Failure mechanism and behavior of a large landslide in glacio-lacustrine silt and clay, Chilliwack River Valley, B.C.

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Abstract: The Slesse Park landslide is a very large, natural instability in stiff, glacio-lacustrine silt and clay on the north side of the Chilliwack River, 600m upstream from the community of Slesse Park.

The failure mechanism consists of two phases. The first phase involves the main body of the landslide moving forward largely as a rigid block. The volume of this block is approximately 2 Mm^3. The main block moves episodically, in response to extremes of rainfall and/or snowmelt. However, the initial cause for instability was likely the result of undercutting of the toe of the slope by river erosion.

The second failure phase was demonstrated in 1997 by several rapid slides within disturbed, weathered clay and silt at the toe of the main unstable mass, the largest of which was sufficiently mobile to cause temporary damming of the river. Rapid flowslides appear to be relatively small and limited to the disturbed colluvium at the toe. However, should the main body of the unstable mass fail catastrophically as one unit, the potential for a more lasting blockage of the river with effects on upstream and downstream safety and resources would be increased.

Introduction

In January 1997 during the wettest winter on record, several rapid mass movements occurred at the Slesse Park landslide site, the largest of which was approximately 50 000m^3. This event was sufficiently mobile to cause temporary damming of the Chilliwack River. Although the landslide dam was breached quickly, without significant damaging consequences, the series of slides delivered a large amount of sediment into the river channel. Geotechnical studies were carried out subsequently, in an attempt to predict future behaviour of the landslide. The purpose of this paper is to summarize the results of the work completed to date and to present an interpretation of the observed behaviour of the landslide. The Slesse Park landslide is in many respects typical of slope movements in glacio-lacustrine deposits in Western Canada.

Climate

The climate of the Chilliwack Valley is typical of Coastal BC with heavy precipitation during the winter and relatively warm, dry summers. Extremes of rainfall and/or snowmelt trigger landslide movement due to subsequent high groundwater conditions. The winter of 1996-1997 was the wettest on record in the Vancouver area. The late January 1997 landslides occurred during heavy rain with snow on the ground.

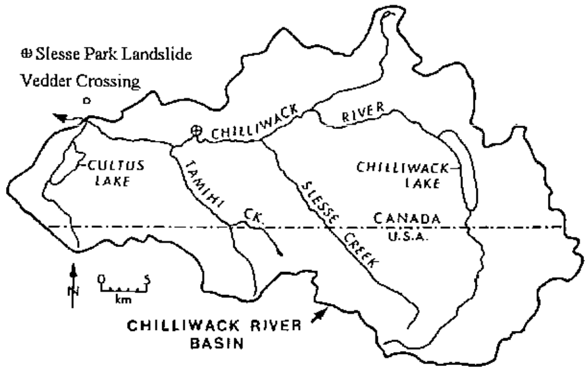
During the same month, major landslides in fine-grained soils occurred near Vancouver, at Salmon Arm in the B.C. Interior, and at Kelso in Southern Washington.

The winter of 1998-1999 was the second wettest winter recorded for the Vancouver area. Although no rapid flowslides of appreciable magnitude occurred, fresh tension cracks and measured displacements are evidence of movement of the main body of the slide.

Site Description

The Slesse Park landslide area is located on the outside of a meander bend along the north bank of the Chilliwack River. The slide area is bordered by Noonie Creek to the west and by what is referred to as Plantation Creek to the east. Central Creek flows through the centre of the unstable area.

Fig. 1. Location map of Slesse Park Landslide. (Source: Clague et al.1988)



The dimensions of the slide are approximately 250m long by 500m wide, encompassing an area of about 13 ha. The riverbank at this location consists of a steep, 40m high bluff eroded in glacio-fluvial deposits, surmounted by glacio-lacustrine clay and silt. Active toe erosion by the Chilliwack River has been periodically ongoing for a number of years. However, a series of major flood events in 1989 and particularly in 1990 initiated remedial action. In 1991, the B.C. Provincial Government constructed a 5m high berm, offsetting the main channel 50m from the slope to address continued undercutting, sedimentation and to provide a sediment and debris storage platform between the toe of the bluff and the river channel.

