

MOSQUITO CREEK EAST RAVINE LANDSLIDE RISK ANALYSIS PHASE II - DETAILED STUDY

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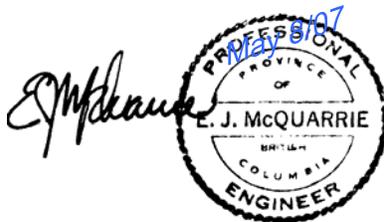


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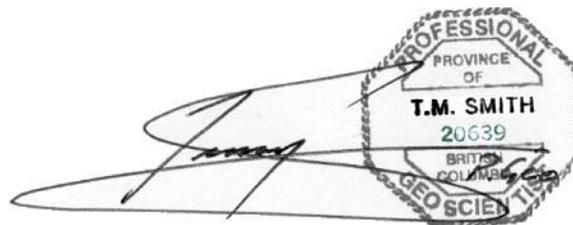
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May 8, 2007
Project #: 006-002

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EXECUTIVE SUMMARY

This landslide risk analysis addresses twenty-seven properties located along the crest of the east bank of the Mosquito Creek ravine between Larson Road and Highway 1. The study utilizes field reconnaissance of the slope, measured setbacks of the houses and other structures along the crest, and a detailed drilling investigation. The risk analysis is based on the field information and limit equilibrium slope stability analysis. While the risk analysis focuses on static conditions, the behaviour of the slope under seismic conditions was also evaluated.

The landslide probability is relatively high along the east bank of Mosquito Creek, as evident by the scars of several old failures, some of which have been documented over the past 20 to 30 years. The natural stability conditions have been adversely impacted by urbanization. Several timber-crib retaining walls were built a while ago to support back yards and are now deteriorating to the point where failures are imminent. Garden waste, excavated backfill and, in a few cases, household refuse has been dumped on to the slope, deteriorating the natural stability conditions. Historic flooding of Mosquito Creek caused past landslides, although recent channel improvements has curtailed such events.

The surficial geology on the east slope of the ravine consists of Capilano Sediments overlying very dense till. While the till on the lower slopes has been subject to erosional failures, most of the slope hazards are located within the Capilano Sediments on the upper slopes. These deposits include a fining downward sequence of sand, silt and clay. The unconfined groundwater aquifer within the Capilano Sediments plays a significant role in the slope stability.

The risks to specific structures depend on the probability of a landslide occurrence, the magnitude of the landslide, its probability of spatial interaction with the structure and the vulnerability of the structure. All of these variables were evaluated for each property along the crest of the east bank. The risk ratings throughout the study area range from low to extreme and even the risk ratings for adjacent structures vary according to the slope conditions, the setback from the slope crest and foundation conditions.

Recommendations for mitigating the risks are discussed and conceptual designs included. Some measures are easily implemented, such as rerouting of the roof and foundation drains or replacing small retaining walls. Other measures are more costly such as buttressing the slope, soil nailing, constructing high retaining walls, deepening the foundations, or relocating the structure.

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1.0 INTRODUCTION

Westrek Geotechnical Services Ltd. (Westrek) conducted a preliminary analysis of the landslide risks along the eastern slope in the Mosquito Creek ravine. This study considered the landslide hazards and both upslope and downslope potential impacts. The results of this preliminary study were summarized in the report titled “Mosquito Creek Ravine East Bank Assessment”, dated July 18, 2006.

Pursuant to this preliminary study, the City of North Vancouver (CNV) retained Westrek to conduct a more detailed assessment including a review of each property located along the crest of the slope. The objective of this detailed study was to evaluate the specific risk to each house and services located near the slope (i.e. the upslope elements at risk). The risk to downslope elements such as the trail and Mosquito Creek are summarized in the preliminary report.

2.0 THE STUDY AREA

The Mosquito Creek watershed is described in the preliminary report. The current study focuses on twenty-seven properties along the crest of the east bank between Larson Road and Highway 1. Most of the houses are located along the west side of Bewicke Avenue or Westview Drive, but houses at the west end of West 17th Street to West 23rd Street were also included. A summary of the houses included in the study are as follows:

710 West 17 th Street	1945 Westview Drive	2101 Westview Drive
711 West 18 th Street	1957 Westview Drive	2103 Westview Drive
1805 Bewicke Avenue	2009 Westview Drive	2117 Westview Drive
1815 Bewicke Avenue	2015 Westview Drive	2121 Westview Drive
1821 Bewicke Avenue	2017 Westview Drive	625 West 22 nd Street
1845 Bewicke Avenue	2041 Westview Drive	626 West 22 nd Street
626 West 19 th Street	2049 Westview Drive	622 West 22 nd Street
1931 Westview Drive	2059 Westview Drive	625 West 23 rd Street
1935 Westview Drive	2069 Westview Drive	632 West 23 rd Street

Other elements at risk, located near the crest of the slope, include a power pole behind 626 West 19th Avenue, a sanitary sewer main behind the houses at 1931 to 2015 Westview Drive (i.e. roughly between West 19th Street and West 20th Street), both a storm sewer and water main at the corner of Bewicke Avenue and West 19th Street, a storm sewer main in the laneway between West 23rd and West 22nd Streets and a sanitary sewer and water main on West 23rd Street.

3.0 INVESTIGATION

3.1 Background Research

Most of the background research was conducted as part of the preliminary assessment and included a review of numerous documents provided by CNV. These documents are listed in the preliminary report and the majority are also mentioned in the Background Summary provided in Appendix A.

3.2 Site Reconnaissance

The site reconnaissance included both the slope and each of the 27 properties along the crest. Prior to conducting the slope assessment, areas of heavy brush were cleared by the CNV to improve visibility. This clearing proved invaluable as it revealed critical items such as timber-crib retaining walls or soil exposures that were previously hidden.

The slope beneath each property was viewed and representative cross-sections measured from the trail up to the crest. Traverse notes included the following:

- Slope gradient and shape (i.e. down the vertical).
- Soil exposures or apparent composition.
- Groundwater discharge or concentrated surface runoff.
- Wet site indicators (i.e. hydrophitic vegetation).
- Signs of surface erosion or shallow slope movement.
- The presence of retaining walls.
- An estimate on the magnitude and runout from the observed slope instabilities.

Each of the 27 properties along the crest of the slope was also assessed in the field. The following parameters were considered:

- Distance from crest of slope to house, sundeck, sheds, etc.
- Distance from the crest to the services (where applicable and/or available).
- Signs of surface subsidence.
- Depth of the house foundation or sundeck footings and signs of settlement.
- Surface drainage conditions.
- Location of rock pits, sumps, footing drains and roof leaders.
- An estimate on the age and condition of the structure.

3.3 Subsurface Investigation

The preliminary assessment in 2005 included drilling three deep test holes, installing two piezometers, and monitoring the piezometers over the winter. To supplement this data, a total of 19 more test holes were drilled using solid stem augers combined with Dynamic Cone Penetration Tests (DCPTs). A few of the properties were accessible with a small track-mounted, auger drill rig but most of the holes were drilled using a portable auger drill provided by Mud Bay Drilling. These test holes were drilled at the following locations:

Test Hole 06-1	1845 Bewicke Avenue
Test Hole 06-2	Easement North of 1821 Bewicke Ave.
Test Hole 06-3	710 West 17 th Street
Test Hole 06-4	710 West 17 th Street
Test Hole 06-5	710 West 17 th Street

Test Hole 06-6	1815 Bewicke Avenue
Test Hole 06-7	1815 Bewicke Avenue
Test Hole 06-8	626 West 19 th Street
Test Hole 06-9	626 West 19 th Street
Test Hole 06-10	1931 Westview Drive
Test Hole 06-11	Between 1957 & 2009 Westview Drive
Test Hole 06-12	1957 Westview Drive
Test Hole 06-13	1945 Westview Drive
Test Hole 06-14	2041 Westview Drive
Test Hole 06-15	2049 Westview Drive
Test Hole 06-16	625 West 23 rd Street
Test Hole 06-17	625 West 23 rd Street
Test Hole 06-18	622 West 22 nd Street
Test Hole 06-19	2121 Westview Drive

The soil conditions were logged in the field by a senior technologist and selected samples were obtained. Laboratory tests consisted of soil classifications and moisture contents. The soil strength parameters were determined from the insitu DCPTs.

In addition to these test holes, another twelve Dynamic Cone Tests (DCTs) were performed using a "Wildcat Dynamic Cone Penetrometer". This portable penetrometer was able to drill sites that were inaccessible to even the portable auger rig. The DCTs used smaller diameter cones and rods and a smaller hammer. The penetration data uses a formula to correlate to Standard Penetration Tests (SPTs) and DCPTs. The Wildcat Dynamic Cone Penetrometer does not sample the soil; therefore, the lithology must be inferred from adjacent test holes and from the density information. These test holes are located as follows:

DC-1	711 Bewicke	4.5 m from top of bank and 3 m from NW corner of house.
DC-2	2009 Westview	Approximately 4 m downslope & 5 m south of property line.
DC-3	2015 Westview	Near top of timber wall; 1 m west of sewer line.
DC-4	2017 Westview	Approximately 5 m west of house & 1 m east of crest.
DC-5	632 W 23 rd	1 m east of crest & 1 m from southwest corner of patio.
DC-6	632 W 23 rd	Approximately 10 m downslope below DC-5.
DC-7	2101 Westview	At slope crest, between 2101 & 2103 Westview Drive.
DC-8	2103 Westview	At slope crest, northwest footing.
DC-9	2117 Westview	1.5 m east of crest & 2.5 m south of property line.
DC-10	2069 Westview	Approximately 0.5 m north of northwest corner.
DC-11	2059 Westview	Approximately 0.6 m north of southwest deck post.
DC-12	2059 Westview	Approximately 13 m downslope of DC-11.

