Landslides in Weakly-Cemented Lake Sediments, Morkill River, British Columbia

Corey R. Froese[1]

David M. Cruden[2]

[1] AGRA Earth & Environmental Limited
4810-93 St
Edmonton, Alberta
T6E 5M4
Telephone: (780) 436 - 2152
Facsimile: (780) 435 - 8425
Email: cfroese@agraee.com

[2] Department of Civil and Environmental Engineering
University of Alberta
Edmonton, Alberta
T6G 2G7

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ABSTRACT

Slopes in weakly cemented lake sediments in the Morkill River Valley in the Canadian Rocky Mountains stand at up to 65 degrees. Instability is due to the softening of the soils by frost action and the leaching of calcite cement. Field density profiles demonstrated depths of weathering and relative carbonate contents. Laboratory tests of carbonate content indicated a positive correlation between calcium carbonate and density in the lake sediments. The relationship was strongest in sands, in which leaching and dissolution were the dominant components of softening. In clays, frost action was the dominant component of softening. Freeze/thaw tests showed over a 50% decrease in strength after one cycle of freeze and thaw in the silts and clays.

RESUME′

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Keywords, Landslide, cemented, lake sediments, British Columbia

INTRODUCTION

Some operational and construction problems in forestry developments in the Morkill River Valley in the Canadian Rockies are associated with surficial landslides in lake sediments. Although landsliding in the valley is neither rapid nor deep, it challenges construction to reduce sediment deposition in salmon-spawning streams from natural and constructed cuts, fills, and slopes. Concerns of environment and government agencies were a driving force in the initiation of this study of the geotechnical properties, distribution and landslide mechanisms of the weakly cemented soils.

An initial air photo inventory of landslides in the area, along with a review of the available geological data, highlighted the possibility of the presence of calcium carbonate as a cementing agent in the soils in the valley. The purpose of this paper is to look at the effects of the cementation on the soils in the Morkill River valley. We first review experience with carbonate sediments in Western Canada and the physical environment in the area. This is followed by a description of the types of landslides observed in the Morkill River valley. We then address the observed effects of weathering on the calcium carbonate cementation in the field and laboratory and discuss how the effects of chemical and mechanical weathering on these sediments contribute to instability of slopes in the area.

CARBONATE SEDIMENTS IN WESTERN CANADA

Ford (1989, Figure 9.34) illustrated the distribution of carbonate and other soluble rocks in Canada; gypsum, limestone and dolomite outcrop over approximately 1.25 million km^2 of Canada. As the rocks described by Ford are soluble, carbonate precipitates may be associated with sediments found in these areas. The areas shown include the present study area, the studies undertaken by Boone and Lutenegger (1997) in eastern Ontario, the studies in the Canadian Rockies near Golden, British Columbia, by Smith and Wass (1994a,b), and the BC Ministry of Highways studies in the Columbia Lakes and South Thompson Regions (Haughton, 1978; Nyland and Miller, 1977). We follow studies of weakly calcareous soils in Western Canada, from east to west of the Rockies and from tills to postglacial deposits.

Studies of the characteristics and physical properties of glacial tills across Alberta (Pawluk and Bayrock, 1969) as well as more specific studies of the glacial deposits in the Banff area (Rutter, 1972) have discussed the amount, distribution and sources of calcium carbonate and calcium oxide. Pawluk and Bayrock (1969) reported calcium oxide ranging from 0.2 to 45 % noting that areas with greater than 10% calcium oxide were found adjacent to the Rocky Mountain Foothills and in the northeast of the province, down-ice from limestone and dolomite outcrops. A comparison of calcium oxide data with results obtained for calcium carbonate equivalent suggested a close correlation and demonstrated that a major portion of the calcium oxide occurred in the tills as dolomite and limestone materials.

Tills in the Bow River Valley have up to 50 % carbonates, Rutter (1972) noted an increase in carbonate content down the Bow River valley. This trend is a reflection of the bedrock, as carbonate rocks are more abundant in the southeastern than in the northwestern part of the area (Rutter, 1972). Lacustrine sediments in the area, partially derived from the calcareous tills, were described as calcareous as well but no values of calcium carbonate content were reported.

In Alberta, the distribution of marl and tufa deposits were reported by Macdonald (1982) as resources for the agricultural treatment of acidic soils. Marl was defined as greater than 50 percent Calcium Carbonate Equivalence (C.C.E), while tufa was defined as greater than 80 percent C.C.E. Both marl and tufa are precipitated from calcium carbonate-rich groundwater discharge, often in springs originating from limestone bedrock (Borneuf, 1982). Extensive deposits of marl and tufa in Alberta were identified by Macdonald (1982).

The British Columbia Ministry of Highways studied geological hazards associated with weakly cemented sediments in the Columbia Lakes and South Thompson and Penticton Regions of British Columbia (Haughton, 1978; Nyland and Miller, 1976). More recently, Geertsema and Schwab (1997, 1995a,b) highlighted the occurrence of calcium carbonate as a cementing agent in the glaciomarine sediments of the west coast of British Columbia near Kitimat and Terrace.

Calcium carbonate has been identified as a cementing agent in the silts of the South Thompson Region of British Columbia. Hardy (1950) attributed subsidence in the Kamloops silts to the collapse of the internal soil structure after the dissolution of calcium carbonate bonds in the silt. Quigley's (1976) study of the lacustrine silt deposits of the Columbia Lake area (Haughton, 1978) and the South Thompson and Penticton area (Nyland and Miller, 1977) identified 7 to 8 % calcium carbonate. Quigley (1976, p. 16) stated: " Small amounts of soluble precipitates or evaporites were found. These are significant in that evaporites occurring at the points of contact between silt grains can have a marked effect on the decrease in stability of the silt structure upon wetting."

Smith and Wass (1994a,b) reported the impacts of skid roads and stump uprooting on the properties of calcareous loamy soils at Golden, British Columbia, approximately 350 kilometres southeast of the Morkill River. Although the studies were primarily concerned with the effects of soil disturbance on planted seedling performance, tests of the carbonate content, soil type and insitu densities were provided. A sandy silt with some clay and 2 to 8 % carbonates had bulk densities from 1.07 Mg/m^3 within the top 0 to 10 cm to 1.81 Mg/m^3 at a depth of 60-70 cm.

Studies of the retrogressive flow slides in sensitive glaciomarine sediments in the Kitimat-Terrace region (Geertsema and Schwab, 1997, 1995a,b) described silts that consisted of glacially-ground quartz, feldspar, illite and chlorite. These mineralogies were similar to those in the sensitive glaciomarine sediments found in eastern Canada and Scandinavia (Geertsema and Schwab, 1997). A detailed study of landslide deposits in the Kitimat-Terrace area looked at the ages of the landslides by carbon dating and the effects of leaching on the calcium carbonate content. Calcium carbonate was found in deep soil deposits but in surficial deposits of relict landslides; low pH values were indicative of the neutralization of calcium carbonate, originally up to 5% by volume, by acids produced from decaying organic matter over time. The porewater in the study areas exhibited very low concentrations of Na^+, Ca^{2+}, K^+ and Mg^{2+}, further indications that the majority of leaching had already occurred (Geertsema and Schwab, 1997).

Our review of the available geotechnical and geological literature did not identify the presence of calcium carbonate as a cementing agent in the soils in the Morkill River valley. Campbell et al. (1973) highlighted the presence of carbonate bedrock but did not discuss the role of cementation in the soils. Perhaps, cementation has not been identified because it does not appear in current geotechnical classifications (Canadian Foundation Engineering Manual, 1992). The first Unified Soil Classification (Casagrande, 1948) classified coarse-grained soils as GC-SC if the dry strength of the soils was provided by colloidal clay or by the cementation of calcareous material or iron oxides. Subsequent versions of the Unified Soil Classification deleted reference to the identification and description of cementation.

PHYSICAL ENVIRONMENT

The Morkill River is a tributary to the Fraser River at the settlement of Crescent Spur, 50 kilometres northwest of the town of McBride, British Columbia. This area, in the Park Ranges of the Rocky Mountains, (Figures 1 and 2) is characterized by folded and faulted sedimentary and metamorphic rocks underlying sub-parallel ridges and valleys which predominantly trend northwest wards (Holland, 1964).