The surface of the failing mass slopes upward at about 16° from the top of the bluff to a steep, 2 to 15m high back scarp. The elevation difference between the river channel and the top of the back scarp is about 80m. The area is forested by second growth fir, alder, and cedar. The area underwent timber harvest in the 1940s. On going surface disturbance is indicated by stressed vegetation and deciduous growth.

Geology

Bedrock geology

At depth, bedrock is likely the eastward dipping Chilliwack Group, which consists of metamorphosed volcanic and sedimentary rocks, including limestone (Monger, 1989). Caverns occur in the limestone but locations are poorly documented. It is possible that they may transport large amounts of water, however, there is no indication that they may be present within the landslide area (Thurber, 1997).

Quaternary history

Two major glacio-lacustrine events occurred in the Chilliwack River valley at ca. 20-21,000 years BP (Saunders, 1985) and ca. 11-12,000 years BP (Clague and Luternauer, 1982 and Saunders et al., 1987). During the latter deglacial portion of the Fraser glaciation, ice in the eastern Fraser Lowland (part of the Cordilleran Ice Sheet) blocked the mouth of the Chilliwack valley at a time when the mid reaches of the valley were ice free. A glacial lake formed between the ice dam at the mouth of the valley and an outwash delta formed in the upper reaches of the valley (ca. 11,700 BP). Several relatively minor advances of Fraser Lowland ice separated by brief periods of recession occurred ca. 11,500 and 11,200 years BP and were responsible for another series of glacial lake conditions within the valley (Saunders et al., 1987).

By approximately 11,150 years BP ice disappeared from the lower reaches of the Chilliwack Valley and subsequent drainage of glacial lakes completed. The ice damming of the Chilliwack valley ceased approximately 11,000 BP with the completion of deglaciation of the Fraser Lowland.

It is believed that the glacio-lacustrine deposits at the site accumulated during the initial blockage of the Chilliwack River valley, perhaps as early as 20-21,000 years BP. Evidence to support this hypothesis comes from wood deposited in a sand unit within the glacio-lacustrine sequence dated at 20,190 ± 1000 BP (Saunders, 1985, Unit 2, Fig. 5.6). Exposures of glacio-lacustrine sediments at similar elevation 2-3km away were overlain by till dated as 15 610 ± 130 BP (Saunders, 1985).

The Slesse Park landslide

Surficial geology

A summary of the quaternary stratigraphy interpreted from exposures along Central Creek gully and the main back scarp (Watson, 1999 and Clague et al. 1988) is shown in Fig. 3.

Unit 1 consists of well-rounded cobbles and pebbles, with a maximum diameter of 30cm, supported in a coarse sand matrix. It is horizontally stratified with minor cross bedding. It is interpreted to be glacio-fluvial in origin. The coarseness, poor sorting, and lack of well defined bedding suggests a flood deposit, perhaps glacial outwash. This unit is very dense, uncemented, and has high permeability.

Unit 2 rests disconformably upon Unit 1. It consists of laminated silt and clay interbedded with layers or lenses of fine sand partings. This Unit is interpreted to be of glacio-lacustrine origin. Dropstones 0.2-3cm in diameter are randomly scattered. The materials are very stiff and overconsolidated with low permeability.

Unit 3 is a well sorted fine and medium sand with a minor silt component. The sand is bedded, with ripples and small scale cross bedding. Zones of massive sand are also present. Beds dip gently toward the west. The sequence exhibits a general coarsening upward sequence. The top 1m contains mainly coarse sand with occasional pebbles; most of the pebbles are concentrated at or near the upper contact. The sands are dense and uncemented. They exhibit high permeability and erosion by piping processes commonly occurs within the unit. The upward-coarsening, dipping structure and the close association with lacustrine sediments suggest that deposition of Unit 3 was as a small delta.

