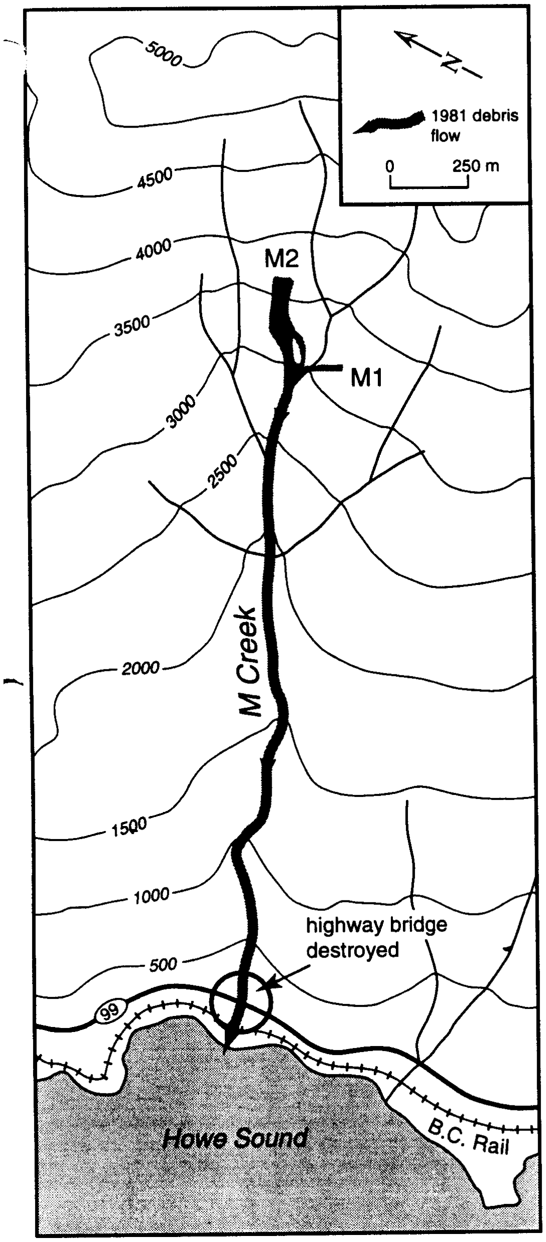

Figure 36. *Map of M Creek debris flow which occurred on October 28, 1981, 2.5 km north of Lions Bay, east side of Howe Sound; M1 and M2 are probable source landslides for the debris flow (modified after Bovis and Dagg, 1992).*

Figure 37. *Alberta Creek debris flow, Lions Bay, which occurred on February 11, 1983. Note damaged buildings and bridges (photo courtesy of British Columbia Ministry of Highways and Communications).*

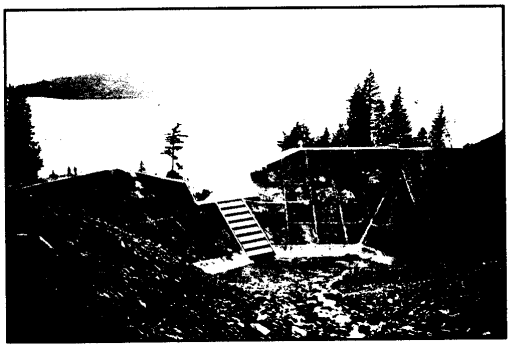

Figure 38. *Debris flow retention structure on Charles Creek, Howe Sound constructed in the mid-1980s; view downstream. GSC 1991-298*

deflection berm for a retention capacity of 60 000 m^3 (Hungr et al., 1987); deflection berms were also constructed to protect the Agassiz Mountain Correctional Institution from debris flows (Martin et al., 1984) creating a total containment capacity of 12 000 m^3. In addition channellization works and deflection berms have been constructed in several locations along the Coquihalla Highway (Slaymaker et al., 1987) for a total cost of $1.1 million.