The results of the drilling and insitu testing are summarized on the test hole logs and Wildcat Dynamic Cone Penetrometer logs included in Appendix C.

More advanced in-situ testing such as Cone Penetration Testing and piezo-cone penetration testing were considered but there was very limited access for truck-mounted equipment.

3.4 Data Analyses

The information collected during the field program was used to generate typical cross-sections through each of the twenty-seven properties along the crest of the east bank of Mosquito Creek. The cross-sections included the profile from the slope survey, the stratigraphy as determined from drilling and surface exposures, and the groundwater levels as determined from surface discharge and the piezometers installed during the preliminary field assessment. The location of houses, sundecks, sewer mains and other structures were noted on the cross-sections. Tension cracks or surface subsidence were also presented on the cross-sections as indicators of a probable failure plane.

4.0 GENERAL SOILS & GROUNDWATER CONDITIONS

Based on the drilling results and surface exposures along the valley walls, the soil conditions along the crest of the slope generally consist of a fining downwards sequence. Surficial sand and gravel overlies sand, then silty sand, silt and then clayey silt to silty clay.

These soil conditions are part of the Capilano Sediments, comprised of marine and glaciomarine deposits. The sediments were deposited between 10,500 and 13,000 years ago when the sea level was much higher. As the sea level gradually lowered (due to isostatic rebound associated with the glacial melting), the deposition environment gradually changed from sea bottom to beach or deltaic. The resulting geologic sequence consists of marine and glaciomarine clays and clayey silts overlain by beach and deltaic sands and gravels. The result is a fining downwards sequence in the soil profile.

These deposits have not been glacially overridden or subject to much more pressure than at present and are near-normally consolidated. Therefore, the granular deposits are generally loose near the ground surface, becoming compact at depth as the confining stress increases. The silt is firm to stiff while the silty clay is firm with low plasticity.

The Capilano Sediments overlie glacial till at depths ranging from 4 to 14 m below the crest of the slope. The high variability in the depth to the till deposit has a significant impact on the slope stability; thereby requiring numerous test holes throughout the study area to delineate this depth.

The groundwater forms an unconfined aquifer within the Capilano Sediments. The groundwater level fluctuates in response to rainfall and snowmelt. The surficial sand and gravel is relatively permeable; therefore, surface runoff tends to infiltrate

into the ground comparatively quickly. The result is a groundwater peak that likely occurs during January and early February near the end of the rainfall season. The groundwater level measurements ranged from 3.7 m depth to 6.0 m during the preliminary assessment.

5.0 STABILITY ANALYSES

Two-dimensional slope stability analyses were conducted using the cross-sections prepared for each property. The soil strength parameters were determined from correlations with the in-situ test results and from back-analyses of representative slopes where landslides have occurred. For each of the 27 properties, the slope stability analysis was used to determine:

- the factor of safety of a general slope failure;
- the factor of safety of a slope failure large enough or extending back far enough to directly impact on various elements at risk such as the house, sundeck, and services.

The factors of safety for landslides of various sizes were used in the risk analyses as described in Section 6 of this report.

The stability analyses focused on static or non-earthquake conditions; however, the BC Government *Geotechnical Slope Stability (Seismic) Regulation* requires that the slope stability assessment for new buildings also consider seismic conditions. Although the regulation applies only to new buildings, it was decided to include the same seismic analysis parameters in this study. The design earthquake for seismic slope hazard assessments has a return period of 10% in 50 years (or 1 in 475 years). The peak ground acceleration (PGA) for this design earthquake in the Mosquito Creek area of North Vancouver is 0.229g.

Pseudo-static stability analyses were used to evaluate the seismic stability of the slope at each property along the crest. Seismic analyses typically use a seismic coefficient equal to a percentage of the PGA rather than the full PGA. The reasoning is that the full acceleration of the mass is not realized before the vibration wave is reversed and the mass is accelerated in the opposite direction. Various authors recommend different values for the seismic coefficient along with variables for ground motion amplification and soil softening. For this study, 65% of the PGA, or 0.15g, was used in the pseudo-static stability analyses.

The pseudo-static method of analyzing slope stability under seismic conditions is popular because of its similarities to static stability analysis. This method is relatively easy to perform in conjunction with the static stability analysis; however, modeling complex dynamic inertial forces as pseudo-static inertial forces affects the accuracy of the results. More complex methods based on evaluation of permanent slope deformation are now being used and would be more applicable if the focus of this assessment was the seismic stability of the slope.

The results of the stability analyses show that the factor of safety for most of the east bank of Mosquito Creek is generally close to 1.0 and rarely exceeds 1.2. At

peak groundwater levels and soil moisture conditions, failures may occur below virtually any of the 27 properties, as confirmed by the presence of numerous landslide scars within the study area. With marginal stability conditions, any alteration of parameters that further decreases the factor of safety could trigger a landslide. Such alterations could include slope steepening by fill placement, an increase in soil moisture conditions, a concentration of water from roof drains onto the slope, or a loss of root support due to logging or windthrow (i.e. blow down of standing trees).

In all cases, the factor of safety is least for shallow surficial failures and increases for larger failures. A shallow, surficial failure would typically be 5 to 10 m wide, 1 to 3 m deep, and extend 1 to 3 m back from the crest. Past landslides within the study area all appear to have been within this magnitude range. While the historic landslides suggest larger failures are unlikely under static conditions, the pseudo-static slope stability analyses indicate that landslides extending back more than 5 m from the crest may occur during a major earthquake. When evaluating the risk to elements near the crest (i.e. houses or services), the proximity of these structures to the crest is a significant factor. Even when considering the factor of safety of the house or sundeck (i.e. a landslide with direct impact on the structure), the stability analyses conclude that many houses near the east bank have a factor of safety less than the normally acceptable minimum factor of safety of 1.5.

6.0 RISK ANALYSIS

6.1 Static Conditions

While the preliminary risk analyses considered elements at risk both upslope and downslope of the hazard, this detailed analysis focused on the upslope elements at risk. The objective of the current study is to estimate the *specific risk* to both the houses and known services or utilities such as the sewer main behind 1931 to 2015 Westview Drive.

Risk analysis is a multi-step process. The first step is to determine the probability of occurrence of a landslide at each specific property (P (H)). Objective criteria were used to determine qualitative hazard ratings based on the results from the stability analyses coupled with site observations. The meaning of these qualitative ratings is somewhat subjective and primarily intended to give a relative rating in order to prioritize future work. The criteria are described in Table 1: -

	<u>Rating</u>	<u>Criteria</u>
<u>Landslide Probability P (H) Under Static Conditions</u>	Low	Factor of Safety > 1.3 under static conditions. Typical slopes with this rating are: <ul style="list-style-type: none"> ▪ 32° or flatter; ▪ No signs of slope movement or past landslides on the slopes below the property. ▪ Slope stabilization or retaining wall (if present) has been engineered.
	Moderate	Factor of Safety between 1.1 and 1.3 under static conditions. Typical slopes with this rating are: <ul style="list-style-type: none"> ▪ 32 to 37° ▪ no retaining wall ▪ no random fill or yard waste ▪ coniferous forest ▪ no signs of slope movement or past landslides.
	High	Factor of Safety <1.1 under static conditions. Typical slopes with this rating are steeper than 37°, or less than 37° but with any of the following: <ul style="list-style-type: none"> ▪ non-engineered retaining wall ▪ random fill or yard waste on the slope or at the crest ▪ primarily deciduous forest ▪ signs of slope movement or past landslides ▪ considerable seepage present on the slopes.

Table 1: Definitions of the qualitative landslide probability ratings.

The next step in the risk analysis is to determine the conditional probabilities (i.e. the spatial and temporal effects). The *probability of spatial interaction* relates to the potential of a landslide to reach or otherwise affect the site occupied by an element at risk (P (S: H)). For example, if a landslide occurs on the slope, what is the probability that the event will extend back to the house or sewer main? The temporal probability relates to the potential of a mobile element, such as an occupant of a house or a moving vehicle, to be at the affected site at the time the landslide occurs (P (T: S)). For the purpose of this study, however, the temporal probability is equal to 1 because the elements at risk are stationary (i.e. the structures are always exposed to the landslide hazard). Given this, the *partial risk*, P (HA) is the product of the *probability of occurrence* of a specific landslide and the *probability of spatial interaction* and is mathematically expressed as:

$$P (HA) = P (H) \times P (S: H)$$

For this study, the partial risk was determined based on the factor of safety against a landslide large enough to directly impact on the structure or element at risk. The factor of safety was determined based on the slope stability analyses (see Section 5.0 of this report) and influenced primarily by the stability conditions of the slope (see Table 1) and the structure’s setback from the crest of the ravine. The probability of spatial interaction is inherent in the factor of safety of the structure, and the *partial risk* is estimated in a single step.