The Morkill River basin was enveloped by the Cordilleran Ice sheet during the Pleistocene (Clague, 1989). The most significant glaciation, the Late Wisconsinan glaciation known as the Fraser Glaciation, occurred between 29,000 to 14,000 years before present (Ryder et al, 1991). Extensive lacustrine sediments deposited by the decay of this glaciation cover the Morkill River Valley.

Mapping of the lacustrine soils in the Morkill River valley (Froese, 1998) concluded that six lakes, A to F, were impounded in the Morkill River Valley by complex stagnation and downwasting of valley glaciers during the Holocene (Figure 3). We hypothesize that the glaciers and their deposits formed natural dams in the Morkill River and tributary valleys, trapping large volumes of sediment. The sediments in these lakes were eroded from the local bedrock in the Morkill and tributary valleys with the calcite derived from the rocks of the Lower Miette Group or from calcite-rich till.

Climatic inputs are hypothesized to have a significant impact on the soils in the Morkill River valley as they are exposed to the extreme fluctuations typical of mountain environments in the Canadian Rocky Mountains. Correlations of temperature data from the area (Environment Canada, 1981) with elevation changes and tree line studies yielded highest and lowest average temperatures of 5°C and –20°C respectively (Froese, 1998). As detailed precipitation measurements were not available in the Morkill River valley, nearby weather station readings were combined with useful generalizations provided in Figure 4.11 of Barry (1981) to estimate precipitation in the upper elevations of the Morkill River valley. Based on these correlations, suggested annual precipitations from 600 to 800 millimetres at lower and upper elevations respectively.

Based on these estimated climatic conditions, weathering scales can estimate the dominant mode of weathering in the Morkill River valley. Using systems to classify the likely form and relative degree of weathering (Peltier 1950), the Morkill River valley is considered to be susceptible to moderate chemical weathering with weak frost action. The upper elevations are considered to be susceptible to weak chemical and moderate mechanical weathering. Based on the Weinert N Scale (Goodman, 1993), the climatic conditions indicate that the dominant mode of weathering in the valley would be leaching and decomposition.

LANDSLIDE TYPES AND PROCESSES IN THE MORKILL RIVER VALLEY

The field mapping program in the Morkill River valley investigated 21 landslides. We first outline the types and processes of landslides in the Morkill silts and then consider the sands. The locations of the landslides are shown in Figure 2. Landslide terminology follows Cruden and Varnes (1996).

Silts in Lakes A,B,D,E

The field investigation included 10 landslides and 71 road cut exposures in the silt sediments of Lakes A, B, D, and E. These soils consist of varves of silt, fine sand and clayey silt. The lateral and vertical distribution of the sediments is presented in Figure 3. Landslides are initiated by earth slides of the upper 0.3 to 0.5 metres of rootmat and soil, followed by continuing retrogression of the rupture surface. The subsequent landslides are composite slides and flows of the silty soils

Visual observations and slope measurements in the field mapping program (Froese, 1998) show natural slope angles adjacent to landslides and in road cut exposures in Lakes A, B, D, E range from 31 to 60°. In the landslides investigated, the slopes of the surface of rupture in the silty soils ranged from 35 to 60°. The variation in rupture surface orientation depended on the grain size, initial calcium carbonate content, duration of exposure and corresponding degree of weathering.

The earth slides in the lacustrine sediments of the Morkill River valley have rupture surfaces ranging from 1 to 4 metres in depth and 12 to 150 metres width. Thin layers of displaced material from retrogressive landslides now cover rupture surfaces. The earth slides in the Morkill River valley silts result from the gradual breakdown of the cohesion of the soil. The breakdown of the soil structure by mechanical processes in the zone of frost penetration, the active layer, combined with the dissolution and leaching of calcite cement reduces the cohesion. The upper layer of soil may be at limiting equilibrium, held together by the rootmat at the surface. Once the rootmat is disturbed, the upper soil and vegetation layer can be expected to slide where slope angles exceed 30 °. Examples of earth slides in the silts are shown in Figures 4 through 10. Figures 5 and 6 show examples of large, natural gullies fed with sediment by slides.

Once the soils are exposed, the loss of the insulating vegetative mat allows deeper frost penetration and disturbance, thus accelerating their erosion. Frost heave has a significant effect on the highly frost-susceptible silty soils (Froese, 1998). The exposed soils are also susceptible to flow during the spring once the shear strength has been reduced sufficiently. Earth flows are described in the following section.

The mechanics of earth flows in the Morkill River valley may follow Cruden and Varnes' (1996, p. 66) description: "Seasonal thaw layers, or active layers, up to a metre or so in thickness may contain water originally drawn to the freezing front where it formed segregated ice. Melting of this ice may generate artesian porewater pressures that greatly reduce the resistance of the active layer to movement."

The field investigation found layering developed parallel to the slope in the profiles in Lakes A, B, D, and E. This layering was indicative of expansion and contraction of the soil matrix due to ice lens formation and frost heave (Figure 11). The melting of these ice lenses leads to excess pore pressures and a decrease in shear strength.

In the Morkill River valley, these earth flows may be initiated after vegetative cover is removed by shallow earth slides. The slide is normally followed by increased erosion due to saturation of soil under the snow pack in spring. Higgins and Modeer (1996) describe similar slope processes from the loess deposits in Eastern Washington, USA. The similarities can be accounted for by the open soil structure created in the

Morkill Silts by frost action and by the subsequent removal of calcite cementation. This open structure is also characteristic of the metastable loess deposits. Figure 12 shows the grain size ranges for the Morkill River silts and for eastern Washington loess are similar.

Evidence of successive flow events was noted in the Morkill River valley. The landslide in Figure 8 appears to have initiated as an earth slide followed by earth flows in subsequent years. The flow deposit shown in Figure 9 has a lateral extent of 40 metres from the toe of the slope with an average thickness of 0.3 m. Evidence of soil on small trees in the area (Figure 10) indicated that when the soil flowed, it reached levels up to 0.3 metres above the present levels without destroying the vegetation. This indicates a moderate to slow flow rate.

Lobate features, evidence of seasonal flow due to frost creep, indicate seasonal flow of the surficial soils (Figure 6). Figure 7 shows the metre or less effective depth of seasonal flow.

Flows from the landslides shown in Figure 6 and two adjacent landslides have been channeled into a gully and directed onto a flat plain adjacent to the Morkill Forest Service Road (FSR) at Kilometre 13. The accumulated soil mass extends 700 metres, is approximately 200 metres wide and over 1.2 metres in depth. Test pits into the displaced mass found evidence of organic debris (leaves) separating layers of soil 0.2 to 0.3 metres thick indicating that the material has been deposited by several events in different years.

Sands in Lake C

We examined 11 landslides and 28 soil exposures in the sands of Lake C. Landslides in the sandy soils of Lake C consist of shallow, translational earth slides. Natural slope angles adjacent to the slides ranged from 35° to 44° with rupture surfaces in the landslides ranging from 37° to 70°. The rupture surface at 70°, in a landslide (Figure 13) that had occurred in late spring 1997, had not then been exposed to frost or chemical weathering.

The contribution of thaw weakening and frost heave is expected to differ from sands to silts. As the freezing front progresses in the sandy soils, there is a downward expulsion of water forward of the freezing front, thus there is no ice lens formation. In silts, varves would be expected to retard the downward flow and water either freezes at these layers and expands, or is diverted along the lower permeability layers. Both processes enhance the loss of shear strength.

The most likely contributor to instability in the sandy soils is the dissolution and leaching of calcite. The higher permeability sand facilitates water flow and allows it to wash calcite out of the soil matrix more readily. Figures 13 and 14 show typical earth slides in the sandy soil of Lake C. The rupture surfaces in landslides in these sediments typically ranged in depth from 1.0 to 1.5 metres. The landslide in Figure 13 was assisted by the removal of toe material during road construction and subsequent excavation during seasonal ditch cleaning.

PERFORMANCE OF SLOPES

We also visited 102 road cut exposures in the sandy and silty sediments of Morkill River valley. Histograms showing the distribution of slope angles in these sediments are shown in Figures 15 and 16. We have divided each bar in the histogram into 2 sections: slopes that were performing acceptably, showing minimal erosion or instability, and slopes that were not performing acceptably. It is apparent that cuts with slope angles greater than 30 ° in the silty and sandy lake sediments have a higher probability of eroding than those with angles less than 30°. Thirty degrees may be a threshold slope angle above which unacceptable performance may occur.