LANDSLIDES IN PLEISTOCENE SEDIMENTS

Numerous landslides have taken place in the Pleistocene sediments of the Vancouver region in the historical period, particularly in the Lower Mainland (Eisbacher and Clague, 1981; Evans and Clague, in press). They are most common along the escarpments composed of unconsolidated Wisconsinan sediments that define the edge of terraced

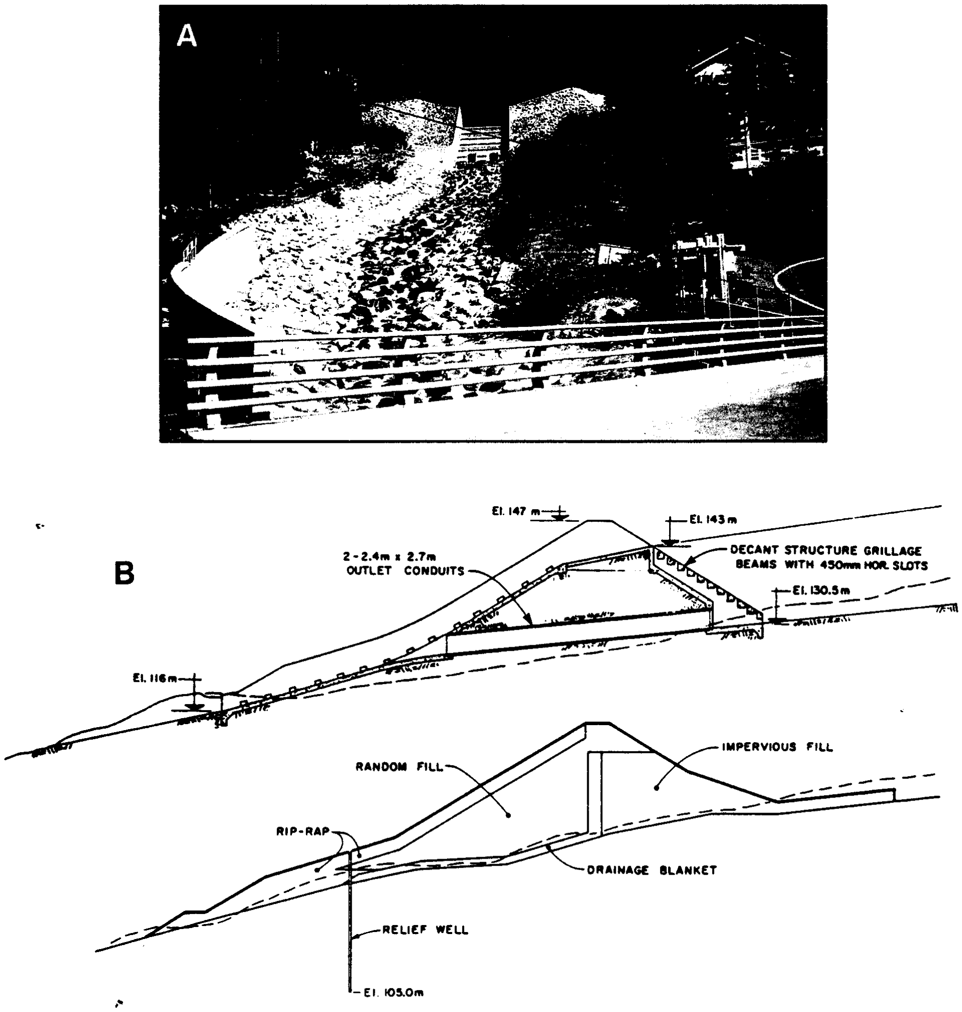

Figure 39. Debris flow retention dam at Harvey Creek, Lions Bay, Howe Sound. ***A)*** *View upstream; GSC 1994-709K* ***B)*** *Structural cross-section (after Hungr and Skermer, (1992) from a sketch drawing by Ker Priestman Associates).*

uplands in the Greater Vancouver area (see Fig. 2 in Eisbacher and Clague, 1981). Materials involved in these events consist of glacial, glaciofluvial, glaciomarine, and glaciolacustrine sediments (Armstrong, 1984) that exhibit considerable geological, hydrogeological, and geotechnical complexity (Eisbacher and Clague, 1981; Evans, 1982; Hungr and Smith, 1985). Problems related to landslides in Pleistocene sediments are not restricted to the Lower Mainland. Recently, Gerath (1993a, b) has pointed out the hazards posed by landslides and related processes on the Redroofs Escarpment on the Sunshine Coast (Fig. 1).