The partial risk is presented qualitatively using the ratings and criteria summarized in Table 2.

Partial Risk To Structure <u>P (HA)</u>	Rating	Criteria
	Very Low	Factor of Safety at structure >2.0.
	Low	Factor of Safety at structure 1.5 to 2.0.
	Moderate	Factor of Safety at structure 1.3 to 1.5.
	High	Factor of Safety at structure 1.1 to 1.3.
	Very High	Factor of Safety at structure <1.1.

Table 2: Definitions of the qualitative partial risk ratings.

Partial risk analysis does not consider the *vulnerability* of the element(s) at risk and, therefore, is not a complete estimate of risk. The *vulnerability* of the element at risk depends on its exposure and fragility. For example, a house with deepened footings, piers or piles could be less damaged by a landslide than a house bearing on shallow spread footings. The extent of the spatial interaction is also a factor, specifically whether the landslide would undermine a large portion of the foundation wall and cause considerable damage or simply affect the sundeck and undermine a corner of the house where the damage may be feasibly repaired.

The final rating is the *specific risk* (R (S)) to the houses and/or the buried services on the affected properties (i.e. the risk of damage to these elements from a potential landslide). The *specific risk* considers the *vulnerability* of these elements (V (L: T)) and is expressed as:

$$R (S) = P (HA) \times V (L: T)$$

Construction records provided by the CNV and field observations regarding the foundations were considered in the specific risk analysis; however, full consideration of the vulnerability of the element would require structural analysis to evaluate the level of damage, which is beyond the scope of this study. The vulnerability is assessed qualitatively or subjectively from a geotechnical perspective only and is presented in Table 3 while rating procedure for *specific risk* is defined on Table 4.

Vulnerability <u>V (L: T)</u>	Rating	Criteria
	Low (Loss or Damage)	Structure founded on piles or foundations extended to till or other stable material. If designed appropriately, the structure should not be undermined but may suffer minor damage if a landslide occurs.
	Moderate (Loss or Damage)	Structure is founded on deep spread footings or the foundations walls are relatively high and rigid. Or the landslide is expected to undermine only a small portion of the house. A moderate level of damage should be repairable, except to sundecks.

	High (Loss or Damage)	Structure is founded on shallow spread footings (or no footings) and could be readily undermined by the landslide. A significant portion of the outside wall could be undermined and/or the structure would probably suffer significant damage. Repairs may be extensive.
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Table 3: Definitions of the qualitative vulnerability ratings.

$R(S) = P(HA) \times V(L:T)$		<u>V (L: T)</u> <u>(from Table 3).</u>		
		Low	Moderate	High
<u>P (HA)</u> <u>(from Table 2).</u>	Very low	Very Low	Very low	Low
	Low	Very Low	Low	Moderate
	Moderate	Low	Moderate	High
	High	Moderate	High	Very High
	Very High	High	Very High	Extreme

Table 4: Specific risk matrix showing the interaction of P (HA) and V (L: T).

The partial and specific risks are summarized on the tables in Appendix B and described in more detail in Section 7.0 below.

The vulnerability of the underground services was not evaluated. Since pipe gradient is critical for gravity services, the vulnerability of the sewer main should be assumed to be high. Any spatial interaction between a landslide and the pipe would probably affect the gradient if not directly damage the pipe itself.

Concrete or brick patios were not considered as elements at risk, nor were retaining walls that are used solely for landscaping. Retaining walls that directly or indirectly support the house or sewer main were considered in that failure of the wall could result in failure of the house or sewer main.

6.2 Seismic Conditions

The landslide risks were also estimated under design earthquake conditions using a similar stepped procedure. The criteria or factor of safety thresholds used to determine the seismic risks are different from those used in the static analyses and there are fewer ratings. The qualitative ratings used in this study range from low to high and are independent of the static risk ratings (i.e. a static rating of very high and a seismic rating of high does not mean the risk is reduced under seismic conditions). Fewer ratings are used because of a lower degree of accuracy in estimating the landslide risk under seismic conditions.

From a probabilistic perspective, the seismic landslide risk may be lower than the static risk in some cases because of the low probability (10% probability in 50 years) of the design earthquake occurring and an even lower probability that a major earthquake occurs during a period when the static slope conditions are most susceptible to triggering a landslide (i.e. seasonal high groundwater table).

For the relative risk ratings, the following criteria were used.

<u>Landslide Probability Under Seismic Conditions.</u>	<u>Rating.</u>	<u>Criteria.</u>
	Low	Factor of Safety >1.2.
	Moderate	Factor of Safety between 1.0 and 1.2.
	High	Factor of Safety <1.0.

Table 5: Definitions of the qualitative landslide probability ratings under design earthquake conditions.

The majority of the slope along the eastern side of the ravine has a seismic factor of safety less than 1.0, meaning numerous landslides could be anticipated during a large earthquake. Earthquake conditions also create the potential for larger, circular slope failures that could extend farther back from the slope crest thereby increasing the probability of a spatial interaction with the house and/or buried services. The result is a partial risk rating under seismic conditions that is often greater than the partial risk under static conditions. The factor of safety criteria used in the qualitative partial risk ratings are as follows:

<u>Partial Risk Under Seismic Conditions.</u>	<u>Rating.</u>	<u>Criteria.</u>
	Low	Factor of Safety at the structure >1.3.
	Moderate	Factor of Safety at the structure between 1.1 and 1.3.
	High	Factor of Safety at the structure <1.1.

Table 6: Definitions of the Partial Risk ratings to the houses under design earthquake conditions.

The partial risk to the structure is then combined with the structure's vulnerability to determine the *Specific Risk Under Seismic Conditions* in the same manner as under static conditions. The seismic risk ratings for each of the 27 properties are summarized on Table B3 in Appendix B, and also discussed in Section 7.

This study considers only loss or damage resulting from landslides. The design earthquake and its amplification could cause some damage to most structures

regardless of their proximity to the slope. Even where the slope does not fail, ground movement could be severe.

6.3 Acceptable Risk & Thresholds for Mitigation

Determining levels of acceptable risk is a matter of public policy and is beyond the scope of this study. The topic is discussed in *Guidelines for Legislated Landslide Assessments for proposed Residential Development in British Columbia* published by the Association of Professional Engineers and Geoscientists of BC in March 2006, which states that:

In British Columbia, the only province-wide adopted level of landslide safety is the statement “that the land may be used safely for the use intended” associated with the Land Title Act (Section 86) for subdivision approvals, the Community Charter (Section 56) for building permits and the Local Government Act (Section 910) for flood plain bylaw exemption. Although the statement has been included in various pieces of provincial legislation for over 30 years, the word ‘safely’ has never been defined.

Common practice in geotechnical engineering is to design new structures with a minimum factor of safety against slope failure of 1.5 under static conditions. Based on the criteria used in defining the qualitative probability ratings in this report, the acceptable specific risk (R(S)) for new houses is “low”.

With respect to existing structures with a specific risk greater than low under static conditions, the selection of an appropriate mitigative measure should also include a cost/benefit analysis. The decision to proceed with or enforce mitigative measures should take into account the specific risk, cost of the measures, the value of the property, and the value of the existing structure. Mitigative measures that are inexpensive or easily implemented could proceed as soon as possible while major or expensive mitigative measures may be delayed provided the risks are known and considered acceptable to all affected stakeholders.

For example, a moderate risk affecting a 30 or 40 year old house may be considered acceptable by its occupants. The risk has probably existed throughout the life of the structure and should have been perceived as acceptable up until now. Such properties may be planned for redevelopment in the near future, at which time mitigation can be more readily implemented within the development plan. Until such time, a greater awareness of the hazards and risks, monitoring of the slope conditions, and proceeding with the less costly mitigative measures may be sufficient.

Where the risk to a structure is high under static conditions, the owners should proceed with those mitigative measures that can be readily implemented. Larger mitigative measures require planning and will depend on the estimated timing of the hazard. For example, a timber-crib wall that shows signs of advanced decay should be replaced as soon as possible while a similar wall without decay could

perhaps remain in place for a few more years. Otherwise, the objective should be to lower the risks as soon as reasonably possible.

Houses with a risk rating of very high or extreme under static conditions warrant immediate attention. The decision to continue to occupy these houses during the winter months when the probability of a landslide is at its highest requires thorough discussion by all parties.

The estimated timing of any landslide is virtually impossible to predict because the factors contributing to the event are highly variable. Typically, most landslides occur during winter months, particularly mid November to February when rainfall is greatest. However, landslides could be triggered by a single extreme 1 day event or a prolonged period of heavy but not extreme rainfall. Since groundwater discharge can also trigger landslides in the Capilano Sediments, even a season with well above average rainfall can trigger a landslide without any particular heavy storm event. Past landslides in Mosquito Creek have also been caused by non-weather related factors such as broken water mains, fill placement over the bank, and logging of timber.