For cohesionless sandy soils, drained friction angles of 30° to 39° are typical (Lambe and Whitman, 1969, Table 11.2) and therefore the soils are considered to be active in a normal fashion. There is expected to be some variation in this slope angle threshold based on initial calcium carbonate content, duration of exposure and degree of weathering. The longer the period of time for which the soils are exposed to surface water and frost action, the deeper the degradation of the soil by weathering and the lower the slope angle threshold.

In the silty soils, 44 of the slopes were found to be standing above the threshold slope angle of 30°, of which 38 of these were performing acceptably. Some slopes performed acceptably at angles over 30° because significant amounts of calcite remained in the soil structure to hold the slope above its friction angle. The grain size distributions of the undisturbed silts are such that leaching is much slower than in sands, until frost action and ice lens formation has broken down the soil structure. The extra time taken for the calcite cement to be removed from the structure may account for the short to midterm performance of slopes noted during the field program.

There were 6 road cut exposures of clay in Lake F, located between km 47 and 50 of the Morkill Forest Road. Slope instability consisted of the gradual softening and erosion of the exposed soil due to frost action. Field observations in a road cut at the eastern edge of Cutting Permit (CP) 602 indicated distinct layering forming parallel to the slope surface due to frost heaving. The soils at the surface are blocky and disaggregated due to the frost action. The blocks indicate reticular ice formation during freezing; water migrates to the edges of soil peds and forms ice, thus separating the soil peds upon expansion of the ice.

SOIL PROPERTIES

Our landslide and slope inventories demonstrated that slopes in the Morkill River valley were relatively steep, indicating the possibility of cementation. Natural slopes up to 65 degrees were noted in silty soils. The limestone in the area led to the assumption that the most likely form of cement in the valley was calcite derived from carbonate bedrock in the area.

Field observations suggest an increase in in-situ density with a corresponding increase in carbonate content in the road cut exposures and landslides. In order to quantify this relation, we undertook in situ testing of selected field sites to quantify the relative change in density with depth of the lacustrine sediments and also the corresponding change in carbonate content (Figure 17). The field estimation of carbonate content used a relative scale that was calibrated in the laboratory using samples taken from the density testing program. The soils in the Morkill River valley were classified as weakly to moderately calcareous based on the criteria outlined in Agriculture Canada (1974). The insitu density tests yielded densities in the undisturbed silty sediments of up to 2.05 Mg/m^3 with corresponding minimum void ratios of 0.36.

We hypothesized that the performance of slopes in the Morkill River valley is a function of freezing and leaching weathering processes acting on the weakly cemented soils. The relative input of each process differs with the grain size of the sediments.

Carbonate Analyses

We investigated the effects of leaching during the field and laboratory investigations by addressing the correlation of carbonate content and in-situ bulk densities in the field. In order to quantify the carbonate contents in the samples taken when obtaining the field profiles, we used a modified vacuum distillation/titration procedure (Froese, 1998) to determine the carbonate content of the lacustrine soils in the Morkill River valley. Carbonate contents of 5.2 to 11.1 % were obtained from unweathered samples.

Figure 18 shows the carbonate vs. density plots for selected sites in the Morkill River Valley. As can be seen from the plots there is a positive correlation for the sites in the silt size sediments and a slightly steeper trend in the sandier material. The clays did not appear to exhibit any relation between calcium carbonate and density. As there is much scatter in the data, the lines show general trends, not precise relationships. We hypothesize that the steeper gradient of the trend for the sands represents abrupt drops in carbonate content due to enhanced leaching in the higher permeability materials whereas the lower permeability of the finer grained soils does not favour removal of calcite by leaching.

A scanning electron microscope (SEM) was used to observe the structure of the lacustrine sediments and the location of the carbonates in relation to the soil matrix. The SEM photos did not show any carbonate grains. Electron diffraction analyses of soil grains indicated trace amounts of calcite in the soil matrix. These observations, with the results of the carbonate content determination and the low void ratios, support our view that the carbonates are located in the soil matrix as cement. Calcite present as cement increases the density and strength of the sediment while decreasing the porosity.

Frost Susceptibility

The effects of mechanical weathering by frost action were also addressed in the laboratory program. Frost susceptibility of the lacustrine sediments was assessed using both the index properties of the soils and laboratory strength testing. The US Army Corps of Engineers (1965) classification criteria, coupled with Davila et al's (1993) correlations for segregation potential indicate the soils tested have a moderate to very high susceptibility to frost action and a low susceptibility to frost heave.

The laboratory testing for the effects of frost action on the soils consisted of unconfined compression tests conducted on samples from CP 601 and CP 602 (Froese, 1998) that had been subjected to 0, 1, 2, 5 and 10 cycles of one-dimensional freeze and thaw (Figure 19). Samples exhibited a 50% decrease in strength after one cycle of freeze and thaw. Visual observations of the samples tested showed that the structure of the sandier sample, CP601, appeared well bonded after 10 cycles of freeze and thaw, while the structure of CP 602, a sample with 43 % clay size fraction, exhibited stratified ice formation and segregation after 10 cycles of freeze and thaw.

To address the effects of exposure on the silty soils, we utilized the results of the freeze thaw tests which indicated that values of cohesion of 60 kPa and 35 kPa were available in the silty and silty clay soils, respectively, after one cycle of freeze and thaw (Figure 19). In order to evaluate the effects of freeze and thaw on the stability of slopes in the fine-grained sediments of the Morkill River valley, an infinite slope analysis was undertaken. The analysis followed Duncan (1996, p.351) and assumed a layer with thickness of 1 metre with a friction angle of 30°. Due to the enhanced permeability after a cycle of freeze thaw, pore pressures are assumed to be dissipated and the fully drained condition was modeled.

The infinite slope analysis demonstrates that values of cohesion of less than 10 kPa are required to maintain a slope of 60° at a factor of safety of 1.0 under short-term conditions. As this value is less than the values of cohesion available after one cycle of freeze and thaw, it is considered that the slopes in the silty and silty clay soils require several cycles of freeze and thaw and prolonged exposure to weathering to soften the soil and lower the cohesion to that at limiting equilibrium.

CONCLUSIONS

The mechanism for instability in the stiff Morkill River lake sediments is the process of softening as a result of mechanical and chemical weathering processes. The processes of frost action and leaching have differing effects on the soils depending on their grain size.

In the sandy soils of lake C, dissolution and leaching of calcite is expected to be the dominant weathering mechanism because of the relatively high permeability of the soil. As seen in the carbonate vs. density plot in Figure 18 and in the density profiles, Figure 17, there is a relatively steep relation between the amount of carbonate present and the density measured in the field in the sandy sediments. This is further substantiated by the observations of landslides in the field. The largest landslides associated with road construction in the Morkill River valley were associated with the sandy lake sediments. Landslides in these soils are predominantly classed as shallow earth slides. These slides are typically 1 to 1.5 metres thick with widths ranging from 20 to 75 metres.

In the silty soils of Lakes A,B,D,E, we consider that frost action is the initial dominating weathering process followed by dissolution and leaching. Once the calcite bonds have been broken due to the nine percent volume expansion upon freezing, the calcite is more readily leached out of the soil structure. The loss of strength noted in the laboratory freeze/thaw testing (Figure 19) coupled with the profiles taken in the field indicate that there is significant effect of frost action followed by slower removal of the calcite, when compared to the sandier soils. Landslides in these soils consisted predominantly of shallow composite earth slide-earth flow events. It is postulated that slides, incorporating the rootmat and upper 0.3 metres of soil initiate the landslides followed by erosion of the exposed slope face in the spring. Prolonged exposure is required to lower the values of cohesion in the soils to a point at which limiting equilibrium is achieved.

In the clayey soils of Lake F, landslides were not noted in the limited number of exposures investigated. The soil profile for clay shown in Figure 17 indicated a very gradual increase in density and carbonate with depth and the relatively flat carbonate vs. density plot (Figure 18). In these soils, the clay minerals are considered to be the dominant cementing agent and the low permeability of the material does not favour percolation of groundwater and leaching of carbonates. These soils are susceptible to gradual breakdown of the soil structure due to frost action (Figure 19).

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REFERENCES

Agriculture Canada, 1974. The System of Soil Classification for Canada. Canadian Department of Agriculture, Publication 1455. 255 p.