Unit 4 is glacio-lacustrine laminated silts and clay similar to Unit 2. The main failure plane is located within this Unit at El. 178 approximately, 5m above the base of Unit 4. Above the failure plane, a zone several metres thick has been remoulded. Above this zone the clay and silt is again laminated with bedding dipping 4 to 20° into slope suggesting varying degrees of backward rotation. This unit exhibits a coarsening upward sequence with the upper 2m grading from silt to uniform, fine grained sand.

Unit 5 is exposed in the back scarp, and in minor scarps at lower elevations. The material is a diamicton composed of a high plasticity clay matrix supporting

FIGURE 2. Geomorphological Map of the Slesse Park Landslide

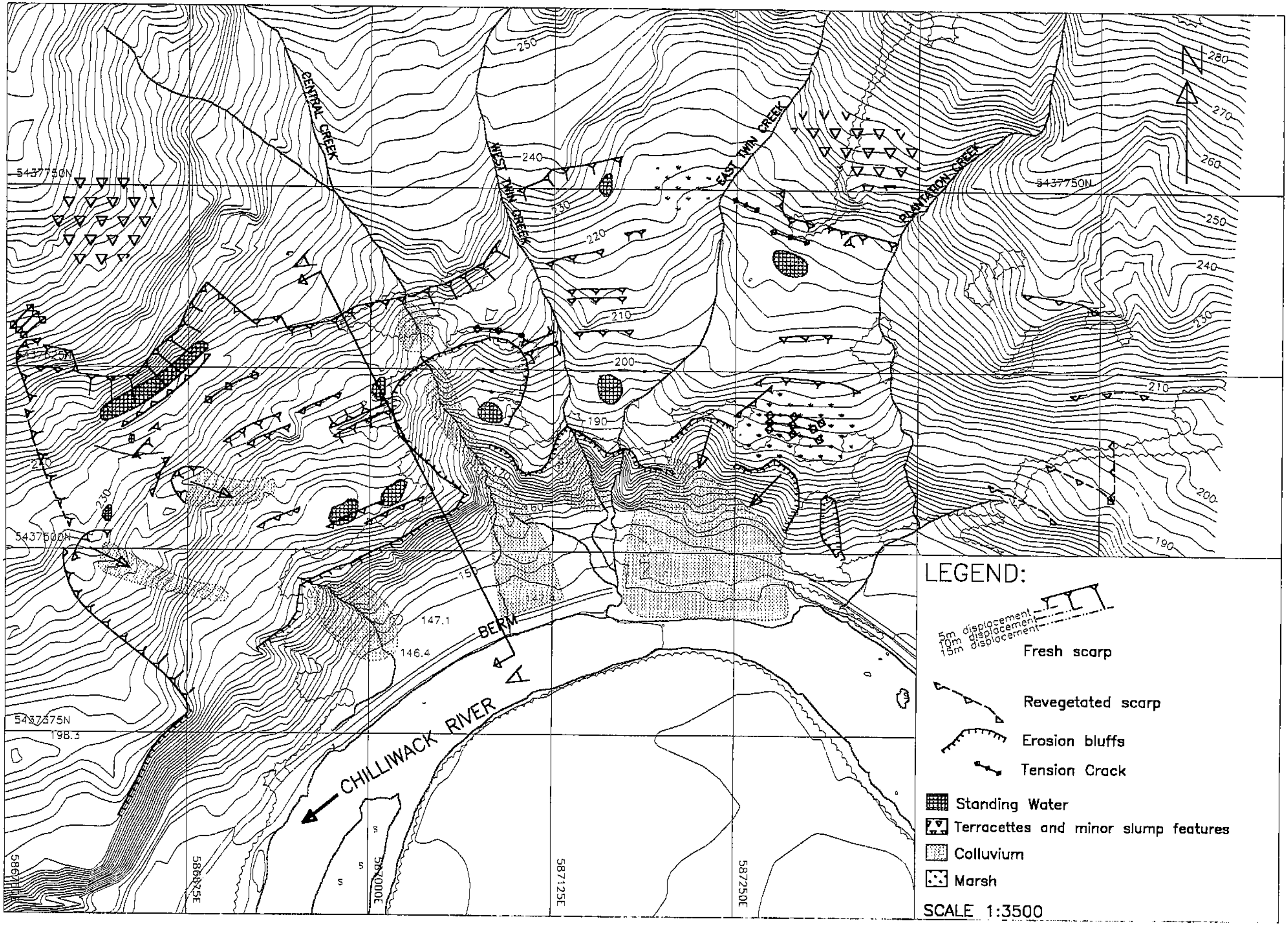
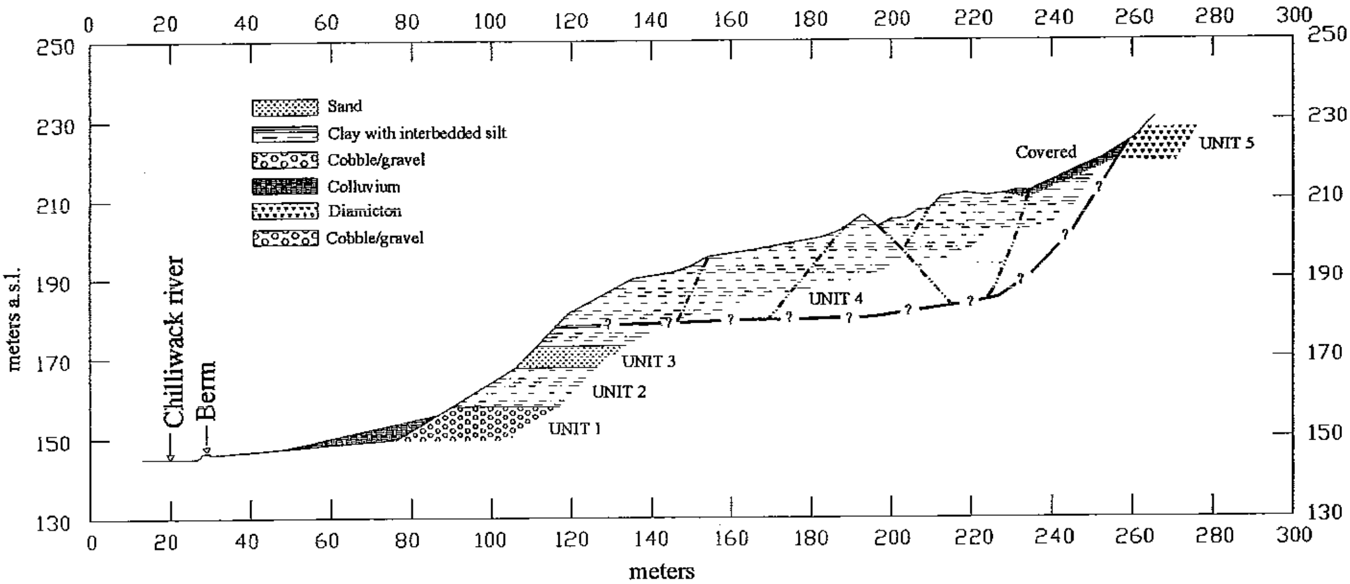


Fig. 3. Cross-section A-A' of Slesse Park landslide (See Fig. 2). Lateral extent of stratigraphic units is not known.



subangular to subrounded clasts. Some clasts consist of laminated silts and clay. This Unit is probably glacial till.

It is not yet evident whether the diamicton exposed in the back scarp overlies or underlies the glacio-lacustrine deposits of Unit 4. Unit 5 may have been deposited on top of the glacio-lacustrine sediments during a readvance of ice into the lower Chilliwack Valley. Subsequent fluvial erosion may have removed the material at lower elevations. Alternatively, the materials of Unit 5may have blanketed the valley walls prior to impoundment of a glacial lake in which case the lacustrine deposits of Unit 4 overlie those of Unit 5. Below the back scarp, a discontinuous blanket of dense sandy gravel covers landslide features formed in Unit 4. At this time, its relationship to the diamicton is not clear.