Without the ability to predict when a landslide may occur, this hazard must be managed based on risk. Time is a factor in risk, since the longer a structure is exposed to a particular hazard, the greater the risk. Mitigative measures not implemented in the short-term should not be forgotten. An implementation plan is recommended based on the risk rating, the age of the structure, the nature of the hazard (i.e. short-term versus long-term), and plans for redevelopment of the property. The plan should be tailored for each property, although properties could be grouped together where, for example, mitigation includes a common slope buttress. The discussions in Section 7 are designed to assist with the preparation of mitigation plans for each property. Heavy reliance on the risk ratings on the tables in Appendix B is not recommended because the discussions in Section 7 offer more details.

7.0 SITE ASSESSMENTS FOR INDIVIDUAL PROPERTIES

Each of the 27 properties along the crest of the east bank was assessed. The results are discussed below including a description of the property, the slope, the hazards and risks, the seismic hazards, and recommended means to mitigate the risks.

7.1 710 West 17th Street

Property Description

This is one of the older houses in the neighbourhood. The house is single-storey with a basement that daylights on the west and south sides. The exposed concrete foundation wall bears directly on native sand without a footing and the bottom of the wall is visible along the west and south sides of the house. The sand beneath the foundation wall is loose and appears to have settled, creating small gaps between the base of the wall and the bearing soil. Except for one large

crack above the basement door on the south side of the house, there are few signs of distress in the foundation. The chimney was dismantled because it was reportedly pulling away from the house. This movement is not expected to have been related to the slope because the chimney sat on a large concrete pad that remains intact.

The roof leaders are connected to a subsurface drain but the location of this drain outlet is not known. There is no visible rock pit and no pipes found on the slope. Nor is the house connected to a municipal storm main.

The house is set back 5 to 7 m from the slope crest and the area between the west side of the house and the slope is relatively flat and landscaped. Test Hole 06-3 along the west side of the house found loose to compact sand to approximately 5.0 m depth, overlying compact silt with some sand and then silt between 6.0 and 10.5 m depth. Till was not encountered within the 10.5 m depth of the test hole.

Test Hole 06-4 near the chimney base on the south side of the house found similar soil conditions but the sand is very loose to 3.6 m depth. The very loose sand overlies compact sand at 3.6 m and then silt at 5.5 m depth.

The southern portion of the yard is noticeably depressed and appears to have been an erosional feature associated with the Mosquito Creek valley that was filled probably decades ago. Test Hole 06-5 drilled in the middle of this part of the yard found sand fill containing some organic soil and overlying the natural topsoil layer at 4.8 m depth. The underlying native soils consist of loose to compact sand to 5.9 m depth and then silt. The upper part of the silt deposit is sandy but becomes clayey beneath 9.6 m. The hole encountered dense soil at 12.0 m depth, which may be glacial till.

The sanitary sewer connection crosses this thick fill deposit, connecting to the sewer main in the park to the south. The watermain is on the north side of the house and avoids this fill area.

Slope Description

The adjacent slope is only 12 to 13 m long, relatively short compared to the valley upstream, with gradients ranging from 38° to 40°. The slope is comprised of loose sand with seepage discharging at the toe of the slope. The slope is forested with conifers adjacent to the house and appears to be relatively natural. The slope to the south is forested with deciduous trees and consists of loose sand fill. No signs of past failures were found despite the steep angle.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	High	High

Despite the steep slope angle, the slope is relatively short. Therefore, there is a high probability of small-scale slope failures but the potential size or magnitude of the failures is relatively small (i.e. less than 50 m³). Such small failures would likely impose 1 to 3 m into the slope while the house is set back at least 5 m; therefore, the house would likely not be directly impacted on by the landslide. However, after a slope failure occurs, the soils exposed in the headscarp often ravel back and settle. Ultimately, the house could be partially undermined if steps are not taken immediately after a landslide to remediate the hazard. Accordingly, the partial risk to the house is moderate.

The house appears to be fairly rigid and has suffered only minor damage despite no footing and no footing burial on the south and west sides. However, without proper footing burial, the house would be prone to damage caused by settlement and lateral movement after a landslide, creating a high specific risk.

The slope is well protected from Mosquito Creek; therefore, the potential for creek erosion causing over-steepening of the bank is very low. The most likely causes of a potential slope failure are windthrow or other loss of timber on the slope, or a rupture of the waterline.

A rupture of the sewer connection leading south across the filled area could cause a slope failure, although the volume of discharge associated with sewer connections is substantially less than a ruptured waterline. The most likely consequence of a ruptured sewer pipe would be a small piping failure at mid-slope along the silt/sand contact. This part of the slope is well away from the house, so the house should not be affected.

Slope movement adjacent to the southern part of the yard could be a concern for the sewer connection; however, the pipe is set back approximately 6 m from the slope and should not be directly impacted by a slope failure. The fill in this area has settled significantly and has probably created a substantial bow in the pipe. Even without a slope failure, lateral slope movement combined with vertical settlement could combine to seriously damage this pipe.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	High	High

Based on the stability analysis, the probability of a landslide occurring is high but given the limited slope height, the volume of the potential landslide is expected to be less than 50 m³, which would not directly impact on the house. The probability of a larger landslide extending back 5 m from the slope crest is moderate. Without proper footing burial, the house could receive significant structural damage due to the ground movement, resulting in a high specific risk.

Mitigation/Remediation

A cost/benefit analysis is recommended before proceeding with any mitigative works. Consideration should be given to the age of this structure and the low probability of a direct spatial interaction with the house under static conditions (the moderate partial risk is due to post-landslide ground movement, which should allow time to vacate the house).

As the slope is readily accessible, buttressing could be employed to reduce the slope angle (as described in Section 9.3) and the specific risk to this structure. In this case, the buttress would have to extend the full height of the slope to reduce the probability of a landslide to low under static conditions. If the objective was to stabilize only the slope directly adjacent to the house, soil nailing would be another option (see Section 9.5 and Figure 5). Alternatively, shallow underpinning of the existing foundation wall along the west and south sides of the house could also reduce the specific risk by reducing the vulnerability.

If future redevelopment plans included the southern part of the yard, this area would have to first be densified before the loose fills were capable of supporting a structure. This could also be an opportune time to improve the slope stability by constructing a slope buttress.

7.2 711 West 18th Street

Property Description

The house is two-stories with a closed-in deck or sunroom on the west side. No cracks were found in a landscape architectural wall on the south side of the house and only one crack was found in a blue tile patio on the south side of the sunroom. No obvious settlement was found on this house.

The yard to the west of the house is divided in two, with grade separation provided by a masonry block wall. This wall shows no signs of settlement and an old tree stump to the south suggests the grade is natural. The lower yard is on the south side and includes two built-in water cisterns with associated connections and drain valves. The house is set back 6 m from the crest of the ravine slope on the south side of the wall.

The north side of the yard is at a higher grade and the crest of the ravine slope has been filled out. Lawn clippings and other garden waste have been disposed over this slope. The house is set back 8 m from the slope crest. An in-ground irrigation system is present within the level yard near the slope crest and a line of dead grass running from the northwest corner of the house to the northwest corner of the yard may indicate an underground drain connection.

The driveway on the south side of the house is level; however, the west edge has subsided. The subsidence may simply follow the trench for the water main connection (the sewer connection is on the north side of the house), or could

indicate slope movement. The house is not connected to the municipal storm system. Presumably there is a rock pit somewhere in the yard west of the house.

Slope Description

The slope adjacent to the driveway is 39° and comprised of organic material, bricks and other debris. The slope forms a bench about 8 m below the crest and the lower slope (below this bench) is 33° and natural. The debris on the upper slope suggests that the cracks and subsidence along the west edge of the driveway could be related to shallow slope movement. The house, however, is situated more than 6 m and the carport is more than 3 m from the slope crest at this location.

The slope adjacent to the south part of the yard (the lower level) is less than 12 m long. The upper slope is 39° to 42° and comprised of fill and debris pushed out over the edge. The lower slope is less than 35° and natural. To date, this slope shows not signs of significant movement.

The slope opposite the north half of the yard is higher because the crest climbs up 3 m and the toe extends farther below. The upper slope is 42° for 4 to 5 m and comprised of organic fill, bricks, and yard debris. The lower slope reduces to 33° for 18 to 20 m and is forested with conifers.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	Moderate	Moderate

The probability of a slope failure is high. Potential failures would likely occur predominantly in the surficial fills dumped over the crest of the slope but such failures often consume some of the natural grade as well. The landslide scarp would probably extend back to the masonry block wall and the two cisterns. The house is set back a sufficient distance and is founded on native sand such that the probability of a spatial impact on this structure is low and the partial risk to the house is moderate. If there was impact, the landslide would probably damage the northwest corner of the house, creating moderate vulnerability and moderate specific risk.