Barry, R.G. 1981. Mountain weather and climate. Methuen, Inc. New York.

Boone, S.J., and Lutenegger, A.J. 1997. Carbonates and cementation of glacially derived cohesive soils in New York State and southern Ontario. Canadian Geotechnical Journal, **34**:534-550.

Borneuf, D. 1982. Springs of Alberta. Alberta Research Council. Earth Sciences Report 82-3. 95 p.

Campbell, R.B., Mountjoy, E.W., and Young, F.G. 1973. Geology of McBride Map-Area, British Columbia. Geological Survey of Canada Paper 72-35.

Canadian Foundation Engineering Manual, 1992. Canadian Geotechnical Society, BiTech Publishers, Richmond, B.C.

Casagrande, A. 1948. Classification and identification of soils. Transactions of the American Society of Civil Engineers. 113:901-991.

Clague, J.J. 1989. The Cordilleran Ice Sheet; in R.J. Fulton, editor, Quaternary Geology of Canada and Greenland, Geological Survey of Canada. pp. 15-96.

Cruden, D.M., and Varnes, D.J. 1996. Landslide Types and Processes. Transportation Research Board Special Report 247, pp. 36-75

Davila, R.S., Sego, D.C., and Robertson, P.K. 1993. Surface area criteria applied to segregation potential . Proceedings, 46th Canadian Geotechnical Conference. pp. 333-342.

Duncan, J.M. 1996. Slope stability analysis. Transportation Research Board Special Report 247, pp. 337-371.

Environment Canada, 1981a. Canadian Climate Normals. Temperature and Precipitation, 1951-1980, British Columbia. Atmospheric Environment Services, Ottawa.

Ford, D.C. 1989. Solution processes: inR.J. Fulton, editor. Quaternary Geology of Canada and Greenland, Geological Survey of Canada, Geology of Canada, No. 1 pp. 617-618.

Froese, C.R. 1998. Landslides in the Morkill River Valley, British Columbia. M.Sc. Thesis. Department of Civil and Environmental Engineering, University of Alberta, 188 p.

Geertsema, M., and Schwab, J.W. 1997. Retrogressive flowslides in the Terrace-Kitimat area, British Columbia: from early post-deglaciation to present and implications for future studies. Proceedings 11th Vancouver Geotechnical Society Symposium, Forestry Geotechnique and Resource Engineering. Bitech Publishers, Vancouver. P. 115-133.

Geertsema, M. and Schwab, J.W. 1995a. The Mink Creek earthflow, Terrace, British Columbia. Proceedings 48th Canadian Geotechnical Conference. pp. 625-633.

Geertsema, M. and Schwab, J.W. 1995b. The Mink Creek earthflow. B.C. Ministry of Forests, Smithers, B.C. Extension Note No. 4. 5 pp.

Goodman, R.E. 1993. Engineering Geology: rock in engineering construction. John Wiley, New York. 412 p.

Hardy, R.M. 1950. Construction problems in silty soils. Engineering Journal, **33**: 775-779.

Haughton, D.R. 1978. Geological hazards and geology of the South Columbia River valley, British Columbia. Ministry of Highways and Public Works, Geotechnical and Materials Branch, Victoria, B.C. 64 p.

Higgins,J.D., and Modeer, V.A. 1996. Loess. Transportation Research Board, Special Report 247, pp. 585-606.

Holland, S.S. 1964. Landforms of British Columbia, a Physiographic outline; British Columbia Department of Mines and Petroleum Resources, Bulletin 48, 138 p.

Lambe, T.W. and Whitman, R.V. 1969. Soil Mechanics, Wiley, New York. 553 pp.

Macdonald, D.E. 1982. Marl resources of Alberta. Alberta Research Council. Earth Sciences Report 82-1, 94 p.

Nyland, D., and Miller, G.E. 1977. Geologic hazards and urban development of silt deposits in the Penticton area. British Columbia Ministry of Highways and Public Works, Geotechnical and Materials Branch. 34 p.

Pawluk, S., and Bayrock, L.A. 1969 Some characteristics and physical properties of Alberta Tills. Research Council of Alberta, Bulletin 26. 72 p.

Peltier, L.C. 1950. The geographic cycle in periglacial regions as it is related to climatic geomorphology. Annals of the Association of American Geographers. **40**: 214-236.

Quigley, R.M. 1976. Mineralogy, chemistry and structure, Penticton and South Thompson silt deposits. Faculty of Engineering Science, University of Western Ontario Report. 17 p.

Rutter, N.W. 1972. Geomorphology and multiple glaciation in the area of Banff, Alberta. Geological Survey of Canada, Bulletin 206. 54 p.

Ryder, J.M., Fulton, R.J., and Clague, J.J. 1991. The Cordilleran ice sheet and the glacial geomorphology of Southern and Central British Columbia. Geographie physique et Quaternaire, **45**: 365-377.

Smith, R.B., and Wass, E.F. 1994a. Impacts of a stump uprooting operation on properties of a calcareous loamy soil and on planted seedling performance. Pacific Forestry Centre: Information Report BC-X-344. Pacific Forestry Centre, Victoria, 19 pp.

Smith, R.B., and Wass, E.F. 1994b. Impacts of skidroads on properties of a calcareous loamy soil and on planted seedling performance. Pacific Forestry Centre: Information Report BC-X-346. Pacific Forestry Centre, Victoria, 26 pp.

U.S. Army, Corps of Engineers (1965). Soils and Geology-Pavement Design for Frost Conditions. Department of the Army, Technical Manual TM5-818-2.

