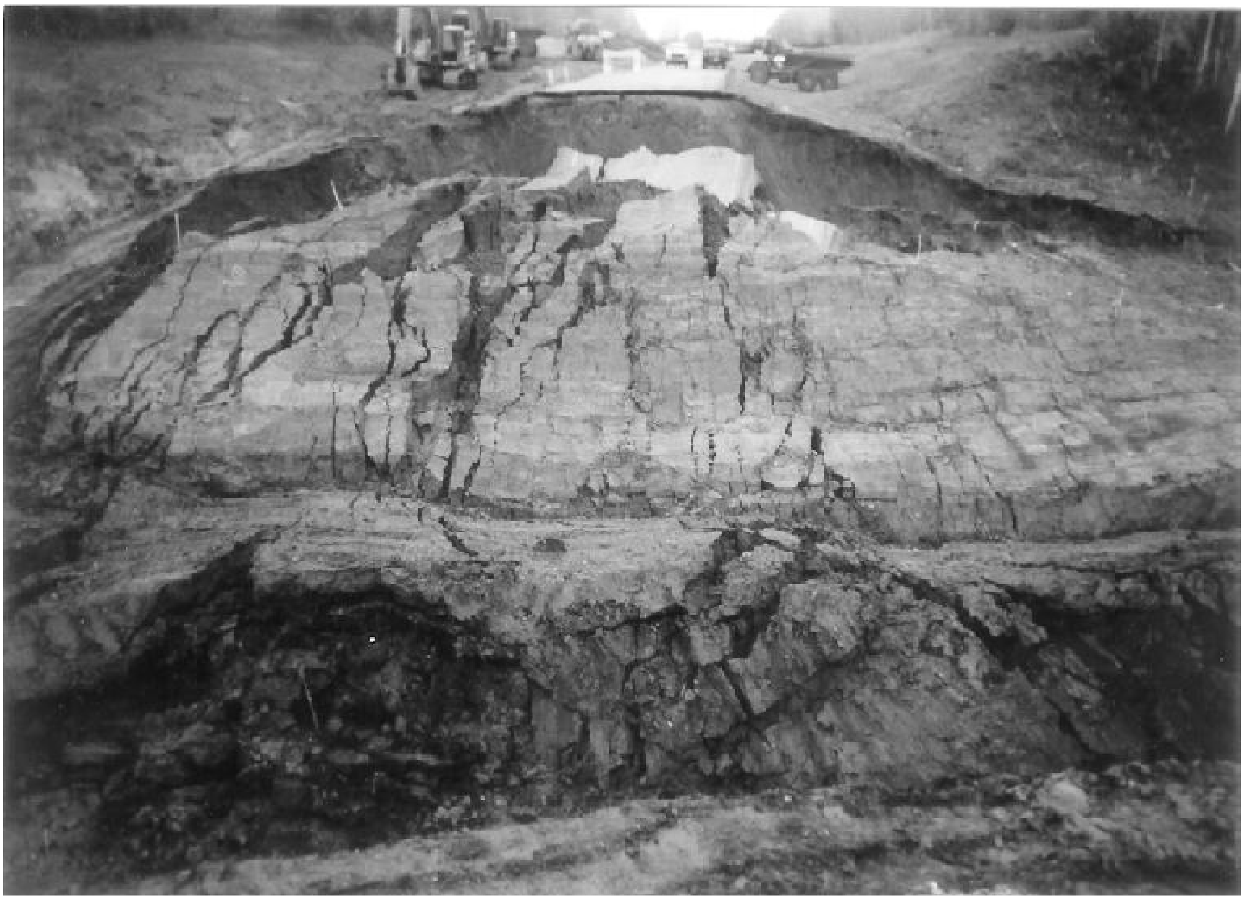

Figure 2: Excavation Slope Failure, Hwy 88 Culvert Replacement Project

By contrast the other two project files contained little, if any, geotechnical information specific to the culvert locations. In these two cases the project was essentially designed and constructed without geotechnical information. Building a major construction project without benefit of site specific geotechnical information is never the desired course of action. In these two instances the lack of geotechnical input during the design process was a contributing cause to the site problems that ultimately resulted in excavation slope failures, construction delays, costly mitigation work and associated friction between client, consultant and contractor.

5. DISCUSSION

A review of failures indicates that the use of Standard Drawings is appropriate as a risk management criterion for culvert replacement projects where the embankment fill height is 6 m or less. However, significant geotechnical problems have been experienced with fill heights in excess of 6 m, and especially where fill heights exceed 12 m.

For these situations it is imperative that a proper geotechnical assessment be undertaken prior to design and construction. In response to these concerns Alberta Transportation has issued Bridge Design Bulletin #2 notifying Consultant forces that a geotechnical investigation is required for any culvert replacement site where the embankment fill height is greater than 6 m. This notice can be found at the following website: http://www.trans.gov.ab.ca/Content/doctype30/production/bulletins.htm

The three culvert replacement projects reviewed herein had a total initial cost of about $5,200,000. The final costs totaled about $11,000,000. It is likely that a portion of the cost overrun would have been incurred as a result of more conservative designs. In these cases the use of flatter excavation sideslopes, and the stockpiling of excavated material outside of the valley may have been recommended as part of a geotechnical risk management plan. The estimated cost for these activities is about $1,500,000. It should be noted that a significant portion of the cost overrun at the Hamelin Creek site was related to slope stabilization work required due to the inclusion of frozen fill in the embankment, which is a construction project management issue and not directly a geotechnical issue.

The cost to undertake geotechnical investigation for all three sites would be about $100,000. The return on investment from a purely monetary perspective is therefore about 30:1 for these sites. The reduction in traffic disruption, and associated societal and political ramifications should also be appreciated.

6. CONCLUSION

Risk management involves identifying a hazard, evaluating the probability of the hazard occurring, assessing the consequences of the occurrence and developing a plan to minimize either the probability or consequences of the hazard.

In the case of a culvert replacement project a possible hazard might be the lack of a geotechnical investigation to support the design and construction phases of the project. For this hazard the probability of a failure was determined to be high for excavation depths in excess of 20 m, moderate for excavation depths between 6 and 20 m, and low for excavation depths less than 6 m. The consequences were illustrated by the three culvert replacement file reviews presented in this paper. In each case the excavation slopes failed resulting in construction delays, cost overruns and contract frustrations.

The risk management plan developed in response to the specific hazard of a lack of geotechnical information was to issue a design bulletin that identified the requirement for a geotechnical investigation for any culvert replacement project where the embankment fill heights exceed 6 m. Review of the policy will be undertaken as appropriate.

7. ACKOWLEDGEMENTS

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8. REFERENCE

Alberta Transportation, 2002, Engineering Consultant Guidelines for Highway and Bridge Projects, Design and Tender, Vol. 1, Chapter 7.