The water cisterns are relatively small and the increased load on the slope is minor. The release of such a small quantity of water onto the slope would likely not trigger a failure but could cause surficial erosion. However, if the water line is connected to the municipal system, a pipe rupture could create a more continuous supply of water and cause substantial erosion.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

Based on the stability analysis, the probability of a landslide occurring under design earthquake conditions is high. The magnitude of the potential landslide is greater under seismic conditions than under static conditions; therefore, the both the partial risk and specific risk to the house increase to high.

Mitigation/Remediation

Disposal of yard and household waste on the slope should cease and the fill and debris removed from the upper slope to allow planting of natural vegetation. Full removal of the existing fill and reduction of the slope angle could reduce the probability of a landslide and the specific risk to the house to low under static conditions.

Decommissioning the cisterns and the in-ground irrigation system in the western yards would be prudent. During this process, water from these features should not be disposed of in a concentrated form directly onto the slope.

7.3 1805 Bewicke Avenue

Property Description

The house is three-stories at the rear (i.e. west side) but is setback 22 m from the crest of the ravine. The rear yard is landscaped with interlocking bricks surrounded by stone masonry. A small pond is located less than 6 m from the slope crest.

A line of settlement is reflected in the interlocking bricks across the west edge of the yard, approximately 1.5 m from the crest of the slope. At the north edge of the yard, this line of settlement extends 7 m from the slope crest, with additional displacement up to 14 m from the slope along the north property line.

This property is connected to the municipal storm main under Bewicke Avenue.

Slope Description

The upper slope is retained by a series of three stepped, timber-crib retaining walls. The upper-most wall is relatively new but the lower two tiers are older and in an advanced state of decomposition. The lowest wall has failed in one location near the south property line.

The slope below these walls is 35° and comprised of native soils and coniferous timber. Although the surficial soil is silty sand, this is probably colluvium that

raveled or washed down from the upper slopes prior to the walls being built. The nearby test holes suggest that the lower slope consists of till below approximately 9 m depth. No signs of past failures or erosion were found on this lower slope.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very Low	Moderate	Very Low

The settlement in the interlocking bricks is caused by movement in the decaying retaining walls, except at the north end of the property where the cracks extend farther into the property. Here, the movement is caused by settlement in the fill that extends onto the neighbouring property to the north.

Considering the advanced decay of the lower two timber crib walls, the probability of a slope failure is high. Such a failure would likely follow the line of settlement in the bricks approximately 1.5 m back from the crest and could extend up to 3 m back from this line. Leakage or failure of the small pond could cause a more localized erosional failure that could extend back to the pond.

The probability of a larger slope failure occurring is moderate. Such a failure would likely extend back 2 to 4 m from the crest of the slope and cause extensive damage to the landscaping. With the house located 22 m from the slope crest, the probability of a landslide occurring that is large enough to impact on the house is very low.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Based on the stability analysis, the probability of the design earthquake triggering a landslide at this location is high. Although seismically induced landslides are often larger than static landslides, the probability of a landslide extending back to the house is low. Both the partial and specific risks to the house are low.

Mitigation/Remediation

Reducing the probability of a landslide to low is probably not viable given the natural slope angle, nor necessary considering the house setback. However, the probability of a landslide can be reduced to moderate (under static conditions) by removing the timber crib walls at the crest of the slopes and pulling back the fill on the upper slope to a uniform 35°. Alternatively, the walls could be replaced with a GRS wall (see Section 9.2). Figure 2 includes a schematic design of the GRS wall option for this property. Coordinating this work with mitigation work recommended

for 1815 and 1821 Bewicke Avenue could reduce costs and improve construction access.

The pond should be decommissioned or as a minimum, lined to ensure the drainage system does not concentrate water onto the slope.

7.4 1815 Bewicke Avenue

Property Description

Test Hole 06-6 drilled in the back yard of this property found 3.5 m of fill comprised of silt with some sand, wood, concrete and glass debris. The fill is loose and has experienced significant settlement. Slope movement was first reported to CNV in 1992. Tension cracks near the crest of the slope are open to at least 1.5 m depth. The fill appears to have been pushed out to level the yard and extends almost 10 m back from the crest of the slope. The fill also extends southward into 1805 Bewicke Avenue and northward into 1821 Bewicke Avenue.

The three storey house on this lot is set back 16.5 m from the crest of the ravine and 6.9 m from the closest point of the settlement. The sundeck posts are at least 2.3 m farther east of this point. The house has one apparent settlement crack on the south side and another almost directly opposite on the north side. The amount of movement in these cracks is relatively small. The house and deck do not show any other obvious signs of settlement.

This property is connected to the municipal storm main under Bewicke Avenue.

Slope Description

The slope is 16 m long sloping at 37° on average. The upper 5 m of the slope is 39° with an old decomposed, log crib retained by alder or maple trees on the slope. The lower slope is 35° and forested with alder and maple. Soil exposures are similar to the fill found in Test Hole 06-6 and include silt and sand with wood, concrete and glass debris.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very Low	Moderate	Very Low

The tension cracks are likely due to movement created by the decomposing log crib found 5 m down the slope. These logs will probably fail and cause a landslide within the next several years. The size of the landslide depends on how the logs fail. If the logs decompose and fail in small pieces while the trees and adjoining sections remain intact, the failures would likely be quite small (i.e. less than 30 m³) and limited to the slope itself. However, if one of the alder or maple trees supporting the logs blows over or once the logs lose the majority of their integrity,

a larger, more catastrophic failure would occur (i.e. 50 to 150 m³). The probability of such an event is high in the mid to long-term (i.e. 5 to 20 years). Such a failure would likely extend back 1.5 to 3 m from the crest of the slope to the existing tension cracks and be as wide as the entire property and could even extend onto the adjacent properties.

There is also a moderate probability of a larger slope failure (i.e. greater than 150 m³) extending back 3 to 5 m from the crest of the slope. Such a failure would also be deeper and deposit a significant volume of material onto the trail below. Based on the extent of visible settlement, ground subsidence could occur up to 10 m back from the existing crest. However, with the house set back 16.5 m and the deck more than 11 m, the partial risks to the house and deck are very low and low, respectively. Damage should be repairable, so the specific risk is very low.

Settlement is a broader issue and encompasses the entire fill area. Since the house appears to be founded on native soil, settlement is primarily a landscaping issue.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	Moderate	Moderate

Based on the stability analysis, the probability of a landslide occurring is high but the probability of a landslide extending back to the house is low. The broad area of loose fill in the west yard creates a greater risk of significant ground deformation. The fill area could settle more than 0.5 m and spread laterally westward, creating a moderate partial risk to the house. Since the house is not founded directly on the fill, damage could be extensive but should be repairable and the specific risk is moderate.

Mitigation/Remediation

Reducing the probability of a landslide to low is probably not viable given the natural slope angle, nor necessary considering the house setback. However, the probability of a landslide can be reduced to moderate (under static conditions) by removing the existing log crib and re-grading the slope to a more uniform 1.5H: 1V (34°). The pulled back material should be removed from site, resulting in the loss of the west edge of the yard. If the owner wishes to maintain the current extent of the yard, a GRS wall could be constructed on the upper slope as described in Section 9.2. Coordinating this work with mitigation work recommended for 1805 and 1821 Bewicke Avenue could reduce costs and improve construction access. This work would also reduce the hazard to the trail below.

The slope should be re-planted in accordance with an overall landscape plan to encourage native vegetation and trees for erosion control and root support.

7.5 1821 Bewicke Avenue

Test Hole 06-2, drilled in the easement immediately north of the northwest corner of the house, found 1.8 m of silty sand fill overlying loose, native sand (the fill is thicker closer to the crest of the ravine). This fill has caused settlement beneath the concrete patio on the west side of the house. The southern 1/3rd of the patio is in good condition but the northern 2/3^{rds} show both vertical and horizontal separation at the joints. No settlement cracks were observed in the house foundation, suggesting that either the footings are probably deeper and bearing directly on native soil, or the fill within the foundation area was properly compacted.

The yard has grades slightly to the west towards the ravine and large tension cracks exist 2 to 4 m back from the fence. The crest of the ravine turns to the northeast, indicated by a bend in the fenceline. The southwest corner of the house is set back more than 10 m from the slope crest however the northwest corner and the northwest sundeck post is only 7 m and 4 m away from the crest respectively.

This property is connected to the municipal storm main under Bewicke Avenue.

Slope Description

The slope consists almost entirely of fill pushed out to create a larger level area. The slope is forested with maple and alder with fir trees only at the toe of the slope. The slope is supported by a stepped timber crib wall with the upper tier following the slope crest and the lower tier situated at mid-slope. This lower wall is highly decomposed and has shifted downslope, probably causing the large settlement in the back yard.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	Moderate	Moderate

The decaying timber wall at mid-slope creates a high probability of a slope failure. Given the location of the wall at mid-slope, the landslide could be large enough to encompass the yard area back to the tension cracks. With a minimum of 7 m from the house to the nearest tension crack, such a failure has a low probability of spatially impacting the house, resulting in a moderate partial risk to the house. Subsequent settlement would probably damage the patio slabs and the sundeck; however, the house foundation appears to be deeper, and damage to this structure should be repairable. With moderate vulnerability, the specific risk to the house is also moderate.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

Based on the seismic stability analysis, the probability of a landslide occurring that is large enough to directly impact on the house foundation is high. Direct impact would probably be limited to the northwest corner of the house; therefore, the damage should be repairable. With moderate vulnerability, the specific risk rating is high.