Rapid earthflow in sensitive glaciomarine sediments

Glaciomarine sediments are widespread in the Lower Mainland (Armstrong, 1984) but only one large landslide has occurred in these deposits in historical times. On January 30, 1880, a major landslide (estimated volume 10^6 m^3) occurred at Haney (Fig. 1) in glaciomarine sediments on the eroding north bank of the Fraser River (Fig. 42; Evans, 1982). Eyewitnesses reported that they heard the cracking of the ground and watched as a "great .. moving mass of earth and trees...slid

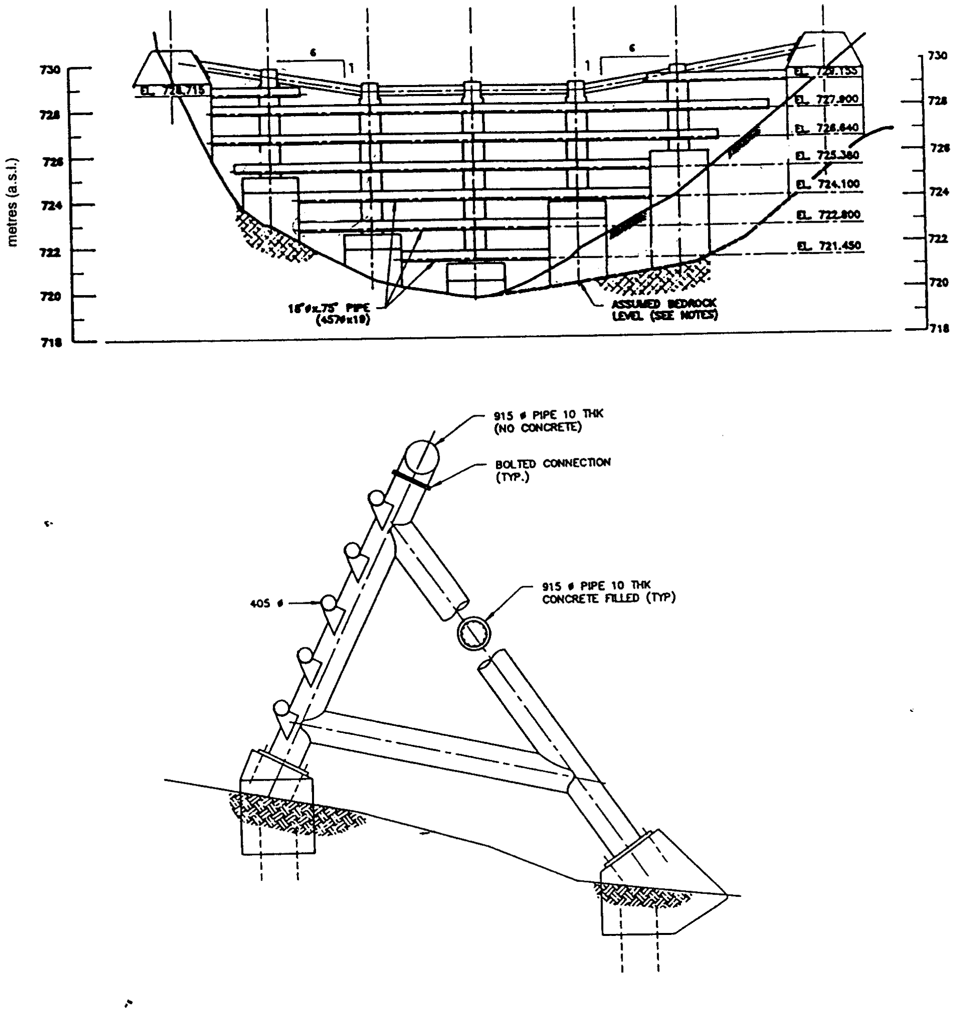

Figure 40. *Conceptual design of debris retention barrier for Whistler Creek (from Hungr, 1993, courtesy Ker Priestman Associates).*

into the Fraser River" (Victoria Daily Colonist, February 5, 1880). The slide partially blocked the Fraser River and resulted in the death of one person (killed by the 12 m high displacement wave caused by the slide). Substantial damage to docking facilities occurred along the Fraser River (Evans and Clague, unpublished data). Excess pore pressures within sandy interbeds in the sensitive glaciomarine silts and clays and erosion at the toe of the slope by the Fraser River are probable causes of the slide (Evans, 1982).

Debris avalanches and debris flows

The occurrence of debris flows and debris avalanches along escarpments in Pleistocene sediments in the Greater Vancouver area have been described by Eisbacher and Clague (1981), Woods (1984), and Hungr and Smith (1985). They are triggered by heavy autumn and winter rains. The steep ravines and gully walls along the escarpments, which range up to 125 m in height, produce channellized debris flows by two initial mechanisms (a) the failure of a relatively thin (1-2 m) cover of colluvium on slopes steeper than 30° or (b) the slumping of material at the head of a gully. Both these initial failures are transformed into debris flows which run out on areas below the escarpments. The possibility of initial failure may be increased by the placement of loose fill at the heads of the gullies or steep ravines (Hungr and Smith, 1985) which has the effect of loading the slope or impeding drainage.