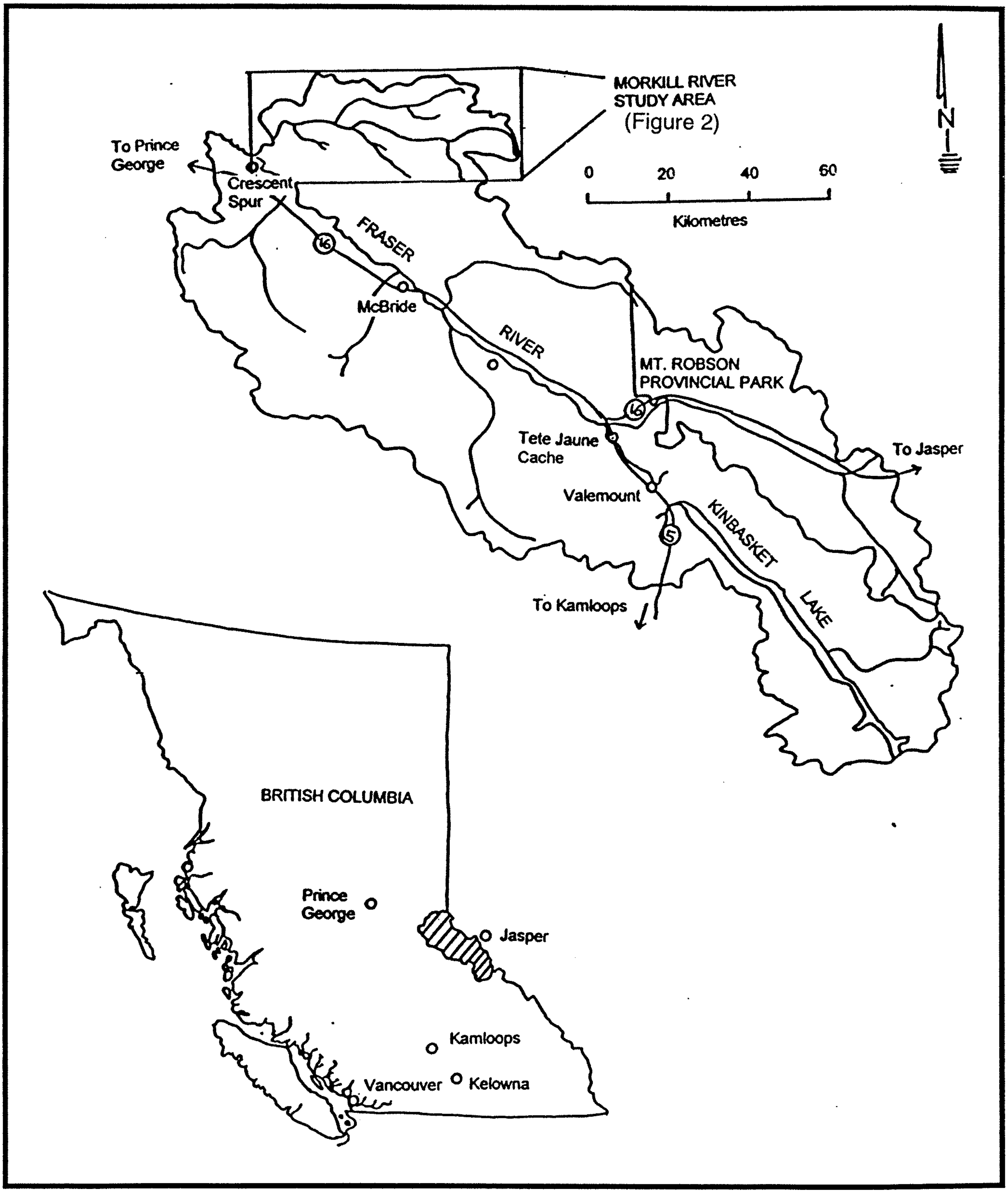

Figure 1 Location plan for the Morkill River study area

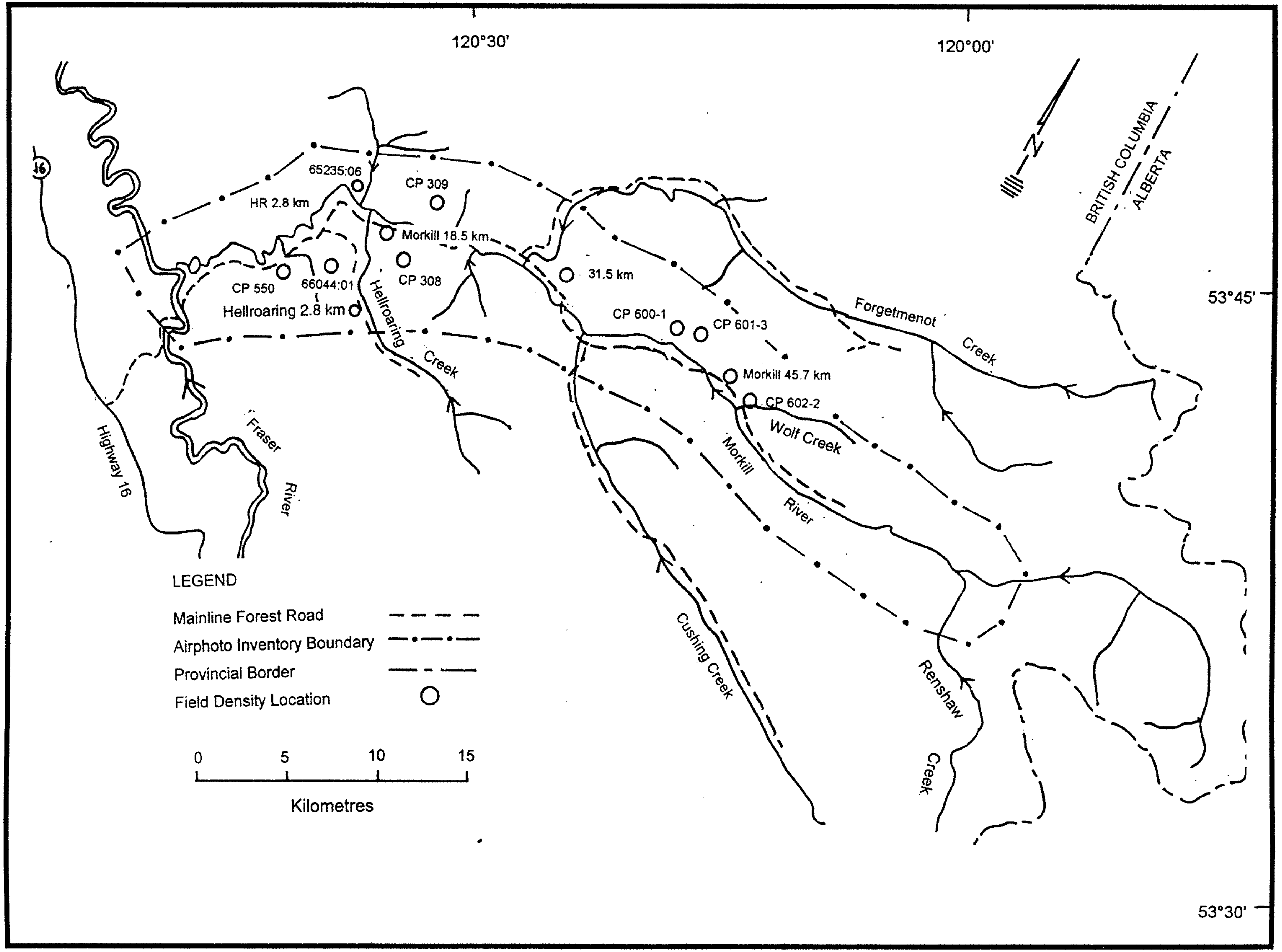

Figure 2 Locations of field density tests and landslide observations in the Morkill River valley

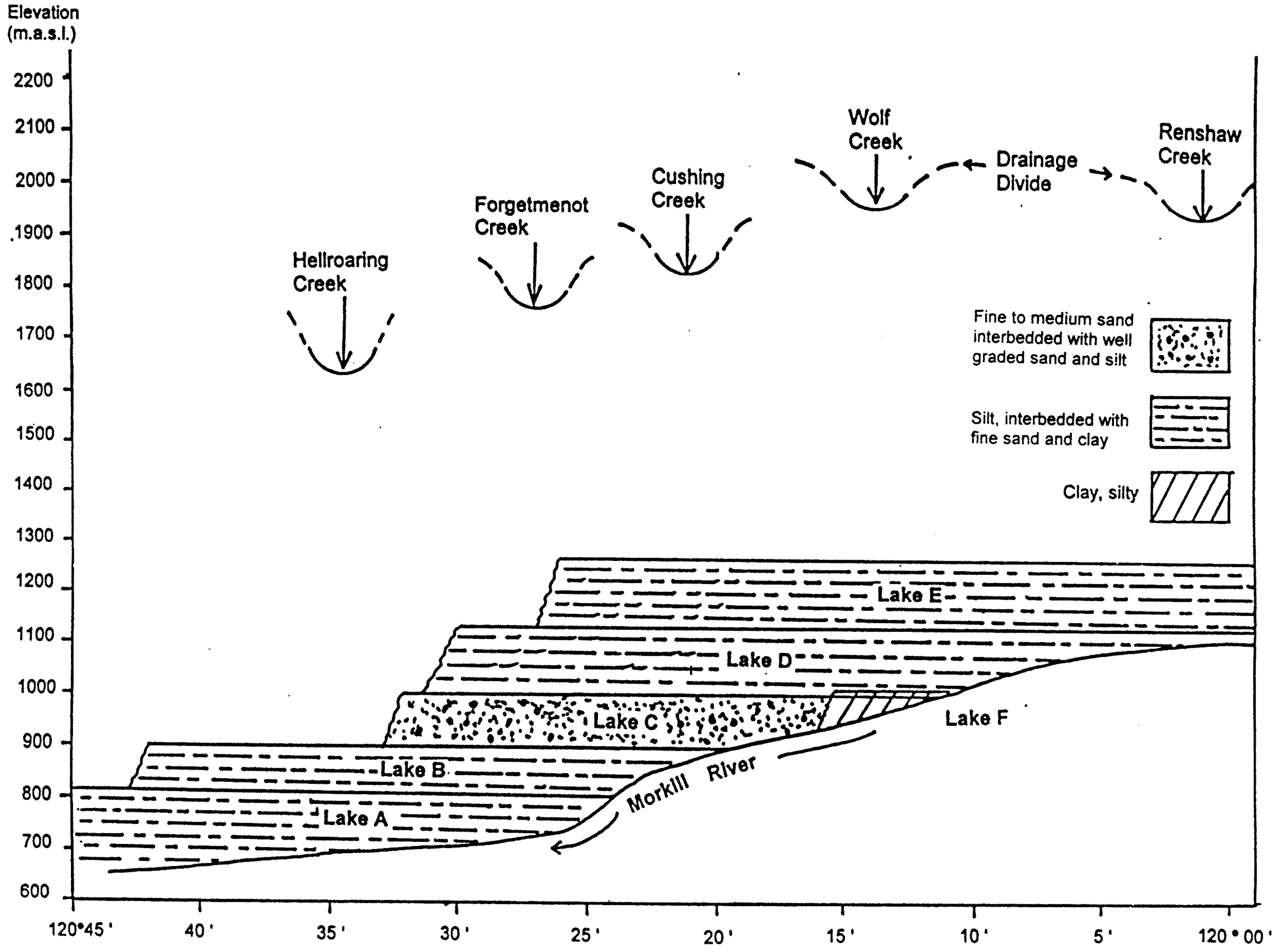

Figure 3 Levels of lake sediments in the Morkill River valley. Locations of creeks shown on Figure 2.