Mitigation/Remediation

Reducing the probability of a landslide to low is probably not viable given the natural slope angle, nor necessary considering the house setback. However, the probability of a landslide can be reduced to moderate (under static conditions) by removing the two timber walls and re-grading the slope to a more uniform 1.5H: 1V (34°). The pulled back material should be removed from site. Alternatively, a GRS wall could be constructed as described in Section 9.2. Coordinating this work with mitigation work recommended for 1805 and 1815 Bewicke Avenue could reduce costs and improve construction access.

Buttressing the slope below the northwest corner of 1821 Bewicke Avenue should improve both the static and seismic slope stability. The buttress would have to extend almost the full slope height and should be constructed in conjunction with a buttress below 1845 Bewicke Avenue (see Section 9.3 and Figure 3).

The slope should be re-planted in accordance with an overall landscape plan to encourage native vegetation and trees for erosion control and root support.

7.6 1845 Bewicke Avenue

Property Description

This house is single storey and constructed fairly close to the crest of the slope. The foundation includes a shallow crawlspace. The southwest corner is set back 10 m from the slope crest; however, the slope curves to the northeast where northwest corner is only 4.2 m from the crest and the north side of the house is 4.3 m. The house has only a few cracks in the foundation walls and the surrounding brick sidewalk shows no signs of movement.

The western and northern yards are relatively level and show no signs of settlement. Test Hole 06-1, drilled near the northwest corner of the house found native, loose sand becoming compact below 3 m depth. No fill was found in the test hole and, unlike the neighbouring properties to the south, this yard has not been filled out towards the ravine. Therefore, the shallow spread footings appear to bear directly on native soil.

A detached garage near the southwest corner of the property is about 2 m from the slope crest but no settlement cracks were noted in the slab-on-grade inside this structure.

The house is not connected to the municipal storm main under Bewicke Avenue. A small rock pit is situated near the crest of the ravine and the roof leaders probably flow into this.

Slope Description

The lower slope ranges from 42° to steeper than 45°. The soil exposures on the slope consist of sandy colluvium that has raveled from above. However, Test Hole 05-1 drilled during the preliminary assessment in 2005 confirmed the presence of till below 8.5 m depth. Therefore, the lower slope consists of very dense till over-steepened by erosion caused by flooding of Mosquito Creek.

The upper slope is 35° for approximately 13 m and consists of native sand and silt. The crest or upper 1 to 2 m is over-steepened at 42° near the northwest corner of the house although the slope is more uniform elsewhere. No seepage was found on the slope, which is forested with both mature conifers and large maple trees. Most of the slope appears to consist of natural soils and the only fill is some yard waste dumped on the upper slope directly behind the detached garage or shed.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

The till deposit on the lower slope has been over-steepened for several decades. The till could ravel but the deposit is very dense and such failures are rarely larger than 10 m³ and have little consequence. Most of the landslides in this valley have occurred in the looser Capilano Sediments on the upper slope.

The upper slope has a high probability of failure. Typical failures should have a headscarp 1 to 2 m back from the existing slope crest. The detached garage is within 2 m of the crest and could certainly be impacted by a failure on the slope below. The presence of yard waste directly below the garage also increases the probability of a landslide occurring at this specific location.

The house is typically set back 8 to 10 m from the slope with a low probability of a spatial impact from a landslide. However, the northwest corner is only 4.2 m back resulting in a high partial risk. The potential consequences could include settlement and/or undermining of the northwest corner of the foundation wall. Repairs could be costly but feasible, resulting in a moderate vulnerability and a high specific risk.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

Under design earthquake conditions, the probability of a landslide impacting directly on the northwest corner of the house is high. Damage to the house could be very significant but still limited to the northwest corner. Therefore, the specific risk to the house remains high.

Mitigation/Remediation

The risk to the house is high only near the northwest corner. Buttrussing the adjacent slope is one option and would blend in with the stabilization work at the end of West 19th Street. Stabilizing the lower slope would accomplish little because the failure is more likely to occur on the upper slope; therefore, the buttress would have to cover at least the lower 2/3^{rds} of the slope (see Section 9.3 and Figure 3) to effectively reduce the probability of a landslide and the specific risk to the house to low (under static conditions).

Access to slope crest is limited, but if access could be prepared either at the crest or from the bottom, soil nailing of the upper slope below the northwest corner of the house could be viable. This mitigation method is described in Section 9.5.

A less costly means of protecting the house (potentially) would be to underpin the northwest corner of the foundation wall. Underpinning the footing to bear at a minimum depth of 2 m (see Section 9.1 for details) would reduce the probability of the house being undermined following a landslide to a level consistent with the rest of the house (i.e. a factor of safety of 1.3) under static conditions.

Connecting the footing and roof drains to the municipal storm main would reduce seepage on the slope by eliminating the existing rock pit. Alternatively, the rock pit could be relocated to the base of the slope.

The garage or shed may not be worth the cost of stabilizing the slope at this location, but disposal of yard waste onto this bank should cease.

7.7 626 West 19th Street

Property Description

This two-storey house is located near the crest of the stabilized slope at West 19th Street and Bewicke Avenue. A Lock-block wall supports an engineered slope directly west of this house. The west side of the house is located at least 6 m back from the crest. The grade is relatively level and was backfilled after the wall was constructed. The sidewalk down the west side of the house is severely cracked but the house shows no obvious signs of settlement.

The back yard is relatively level. A large concrete patio slab has several cracks but also lacks sufficient expansion joints. These cracks are probably caused by concrete shrinkage during the curing process. A brick barbeque pit near the slope is still in good condition but the concrete slab has separated at a joint immediately behind the barbeque pit and along the crest of the slope.

A power pole at the far north end of the property is setback 6 m from the slope crest while a guywire is located just 1.6 m from the crest.

Test Hole 06-8 found native sand beneath the topsoil. The sand is loose near the surface, becomes compact and overlies silt near 2.5 m depth. Based on the test hole results and surface exposures, till is expected at about 4.5 m depth.

This property is connected to the municipal storm system.

Slope Description

The slope adjacent to the west side of the house is supported by a Lock-block retaining wall at the base of the ravine. The slope above the wall is approximately 32° and comprised of engineered pitrun fill. Some movement of the slope is normal and is needed to generate active earth pressures behind the retaining wall, but no signs of excessive movement were observed. A small scarp at the crest of the slope is described in the report by MacLeod Geotechnical (October 30, 1995) and is apparently a remnant from construction of the wall and slope.

The slope adjacent to the back yard is over-steepened at more than 45°. The lower slope consists of very dense till and is overlain by silt or silty clay. The upper 2.5 m consists of sand but the slope is covered by wood and yard waste dumped over the bank.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Low / High	Low	Moderate	Low

The retaining wall was engineered and is assumed to be stable. Provided this wall remains stable, the probability of a slope failure on the west side of the house is considered low. A failure on the 32° slope above the wall would have a moderate probability of spatial interaction with the house, resulting in a low partial risk to the house.

The slope adjacent to the back yard is steeper and more unstable. Since till is relatively shallow, failures should be limited to the upper 4.5 m of clay and sand. As such, the potential size of failure is probably quite small and would consist of several raveling or small slab failures.

The probability of slope failure increases dramatically when organic yard waste and other debris is dumped over the bank. As this material decays, it adds significant weight to the slope with little strength. When the debris eventually fails, it tends to entrap some of the native soils, creating a larger landslide. In this case, the barbeque pit and other landscape features along the edge of the back yard would be susceptible to damage but the house has a very low probability of a spatial impact and a low partial risk.

The power pole at the north corner of the yard could be damaged because the guywire is located less than 2 m from the crest.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate / High	Moderate	Moderate	Moderate

Under design earthquake conditions, the probability of a landslide above the Lock-block wall increases to moderate and the partial risk to the house also increases to moderate. Undermining of a portion of the west foundation wall could cause structural damage but should be repairable, resulting in a moderate specific risk.

If the Lock-block wall failed during the earthquake, the probability of a landslide directly impacting on the house increases to high and the entire west wall of the house could be damaged. Therefore, seismic stability of the retaining wall is critical to the stability of the house but is not known.

The steeper bank adjacent to the back yard has a high probability of small failures during a heavy earthquake but with a very low probability of impacting on the house.

Mitigation/Remediation

No further stabilization work is needed to protect the house under static conditions. Stabilizing the bank under seismic conditions is not feasible, although the seismic stability of the Lock-block retaining wall should be evaluated.

The owner may wish to reconstruct the barbeque pit farther away from the slope. Similarly, BC Hydro should consider relocating the guywires supporting the power pole at the back or even relocating the power pole itself.

Disposal of yard and wood waste over the bank should cease.

7.8 1931 Westview Drive

Property Description

The property has a long, gradual (10%) grade sloping to the west, extending beyond the property line to the crest of the ravine. The house is 3 stories at the back and is set back 17 m from the property line, 27 m from the fence, and 34 m from the slope crest.