Figure 41. Debris deflection barrier (or berm) constructed to protect Trans-Canada Highway and Canadian National Railway rail track, 5 km southwest of Laidlaw in the Fraser Valley. GSC 1994-492E

Open slope debris flows or debris avalanches also occur (Eisbacher and Clague, 1981).

A typical example of this style of landslide is the Port Moody debris flow of December 1979 (Eisbacher and Clague, 1981; Woods, 1984) (Fig. 43). Triggered by torrential rains, a slide involving 4000 m^3 of dumped fill at the crest of a ravine, entered a steep sided gully and surcharged loose material in the floor of the gully. Under undrained loading the debris began moving on a slope of 15°, entrained other materials from the gully bottom, and travelled a distance of 600 m over an average slope of 9°. The debris flow demolished one house and inundated other houses and apartments with debris (Fig. 43). Evidence noted by Armstrong, (1984) suggests that the escarpment had been subject to large debris flows in the prehistoric past.

Figure 42. Airphoto of site of 1880 Haney landslide (from BC 7056-116).

Catastrophic seepage erosion

Catastrophic seepage erosion (Hutchinson, 1982), which is also known as caving erosion (Hungr and Smith, 1985), results in what are locally referred to as "washouts"; it occurs both on natural slopes on the escarpments, and in the excavated faces of gravel pits (Allan, 1957; Armstrong, 1984). The process has considerable destructive potential and, according to Armstrong (1984), is the dominant mass movement phenomena occurring in the Fraser Lowland.

Seepage erosion (Fig. 44) occurs in steep slopes where thick, pervious sand, sandy silt, or gravel beds are confined between overlying impervious Late Wisconsin till and/or glaciolacustrine stony clay (Hungr and Smith, 1985) and underlying impervious or less pervious materials. Seepage erosion in the pervious layer undercuts the overlying material resulting in its collapse. Under sustained or increased seepage this type of erosion may increase progressively by the rapid retrogression of a seepage front thus creating significant gullies in a matter of hours. The failed material, which is easily liquified, flows rapidly from the seepage front to the toe of the escarpment where it accumulates in a fan. Seepage erosion may therefore result in inundation of areas downstream in the depositional fan area and also endanger areas upstream by the rapid retrogression of the seepage front.

On natural slopes, the famous UBC Campus washout of 1935 in the Point Grey seacliff, resulted from seepage erosion (Armstrong, 1984). At the cliffs, which are up to 70 m high, a thin veneer of till overlies Quadra Sand and, at the time of the washout, cliff slopes were being steepened by marine erosion. According to Armstrong (1984), the lowest 15 m of Quadra Sand in the section contains impervious clayey silt and organic sediment and much seepage occurs at the upper boundary of this zone. In January 1935, following two days of torrential rain after a week of heavy snowfall, seepage erosion removed about 100 000 m^3 of Quadra Sand, creating an instant canyon about 100 m long in less than two days. During the period of erosion, which drew a crowd of spectators, the steep walls of the canyon repeatedly collapsed sending surges of sand and water down to the sea (Eisbacher and Clague, 1981).

Figure 43. Seepage erosion in glaciofluvial sand at gravel pit in Coquitlam River valley. Note field book for scale (courtesy of O. Hungr, Thurber Engineering).