Figure 4 Earth slide in silty soils on the Hellroaring Road at 2.8 km (Figure 2)

Figure 5 Earth slide incorporated into large gully (65235:06, Figure 2)

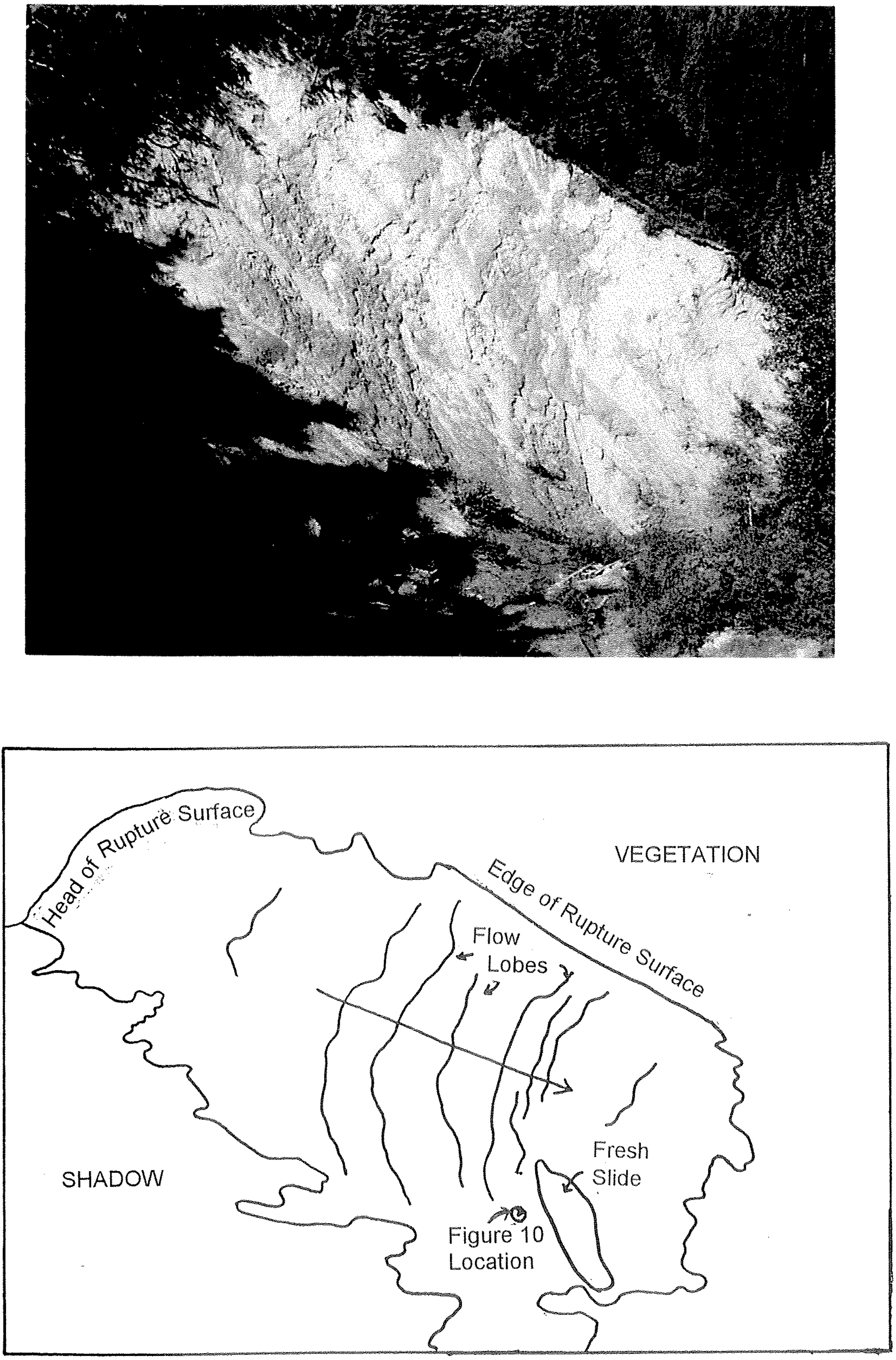

Figure 6 Slide 66044:01 (Figure 2) Photo and overlay showing lobate flow features in large gully incorporating a large composite earth slide-earth flow

Figure 7 (Above) Slide 66044:01 (Figure 2) Approximate depth of rupture surface for slide shown in Figure 6. (One metre long shovel for scale)

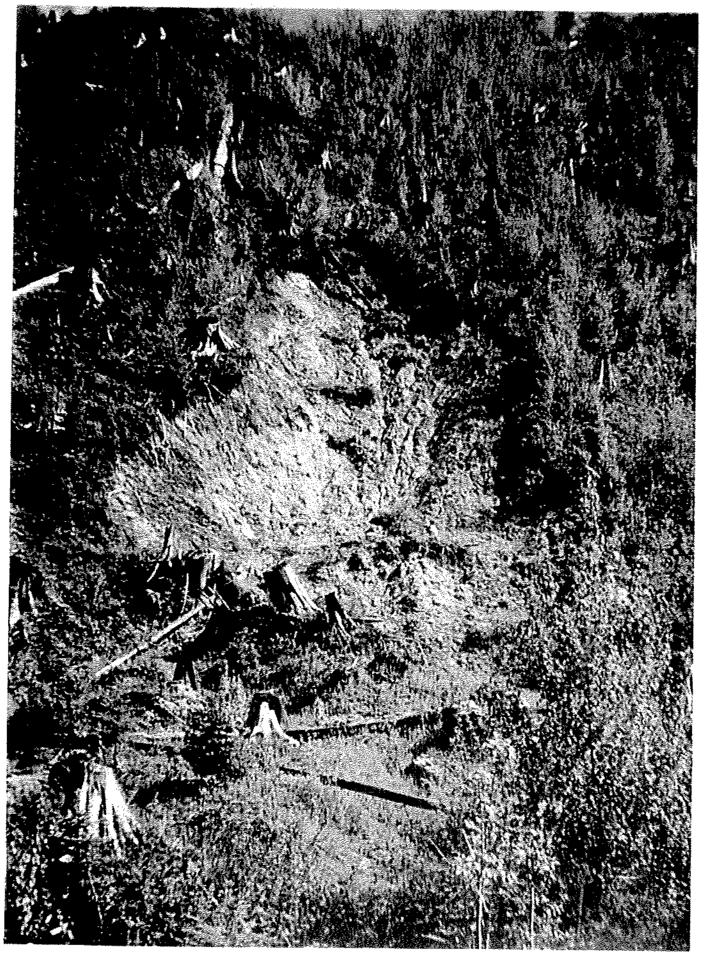

Figure 8 (Left) Slide 66044:03 (Figure 2) Composite earth slide-earth flow in harvested cut block

Figure 9 Slide 66044:03 (Figure 2) View from head of rupture surface showing path of initial accumulated mass (A) and subsequent earth flow (B). Person in lower left corner for scale.