A small shed is located on CNV property within 2 m of the ravine crest while the sewer main is located 12 to 15 m back from the crest. A large cedar tree near the crest and a large cottonwood tree and stump just inside the fence indicate that the soil conditions are natural with minimal fill placement on the gentle slopes near the crest. Test Hole 06-10 was drilled about 3 m west of the sewer main and found 0.6 m of topsoil and landscape fill overlying native sand. Firm to stiff silt was found at 1.1 m depth. Similar conditions are exposed on the slope where the silt overlies till at 3 to 4 m depth below the crest.

The roof and footing drains reportedly lead into a rock pit located 25 m back from the crest of the slope. This was not confirmed in the field.

Slope Description

The upper 4 m of the slope is standing nearly vertical and exposes a small cobble and mortar wall less than 1 m high at the crest, overlying a thin deposit of sand, then over-consolidated silt or clay. Till is exposed between 3 and 4 m below the crest and consists of very dense silt and sand with some gravel and cobbles. The lower slope is 8 m long, ranges between 38° and 40°, and consists of material that has slid or raveled from above. The till deposit is buried beneath this scree or fine-grained colluvium.

This escarpment reportedly developed in 1955 when Mosquito Creek flooded and eroded the bank and has been slowly retrogressing since. The slope process is very slow because the silt or clay deposit is heavily over-consolidated and has significant cohesion, and the underlying till deposit is very dense. These deposits tend to ravel or fail as small blocks with a volume of just a few cubic metres.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very Low	Moderate	Very Low

The slope hazards at this site should be considered both in the short-term and long-term. The short-term hazard is the type of failure that occurs periodically (i.e. includes small raveling or block failures rarely more than a few cubic metres in volume). The only element exposed to this short-term hazard is the garden shed

located on CNV property. The shed is so close to the ravine crest that even a small raveling failure could begin to undermine it.

In the long-term, the slope will retrogress back to a uniform 36° to 38° slope, but the process could take several decades. The process would accelerate greatly if the creek flooded again, but the flood hazard has been reportedly mitigated. Assuming the toe of the bank does not erode any further, once the upper slope has fully retrogressed, the crest should be close to the existing fence. The shed is situated within this area and would eventually be completely undermined if not moved beforehand.

The sewer main is located 4 to 8 m back from the fence (still on CNV property) and the estimated line of long-term retrogression. The probability of a single failure large enough to directly impact on the sewer main is very low while the probability of long-term retrogression reaching the sewer main is low.

The house is setback more than 20 m from the estimated long-term retrogression line and has a very low partial and specific risk.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Both the house and sewer main are setback far enough from the slope such that the probability of a landslide directly impacting either of them is low even under design earthquake conditions

Mitigation/Remediation

The shed should be moved farther from the ravine crest.

No work is expected to be required to protect the sewer main for at least the next decade. This should be reviewed periodically by the CNV.

7.9 1935 Westview Drive

Property Description

The property is similar to 1931 Westview Drive and has a long, gradual (10%) grade sloping to the west. The house is 3 stories at the back and is set back 17 m from the west property line and approximately 30 m from the crest of the ravine.

The sewer main is located 10 to 15 m back from the crest. Large fir trees near the slope crest indicate that the soil conditions are natural with minor landscaping fills present. Test Hole 06-10 was drilled about 3 m west of the sewer main, immediately south of this property and found 0.6 m of topsoil and landscape fill

overlying native sand. Firm to stiff silt was found at 1.1 m depth. Similar conditions are exposed on the slope where the silt overlies till at 3 to 4 m depth below the crest.

The roof and footing drains reportedly lead into a rock pit located at least 25 m back from the crest of the slope. This has not been confirmed.

Slope Description

The upper 4 m of the slope is standing nearly vertical and exposes a small cobble and mortar wall less than 1 m high at the crest, overlying a thin deposit of sand, then over-consolidated silt or clay. Till is exposed between 3 and 4 m below the crest and consists of very dense silt and sand with some gravel and cobbles.

The lower slope is 8 m long, ranges between 38° and 40°, and consists of material that has slid or raveled from above. The till deposit is buried beneath this scree or fine-grained colluvium.

This escarpment reportedly developed in 1955 when Mosquito Creek flooded and eroded the bank and has been slowly retrogressing since. The slope process is very slow because the silt or clay deposit is heavily over-consolidated and has significant cohesion, and the underlying till deposit is very dense. These deposits tend to ravel or fail as small blocks rarely larger than a few cubic metres.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very Low	Moderate	Very Low

The short-term hazard consists of small raveling or block failures rarely more than a few cubic metres in volume. Neither the sewer main nor the house is exposed to this small-scale hazard and the partial risk to both is very low in the short-term.

In the long-term, the slope will retrogress back to a uniform 36° to 38° slope, but the process could take several decades. The process would accelerate greatly if the creek flooded again, but the flood hazard has been reportedly mitigated. Assuming the toe of the bank does not erode any further, the slope is expected to retrogress approximately 4 to 6 m.

With the sewer main located more than 10 m back from the existing crest, the partial risk to the pipe in the long-term is low.

The house has a very low probability of a spatial impact with both hazards.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Under design earthquake conditions, the probability of a spatial impact to the sewer or the house is low and very low, respectively.

Mitigation/Remediation

No work is expected to be required to protect the sewer main for at least the next decade. This should be reviewed periodically by the CNV.

7.10 1945 Westview Drive

The rear yard is substantially landscaped with small concrete block retaining walls, garden beds, trellises and a small pond. The house is set back 16 to 17 m from the property line and another 8 m from the crest of the ravine. The sewer main is located approximately 10 m back from the slope crest on the south side of the property and 15 m back on the north side. The small pond is situated more than 15 m back from the slope crest.

The property is not connected to the municipal storm system and no rock pit was found.

Test Hole 06-13 was drilled west of the sewer main and found 1.2 m of loose sand overlying compact or very stiff silt. The silt softens below 4 m depth but very dense till was found at 5 m depth.

Slope Description

This slope is part of the same near-vertical escarpment found on the properties to the south. The upper 1.2 to 1.5 m of the slope consists of loose sand that has raveled back to less than 40°. The sand overlies silt standing nearly vertical to about 5 m below the crest. The lower slope ranges between 38° and 40° and consists of till buried beneath scree that has slid or raveled from above.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very Low	Moderate	Very Low

The short-term hazard consists of small raveling or block failures rarely more than a few cubic metres in volume. However, if the small pond leaks or ruptures, the concentrated water could cause a small slump in the order of 10 to 20 m³, causing the crest to rapidly fail back 2 to 3 m.

In the long-term, the slope is expected to retrogress back to a uniform 36° to 38° slope, but the process could take several decades. Assuming Mosquito Creek does not flood its banks again, the crest of the slope could be expected to eventually retrogress back 4 to 6 m from its present location.

The sewer main is located 10 to 15 m back from the slope crest and the probability of a landslide impacting on the sewer is very low in the short-term and low in the long-term. The house is set back almost 25 m from the crest and the probability of a landslide reaching this point is very low during both the short-term and long-term.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Under design earthquake conditions, the probability of a landslide directly impacting either the sewer or the house is low.

Mitigation/Remediation

Although there are no elements at risk, the owners should consider removing the small pond. As a minimum, the drainage procedures should be reviewed to ensure the water is not being concentrated onto the slope, and inspect the liner each time the pond is drained.

No work is expected to be required to protect the sewer main for the next decade but the situation should be reviewed periodically by the CNV.

7.11 1957 Westview Drive

Property Description

This property is located immediately north of the near-vertical escarpment. The back yard is relatively level and the house is set back 18 m from the crest of the ravine. The sewer main crosses the middle of the yard and is 8.5 m from the slope crest at the south side and 12.5 m on the north side. A portable garden shed is located at the crest of the slope.

A pond at the base of a large fir tree at the southwest corner of the property has been decommissioned. According to the owner, the concrete lining was penetrated before the pond was filled with drain rock. The pond does not appear to retain water.

Large conifers across the crest of the slope suggest the grade is natural. A depression in front of the shed may have been caused by removing a large tree

stump. Test Hole 06-12 was drilled near the slope crest in the back yard and found 0.8 m of sandy, silty fill overlying native, loose to compact sand. Loose to compact sandy silt was found below 3.9 m depth while the DCPT found very dense soil (probably till) at 8.0 m depth. Test Hole 06-13 drilled on the property to the south found very dense till at approximately 5 m depth, indicating that the till deepens to the north.

This property is not connected to the municipal storm system and no rock pit was found.

Slope Description

The upper slope is fairly uniform; 42° for 12 m and is forested with large conifers. The lower slope consists of very dense till and is steeper than 45°. Small aprons of silt and fine sand have raveled from the upper slope and cover the till on the lower slope. Despite the raveling, the slope shows no other signs of past instabilities or concentrated seepage.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very Low	Moderate	Very Low

Although no signs of recent slope failures were evident, the upper slope is over-steepened at 42° creating a high likelihood of a landslide within the upper silt and sand deposits. The till on the lower slope is less prone to failure and limits the depth and size of the potential failure. The maximum probable failure would be up to 10 m wide and extend 3 to 4 m back from the existing crest. The garden shed would likely be destroyed by this type of event if it is not moved beforehand. However, the probability of a landslide impacting on the house and sewer main is very low and low, respectively.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Under design earthquake conditions, the probability of a landslide creating a spatial impact with the sewer or house is low and very low, respectively.