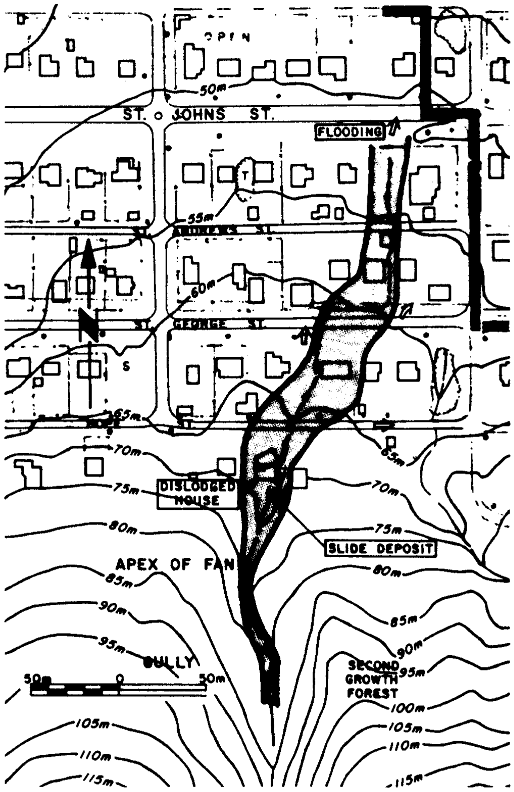

Figure 44. Map of run-out of 1979 Port Moody debris flow (after Woods, 1984).

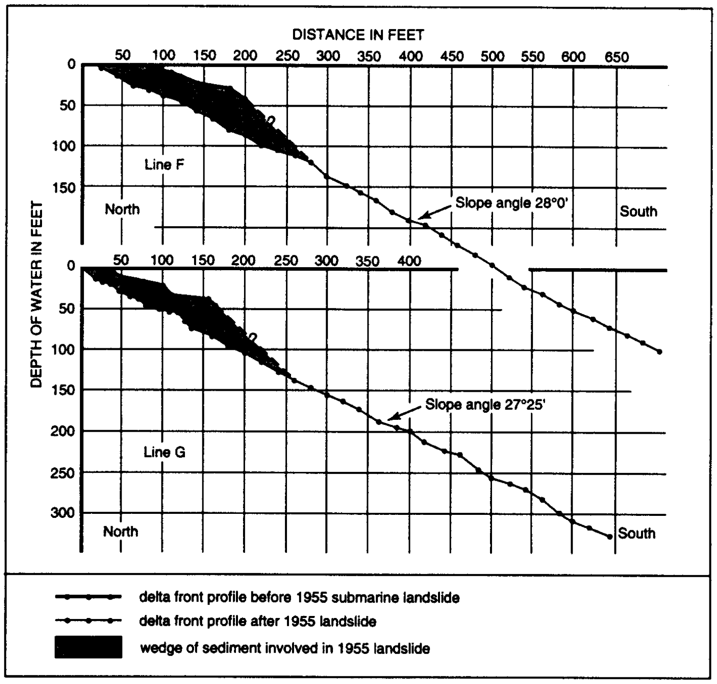

Figure 45. Vertical sections through Woodfibre delta front before and after 1955 slide (modified after Terzaghi, 1956).

Another major catastrophic seepage erosion event in a natural slope is described by Allan (1957) and Armstrong (1984) in the Coquitlam River valley. It occurred in 1952 and was initiated by seepage at the base of a 100 m section of pervious sands and silts at its contact with impervious, partly compacted glaciofluvial gravel. Within 24 hours, approximately 300 000 m^3 of material was washed out into the Coquitlam River blocking it for several days and an amphitheatre-shaped gully complex up to 300 m long had formed in the valley side.

Catastrophic seepage erosion is particularly common in the faces of gravel pits in the Vancouver region (Armstrong, 1984). According to Hungr and Smith (1985) seepage erosion in Coquitlam River gravel pits may take place at a rate of 50 $m{\bullet}a^{-1}$. In 1953 in a pit at Mary Hill, for example, sand and gravel was being mined from beneath an impervious cap of till. A mechanical shovel cut through a silty bed of gravel and tapped a groundwater reservoir which led to excessive seepage. Within 15 hours, 70 000 m^3 of material had flowed from the face.

Landslides in glaciolacustrine deposits

Glaciolacustrine sediments were deposited in the mountain valleys of the Vancouver region when glacier ice in the Fraser Lowland blocked their outlet (e.g., Saunders et al., 1987). The deposits are not widespread but consist of varved silts and clays and are prone to landslides. Extensive retrogressive landslides have occurred in these deposits, for example, on the north side of the Chilliwack River valley, westward from Tamihi Creek (Fig. 1; Armstrong, 1984).

SUBMARINE FAILURES (OUTSIDE FRASER DELTA)

Submarine failures are common in the Vancouver region particularly on delta fronts in both marine and lacustrine environments. The failures largely involve unstable wedges of sediment which form as a result of rapid subaqueous deposition. Instability on the Fraser Delta front is described in Luternauer et al. (1994).