Main Instability

Due to difficulties of site access, no drilling has been undertaken. A reasonably detailed reconstruction of the sliding mechanism can be made by the study of the slide morphology. This effort is aided considerably by an excellent exposure of the toe of the rupture surface near the top of the steep bluff face.

A relatively continuous back scarp defines the upper limit of the landslide. It consists of steep, freshly exposed soil scarps that vary in height from 2 to 15m. The main body of the slide appears to be moving forward towards the river over a distinct failure surface located within the laminated silts and clay of Unit 4 (approximate El. 178m). This sliding surface is knife-edged and can be traced for almost 500 m along the river escarpment. It is an extremely smooth slickensided discontinuity dipping 1° to the west (Fig. 4, Fig. 5). The displaced material above the sliding surface is remoulded to varying degrees whereas the material below remains intact and undisturbed. The estimated volume of displaced material is 1.84 million cubic meters (Thurber, 1997). In estimating this volume, it was assumed that the lateral scarps cut up steeply with the same slope as the back scarp.

Fresh soil exposures, thrown trees, and stressed vegetation including stretched roots are evidence to indicate recent to very recent movement in the headscarp area over a distance of more than 500m. However, the ground surface between the freshly disturbed back scarp and the slide toe is forested and shows relatively few signs of fresh disturbance, suggesting that the main body of the slide is moving forward largely as a rigid blocks with some internal deformation. Fig. 3 shows a cross section of the slide observed just west of Central Creek. This figure includes a reconstruction of the rupture surface consistent with the morphology of the slide features. The rupture surface can be described as a compound sliding surface (Hutchinson, 1992). It cuts steeply from the ground surface to a subhorizontal bedding plane then follows the bedding plane until it daylights at the bluff face. At the rear of the slide, back tilted blocks covered by mature vegetation suggest rotational movement has occurred. In the lower slide area, a prominent ridge feature observed at approximately El. 215 suggests translational sliding. Laminations within the failure prism of this ridge dip 5° into the slope.

The back scarp and the major deformational features of the slide mass have been in existence for a number of decades. They are evident on the oldest airphoto (1940 - B.C. 209:59,60) and are overgrown by mature conifers.

Fig. 4. Bluffs exposed along River. Note the location of the main failure plane.

Fig. 5. Slickensided surface of main failure plane. Photograph shows an area 30cm x 30cm.

The main body of the slide appears to move episodically in response to climatic conditions, especially snow melt and/or rain on snow events and associated groundwater conditions. The last movement (approximately 1m) took place in 1999. Slope movements are numerically indicated by measuring distances between trees marked with metal reference markers. These extensometers, installed in 1997, have since recorded displacements of up to a maximum of 2.5m. Most of this movement occurred during the winter of 1998-1999.

Secondary movements

Episodic movement of the main instability is directly responsible for secondary movements. The main movement, combined with erosion of the granular soil beneath the clay, produce oversteepening of the crest of the bluff. The clay material is then removed from the toe of the main sliding mass by the secondary movements. Field and airphoto observations indicate three types of secondary movement:

The first type, block falls and minor slumps along the crest, occur periodically each year and are probably more frequent following a period of displacement in the main mass. Erosion by piping within the sand unit approximately 10m below the main weak surface undermines blocks of fractured silt and clay, increasing the frequency of failure.

Prior to the construction of the protective berm in 1991, the debris from such minor landslides likely impacted directly into the river channel and was removed by fluvial processes. Upstream and downstream of the apex of the meander bend, however, where the river channel was not in direct contact with the escarpment toe, the debris accumulated along the base of the bluff forming a relatively steep colluvial apron. In some areas, the apron built up to the full height of the bluff and was colonized by vegetation. This apron consisted of a mixture of blocks of clay and silt, large and small woody debris, set in a matrix of softened remoulded clay. A similar apron is now in the process of being built on the storage platform behind the river dyke.