Figure 10 Slide 66044:03 (Figure 2) Soil on young spruce trees is indicative of recent earth flow activity

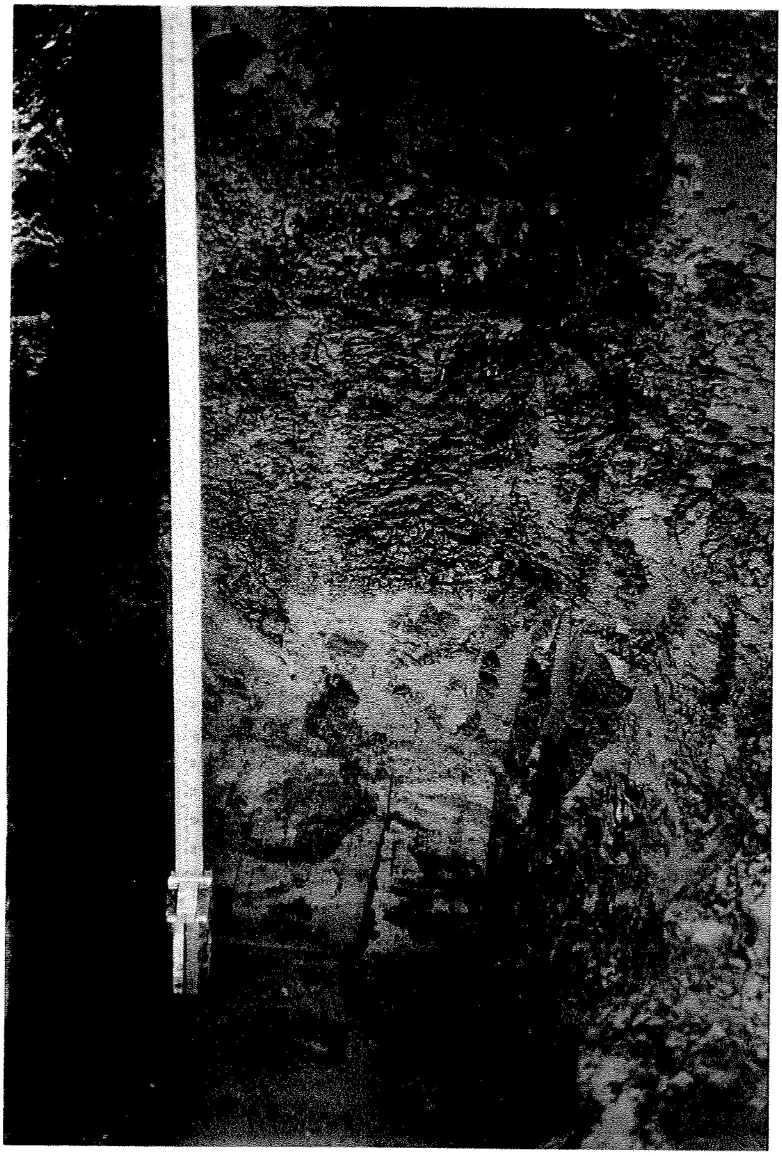

Figure 11 Profile at CP 308 (Figure 2) showing evidence of disaggregation of soil due to ice lens formation in upper 0.5 metres

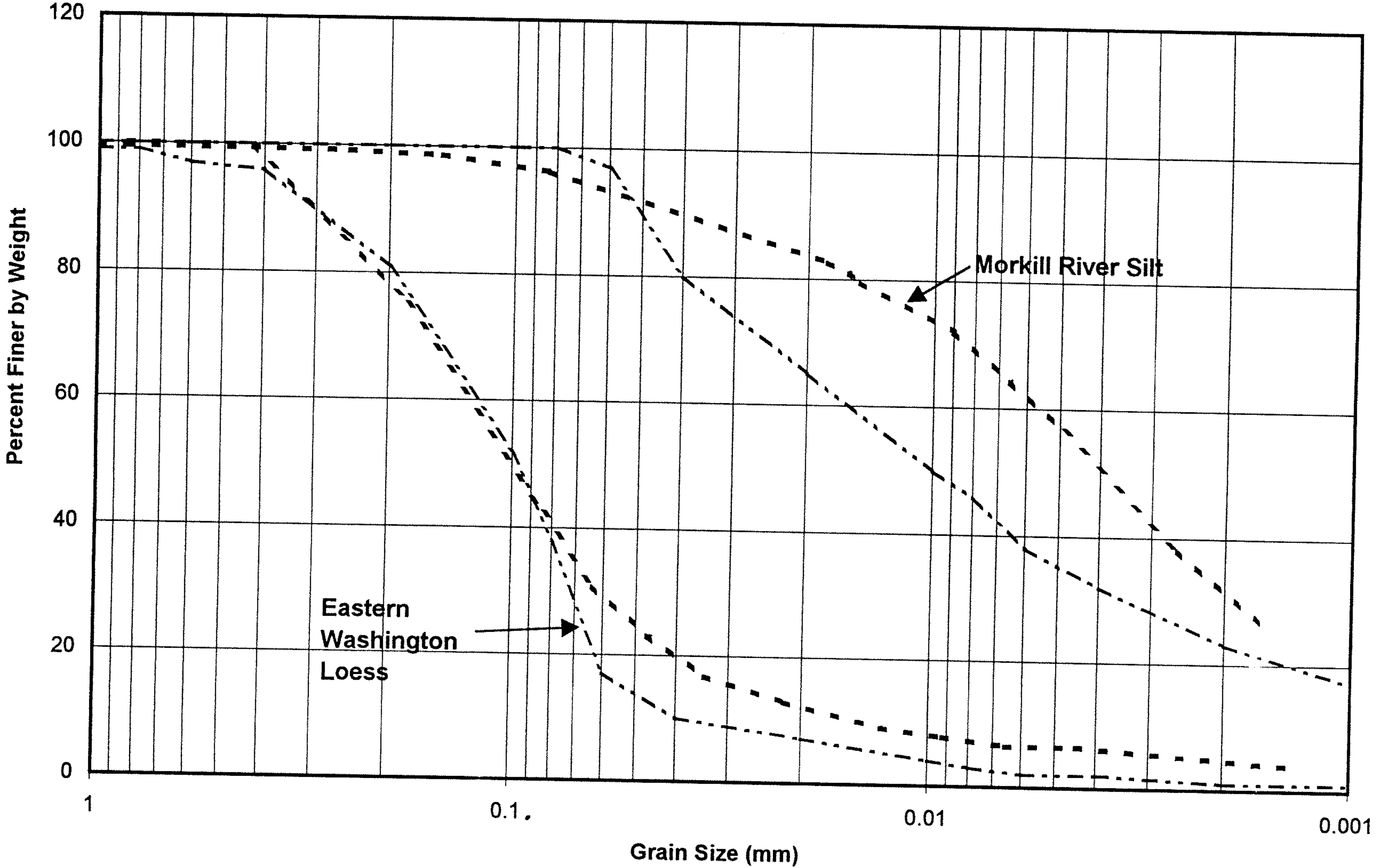

Figure 12 Comparison of grain size ranges for Morkill River Silt and Eastern Washington Loess (after Higgins and Modeer, 1996)

Figure 13 Morkill 45.7 km (Figure 2): Earth slide in sandy soils adjacent to road

Figure 14 Morkill 31.5 km (Figure 2): Earth slide in sandy soil below an abandoned cutting permit access road