Marine

Submarine failures have been documented in (Fig. 1) Howe Sound on several deltas. In 1955, at Woodfibre, failure of a delta slope at the mouth of Woodfibre Creek damaged warehouses and wharf facilities constructed on the delta. The cost of the damage was in the range of $500 000 to $750 000 (Bornhold, 1983) and the pulp mill was forced to shut down region is within Keefer's (1984) limit for the occurrence of disrupted slides. The earthquake did not trigger the Hope slide which, as noted above was in a state of limiting equilibrium. With reference to the 1946 Vancouver Island earthquake, Rogers (1980) mentions a slump at Matsqui triggered by the earthquake at an epicentral distance of about 250 km. It is also noted that the earthquake triggered several major landslides on Vancouver Island itself (Mathews, 1979) including the 1946 Mount Colonel Foster rock avalanche (Evans, 1989b).

DISCUSSION AND CONCLUSIONS

Landslides in the Vancouver region have had a direct impact on mining camps, residential communities, transportation routes, energy generation and transmission facilities, industrial sites, and on the quality of the forestry and fishery resource base.

The highest impact of landslides in the Vancouver region, in terms of direct cost, cost of mitigation, and loss of life, is by high frequency low-magnitude events ($\leq$100 000 m^3). These events have an annual frequency of about 1:10 and consist of rainfall triggered debris flows and debris avalanches from steep mountain watersheds and escarpments in Pleistocene sediments, catastrophic seepage erosion events, and rockfalls and small rock avalanches.

Canada's second largest landslide disaster (1915 at Jane Camp, Britannia Mine; 56 deaths) and the country's largest known historical rock avalanche (1965 Hope slide) have occurred in the Vancouver region. The Hope slide occurred in two phases separated by 3 hours and occurred at the same location as a prehistoric landslide of similar magnitude. Several large rock avalanche debris accumulations in the region are seen to be the product of multiple events separated by as much as thousands of years.

Two major landslides with volumes in excess of 20 000 000 m^3 have blocked major transportation corridors in the Vancouver region since 1855, viz. the Rubble Creek and Hope events. This indicates an annual frequency of 1:100. Previous to 1855, published and unpublished field data indicate that the same transportation corridors have been blocked by landslides of similar magnitude about ten times since deglaciation, indicating a frequency of 1:1000, assuming no decay effect. Thus the historic frequency appears to an order of magnitude greater than the prehistoric frequency. No explanation of this discrepancy is offered at present.

Noncatastrophic mountain slope deformation has had important direct impact on civil engineering structures, and indirect impact because of uncertainty about their future behaviour.

The Garibaldi Volcanic Belt is highly susceptible to major landslides ($\geq$0.5 million cubic m). The Mount Garibaldi volcanic complex and Mount Cayley volcano (Hickson, 1994) have been the subject to frequent large-scale landslide activity in the Holocene which continues into the present century. At the debris accumulation fans formed by such activity, stra graphic evidence and radiocarbon dates suggest that they ha formed by multiple landslide events.

Pleistocene deposits in the region show a wide variety landslide types reflecting the stratigraphical, geotechnic and hydrogeological complexity of the materials. Landslid in these materials are generally triggered by heavy rains.

Submarine failures have occurred on steep delta slopes both marine and lacustrine environments in response to rap deposition in a high energy geomorphic environment.

It is noted that even in the absence of a significant histor cal earthquake, the frequency of landslides and the variety landslide styles in the Vancouver region is notable. Larg prehistoric earthquakes have undoubtedly triggered lan slides in the region. Any future large earthquakes affectin the region must be expected to trigger widespread slop movements.

As our knowledge of the distribution of landslides in bot space and time increases and our ability to quantify landslid mechanics improves, land use decisions based on this bett understanding are increasingly being made. This has th effect of increasing the amount of land sterilized (i.e. take out of productive use), due to exposure to perceived landslid hazard. In addition, as landslide hazards become bett known, retrofitting of existing facilities is increasingly bein undertaken, frequently at substantial cost. Both of thes responses to an increased knowledge of landslides in th Vancouver region contribute to their indirect cost.

Because of the increasing vulnerability of developed site associated with rapid economic development, it is conclude that all of the landslide types and processes discussed her will have increasing impact on facilities in the Vancouve region. Much research remains to be done on the nature o their occurrence and the mechanics of their behaviour.

ACKNOWLEDGMENT

We are grateful to Dr. Greg Brooks, Geological Survey o Canada, for a thorough review of the original manuscript.

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