The second type of movement was illustrated by the events of January 1997, following a major movement of the main mass. The eastern portion of the landslide site underwent failure. The colluvial apron became oversteepened, possibly by thrusting of the material from above. A massive undrained failure occurred, moving much of the apron across the storage basin, berm, and river channel. The material in this flow consisted of blocks of intact silt and clay and woody debris entrained in a soft remoulded clay matrix.

A smaller failure of similar type took place a few hours after the initial event. This landslide involved a volume of approximately 4,000 m^3 of colluvium. The total displacement of the slide front was approximately 30m and the peak velocity was of the order of 3m/sec.

Rapid flowslides appear to be relatively small and limited to the disturbed colluvium at the toe. However, a third type of secondary movement occurred shortly prior to 1952 as evidenced in air photographs of that year (BC1623:11,12). This event appeared to involve rapid, undrained failure of the disturbed soil above the crest of the bluff at the western margin of the main slide area. The entire mass between the main back scarp and the bluff moved by several metres. Its frontal portion appeared to have detached and flowed over the bluff, and reached the river channel.

Groundwater

It has been noted that slope movement is triggered by events of heavy precipitation and/or snowmelt and subsequent groundwater conditions. Due to the lack of instrumentation monitoring pore pressures, it is difficult to make quantitative descriptions of ground water conditions within and adjacent to the slide. However, several observations have been made.

It is likely that due to the stratigraphy and varying permeability of materials, several perched water tables exist within the slide area. A perched water table with artesian flow was encountered during the installation of a piezometer to the east of Central Creek gully. During augering for piezometric installation, water filled the hole to within 10cm of the ground surface. However, the water level measured in the piezometer three weeks following installation, was 3.3m below ground surface.

In some places the water table is probably perched at ground surface as evidenced by water ponded in the grabens formed by backtilted blocks.

Seepage and piping erosion has been observed within the sand of Unit 3. In some places the colluvial apron at the base of the bluffs covers the exposure of this layer. This may contribute to pore pressure build-up in the slope and instability of the colluvial material.

It is possible that softening may occur adjacent to the failure plane due to the ingress of water through a relatively permeable 1.5cm thick sand lense overlying the failure plane.

Soils properties

Laboratory test results for samples collected from the landslide are presented in Table 1.

Table 1. Material Properties

Location	CC (%)	LL (%)	PI (%)	LI(%)
Clay from main weak surface	66	28	36	0.1
0-4cm above weak surface	-	57	31	-
0-4cm below weak surface	26	37	17	-
Flow slide colluvium	-	27	20	0.97
Intact clay in scarp of secondary flow slide	-	46	22	0.05

Bulk properties

The glacio-lacustrine clays are of medium to high plasticity. However, they are interbedded with low plasticity silts and fine sand laminations. The low liquidity indices of the intact clay suggest that the relatively undisturbed landslide material is moderately to highly overconsolidated. Overconsolidation may have been accomplished if overridden by subsequent advancement of glacial ice. The unconfined compressive strength of the intact laminated silt and clay was estimated as 3kg/m^2.

Remoulded clay in the disturbed parts of the exposures often show liquidity indices close to 1, probably as a result of swelling.

Material textures exposed in the back scarp are widely variable, ranging from massive clay of high plasticity, to sand, to very dense sandy gravel.

Material adjacent to the main sliding surface

The clay layer that contains the slickensided failure surface is uniform, light grey and approximately 1cm thick. Of the materials tested, this clay shows the highest plasticity (PI=32%) and the highest clay content (66%). Material sampled within 4cm below the slickensided surface has a lower plasticity (PI=17%) and clay content (26%). A fine sand 1.5cm thick overlies the failure surface. Material sampled from 0-4 cm above the sand was remoulded. The plasticity of this material was between that of the undisturbed material below the sheared clay surface and the clay material in which the main failure occurs.