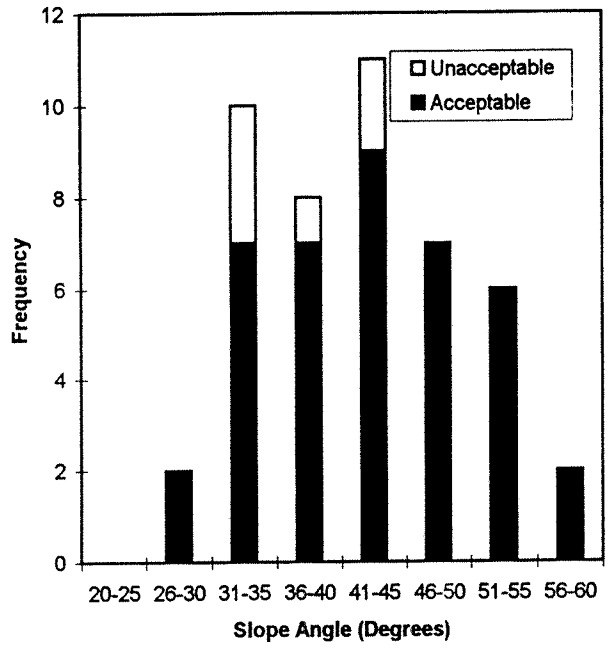

Figure 15 Slope angle frequencies in silty soils

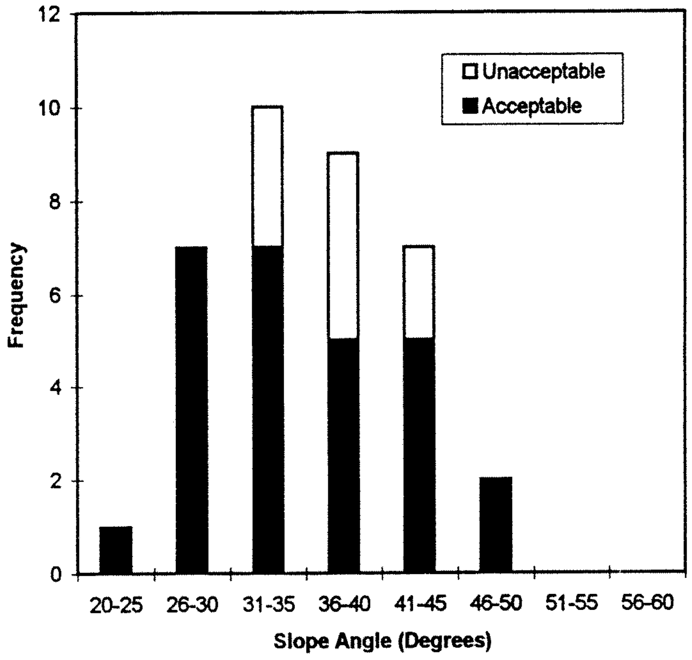

Figure 16 Slope angle frequencies in sandy soils

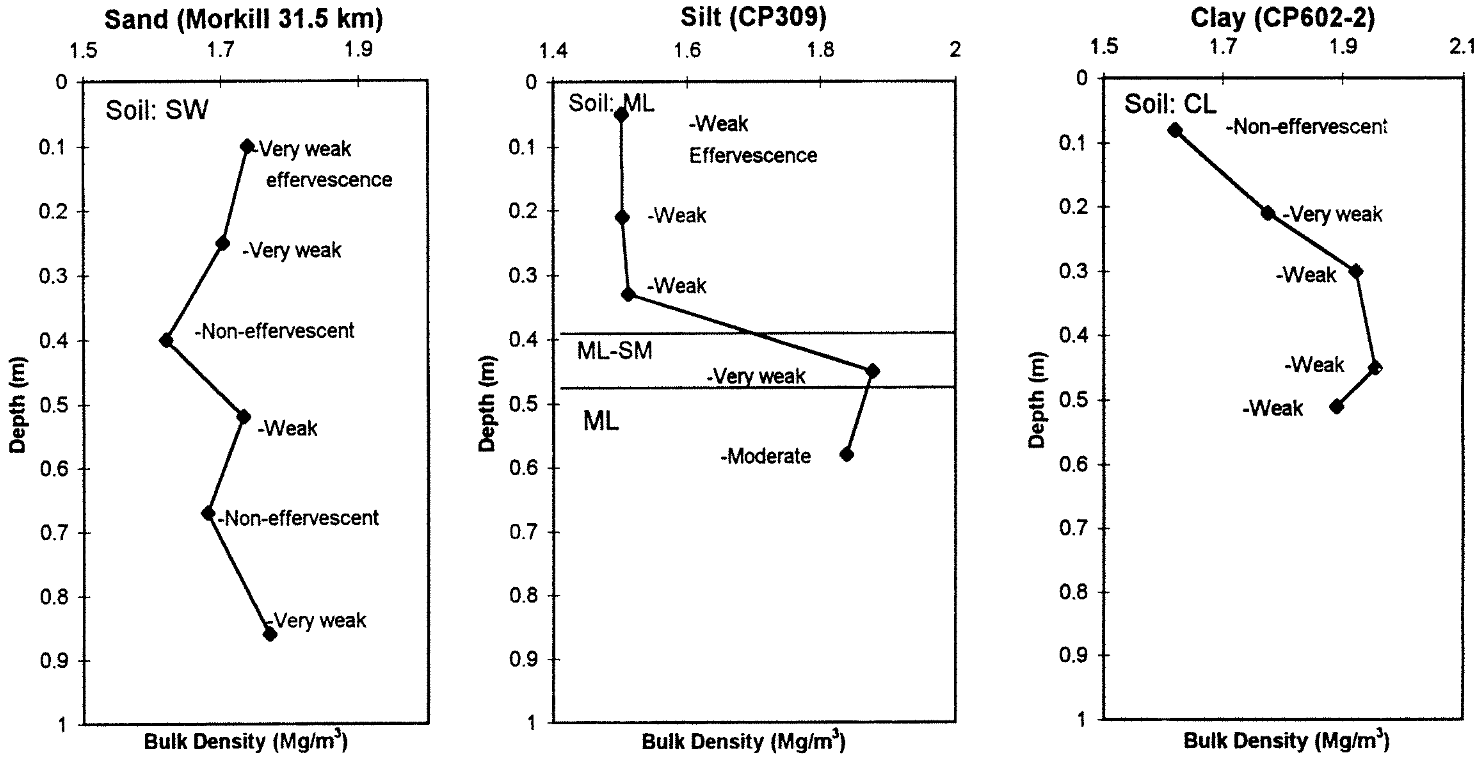

Figure 17 : Typical density profiles for sites in the Morkill River valley in a) sand, b) silt and c) clay. Sample locations show Figure 2.

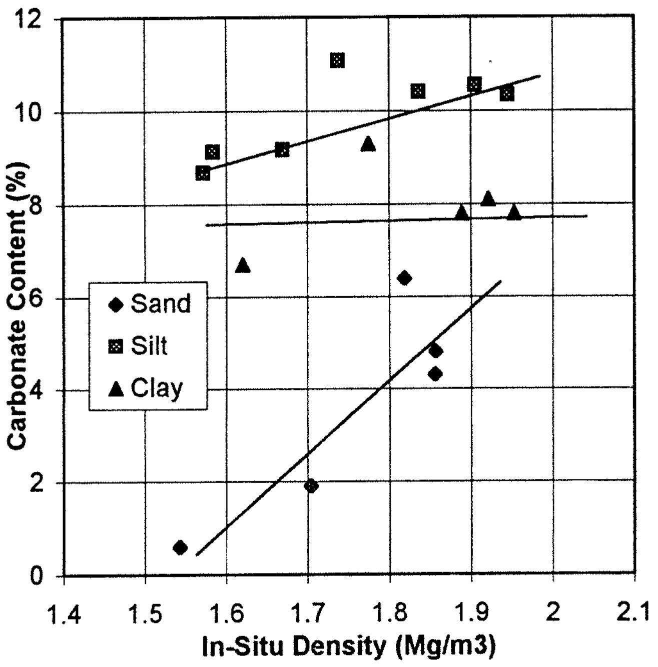

Figure 18. Relationships between calcium carbonate content and density for typical profiles in the Morkill River valley.

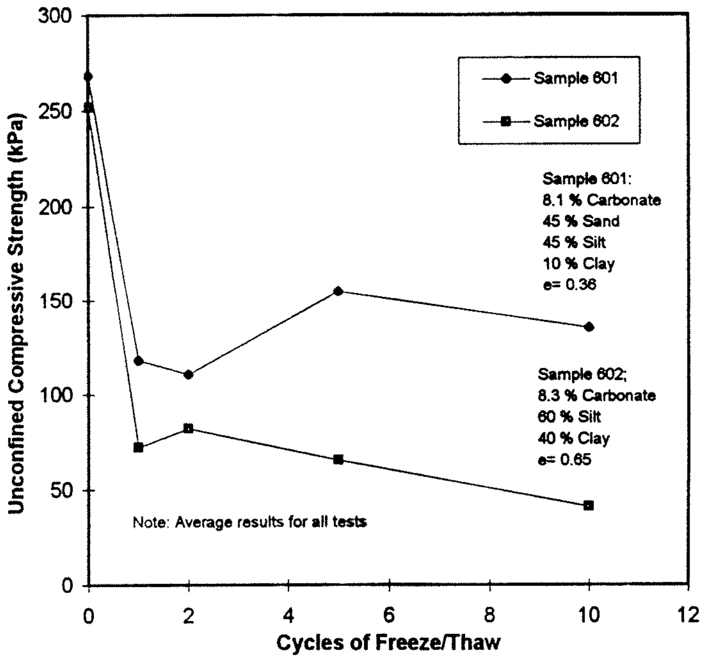

Figure 19. Strength change in Unconfined Compression Test samples subjected to cycles of freeze and thaw.