The mineralogy of the clay sampled from the slickensided surface is primarily low activity clay (chlorite, illite and/or kaolinite) and glacially ground rock flour (quartz and feldspar). No smectites were discovered.

Given that large displacements of the main unstable mass have occurred, it is assumed that the weak surface is at its residual strength. Therefore, for the purposes of slope stability calculations, a residual friction angle of 12° was assigned to the highly plastic clays that the weak surface exploits (Thurber, 1997).

Interpretation

The large instability at Slesse Park is primarily due to a compound failure of approximately 1.84Mm3 of material along a subhorizontal, knife-edged failure plane located within laminated glacio-lacustrine silt and clay. The displaced mass would appear to move forward as a rigid block over a ductile clay surface at residual strength. The movement is generally slow and episodic, and likely in response to groundwater conditions influenced by intense and/or prolonged rain or rain on snow events.

Climatic events are believed to trigger slope movement however, a primary reason for the initial instability was likely undercutting of the toe of the slope by the Chilliwack River prior to the construction of the berm in 1991. Although the principal sliding surface is now located approximately 30m above river level, the landslide is still responding to past removal of toe support.

The main instability is the direct cause of three types of failure in which extremely rapid, undrained failure of disturbed, weathered clay and silt occurs at the toe of the main unstable mass.

Although the glacio-lacustrine material sampled at the site is not sensitive in its intact condition, it appears that bulk sensitivity develops as a result of severe deformation. Growth of cracks and straining of the dry mass is accompanied by ingress of water and swelling locally, raising the moisture content close to the liquid limit. Consequently, while the main instability is ductile in character and slow moving, the secondary movements can be extremely rapid. To date, these secondary movements involved only small portions of the unstable volume. Should they involve a greater proportion of the available mass of nearly 2 million m^3, the consequences could be of a more serious nature.

It is uncommon for stiff, overconsolidated silts and clay to display brittle, flow type failure. However, such failures have been documented in landslides along the Nass River (Geertsema, 1998) and the Peace River, (Evans, Hu, and Enegren 1996) where thick sequences of glacially overridden lacustrine deposits have been undercut by fluvial erosion.

Conclusion

The failure mechanism of the Slesse Park landslide consists of two phases. The first involves the main body of the landslide moving forward largely as a rigid block. Movement is episodic in response to extremes of precipitation and/or snowmelt.

The second failure phase involves rapid, undrained failure of disturbed, weathered colluvium at the toe of the main unstable mass. To date, rapid flowslides appear to be relatively small and limited to the disturbed colluvium. The largest rapid flowslide was reported in January 1997 (Thurber, 1997) during the wettest winter on record for the Vancouver area. The flowslide was sufficiently mobile to cause temporary damming of the Chilliwack River. However, the landslide dam was breached naturally, without serious consequence.

Consequences of failure depend largely on the magnitude of the failure and timing of the event. Should a greater volume of the unstable mass fail rapidly, temporary impoundment of the River to an unknown height would result and potential for catastrophic dam breach. The peak discharge in the Chilliwack River following a catastrophic dam breach could be comparable to a major flood. Public safety and potential damage to structure is of concern..

A threat to fisheries resources also exists as it relates to fish habitat and spawning. Water quality would likely be degraded in the event of a large landslide.

Due to the potential for serious consequences of rapid failure of the Slesse Park landslide, further study is in progress and include:

-Continued monitoring of slope movements.

-Detailed mapping of the stratigraphy and surface expressions.

-Slope stability analysis.

-Soil testing to determine the engineering properties and the degree of overconsolidation of the landslide materials

-A comparison of the Slesse landslide to other landslides in stiff, overconsolidated silt and clay to further the understanding of the factors that contribute to the rapid failure of these materials.

Should resources be available, a program of drilling to address extent of failure plane and stratigraphic relationships and a groundwater study to address source and movement of groundwater within the site would assist in the quantification and qualification of the landslide.

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