Mitigation/Remediation

The owners should move the garden shed at least 3 m from the slope crest to reduce the potential consequences of a landslide.

The old concrete lined pond has reportedly already been punctured and does not appear to retain water. However, if the owners notice water being retained in the future, the lining should be removed or broken. At no time should the pond be reactivated.

7.12 2009 Westview Drive

Property Description

The fenced yard extends southward into the municipal right-of-way. The sewer main is located only 2 m from the crest of the ravine. The grade is relatively level and shows no signs of settlement. However, when the house was built in 1983, fill was piled onto the back of the property and reportedly damaged the sewer pipe (CNV letter April 7, 1983).

The house has a basement partially below grade and is set back 11.5 m from the slope crest. A small garden shed is located in the right-of-way, very close to the crest of the slope.

Test Hole 06-11 was drilled in the right-of-way on the south side of this property and found native, loose sand becoming compact below 1 m and overlying loose to compact sandy silt at 2.2 m depth. The silt becomes firm, clayey silt at 5.5 m depth and appears to overlie till at 7.5 m depth.

The roof and footing drains reportedly drain to a rock pit located at the toe of the slope, although the rock pit was not confirmed in the field.

Slope Description

The slope has an arcuate shape in plan view and may be the result of an old landslide. The timber is entirely deciduous and appears to be more than 40 years old, indicating that if a landslide occurred, it probably occurred 40 to 50 years ago.

The crest of the slope is 42° for 2 to 3 m and then flattens to about 27° for an overall slope angle of 31°. This slope is flatter than most others along this gully, also suggesting that this may be an old landslide scar. A hand-dug test pit on the slope found loose, silty fine sand and a Dynamic Cone Test (DC-2) at the same location found loose soil overlying dense material at 3.2 m depth. The elevation of this dense layer agrees closely with the till layer found in Test Hole 06-11 and the till exposed on the slope below.

The lower slope is 39° for approximately 10 m and consists of very dense till overlain by colluvium or landslide debris.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Low	Low	Moderate	Low

The landslide that may have occurred at this location several decades ago reduced the angle of the upper slope to create one of the flatter slopes found in this ravine. The lower slope consists of till; therefore, the potential landslide would likely be limited to the upper slope. At an overall slope angle of 31° and no apparent seepage zone, this upper slope has a low probability of landslide occurrence. The most likely slope failure mechanism would be minor raveling or slumping along the crest. However, a leak or rupture of the sewer main could trigger a larger failure up to 10 m wide and extending about 2 m back from the crest.

With the sewer main located 2 m back from the slope crest, the sewer pipe would have a high probability of spatial interaction if a landslide occurs at this location. When coupled with the low probability of occurrence, this results in a moderate partial risk to the sewer main.

The house is set back more than 10 m from the slope crest and the probability of a landslide large enough to impact on the house is low. The house foundation is slightly deepened because of the partial basement. Although based on the rating system, this does not reduce the vulnerability to low, it should provide some mitigation. Regardless, the specific risk to the house is low.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Under design earthquake conditions, the probability of a landslide occurring increases to high. With the sewer main located close to the crest of the slope, the partial risk to the pipe also increases to high. However, the more than 10 m setback and a partial basement, the probability of a landslide undermining the house foundation remains low.

Mitigation/Remediation

With a low probability of a landslide occurring under static conditions at this location, remedial work may not be necessary. However, considering the risks under seismic conditions, the potential for damage to the sewer main, and the need for mitigative work on the property to the north (see 2015 Westview Drive below), consideration should be given to constructing a buttress across the lower slope of both 2009 and 2015 Westview Drive, as described in Section 9.3 and shown on Figure 4.

7.13 2015 Westview Drive

Property Description

The property is sloped gradually to the west. An old, two-tiered timber-crib wall at the crest of the ravine has slid more than 0.5 m downslope, creating a failure scarp 2 to 3 m behind the wall. The sewer main is located 3 to 4 m back from the wall immediately behind the failure scarp and is buried less than 1 m deep. A hand-dug test hole within the slumping soil exposed fill comprised of sand mixed with topsoil. A Dynamic Cone Test (DC-3) behind this wall found loose soil to 2.7 m depth overlying compact soil. The failure plane is probably located at the base of the loose soil at 2.7 m depth.

The sundeck posts are 9.5 m back from the slope crest, while the remainder of the house is set back 13.5 m. The house is actually closer to the slope at the south end of 2017 Westview Drive (the adjacent property to the north) where the setback is only 5.2 m; therefore, this house could also be affected by a slope failure below 2017 Westview Drive. A 0.5 m high cobble and mortar wall situated to the west of the sundeck is in reasonable condition. When the house was built in 1983, fill was piled onto the back of the property and reportedly damaged the sewer pipe (CNV letter April 7, 1983).

The roof and footing drains reportedly drain to a rock pit located at the toe of the slope, although the rock pit was not found in the field. Considering the slope movement that has occurred, the drain pipe buried beneath the slope is probably damaged and the stormwater is probably draining onto the slope.

Slope Description

The upper slope is dominated by the tiered, timber crib wall that has moved more than 0.5 m down the slope. The slope below the toe of the wall is approximately 30°. An older log crib wall was found at mid-slope, 8 m downslope of the upper wall. This lower wall is in very poor condition and is broken in several places. The lower slope is 37° and consists of very dense till overlain or covered by a thin apron of fill or sandy colluvium.

A 150 mm diameter, thin walled ABS pipe was found on the upper slope. The pipe ends at the mid-slope wall and is broken, possibly in several places. The water carried by this pipe probably discharges into the fill on the slope, contributing to the slope instability.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	Moderate	Moderate

The failure scarp behind the upper wall appears to be created by movement throughout the upper slope. The slope movement is probably caused by decaying of the mid-slope wall. The probability of a significant landslide covering the entire width of this lot and extending back to the visible failure scarp is high. Considering the amount of movement and the proximity of the sewer main, the partial risk to the pipe is high. CNV’s inspection of the pipe found no signs of damage or settlement suggesting that the pipe is located just east of the scarp. However, after the landslide occurs, the failure scarp should be expected to ravel back and the soil behind the scarp will strain westward and downslope, possibly causing significant damage to the pipe.

The house is located 13.5 m from the slope crest or approximately 10 m behind the failure scarp that has developed behind the upper wall. The sundeck is approximately 4 m closer to the slope. The stability analysis indicates that the partial risk to the house and sundeck is moderate. The magnitude of past landslides in the Mosquito Creek valley suggest that the house and deck would probably not be directly impacted by a landslide but could be damaged by subsequent retrogression of the headscarp or by settlement and lateral spreading behind the headscarp. Damage should be repairable.

The house is closer to the slope crest on property to the north (2017 Westview Drive) and could also be affected by a slide on this neighbouring property. However the probability of a landslide occurring on this adjacent property is lower and the greatest risk to 2015 Westview Drive is still from the slope below the retaining wall.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

With the slope already unstable under static conditions, a significant earthquake would almost certainly cause a landslide and the partial risk to the sewer main is very high. Landslides triggered by large earthquakes can be larger than statically-induced landslides; therefore, the partial and specific risks to the house both increase to high.

Mitigation/Remediation

Mitigation of the slope hazard must involve stabilizing both the upper and middle slope regions. Both areas require mitigation to adequately stabilize the slope and reduce the probability of landslides and the specific risk to the house and sewer main to low (under static conditions). Various mitigative options are discussed below and shown on Figure 4. Regardless of the option selected, the roof and footing drain connection to the rock pit at the toe of the slope should be re-established and a sump and clean-out added near the crest of the slope so that the pipe can be inspected in the future.

Upper Slope Option 1

The weight on the upper slope must be reduced by removing the entire mass of soil that has shifted downslope. This involves removing the upper retaining wall and flattening the upper slope to less than 30°. The final slope crest would be 4 to 5 m back from the existing wall and may expose the sewer main. The pipe may have to be relocated (see Upper Slope Option 3).

Upper Slope Option 2

Another option is to replace the upper timber-crib wall with a GRS wall; however, there may not be sufficient distance between the wall and the sewer pipe to allow for the reinforcement. Before de-constructing the upper wall, the sewer pipe should be exposed to remove the soil mass on top until after the work is complete. The pipe could also be anchored back to the slope to protect from movement.

The next step would be to determine the depth of the failure plane, which is probably along the base of the fill. The base of the new wall should be founded on native soil below this failure plane and the backfill reinforced with geogrid. The viability of this option will depend on the height of wall required to reach native grade. The length of geogrid reinforcement depends on the wall height, but will be limited by the distance between the pipe and the wall (see Upper Slope Option 3).

Upper Slope Option 3

Because of the proximity of the pipe to the slope crest, neither Option 1 nor 2 will improve the factor of safety sufficiently to reduce the partial risk to the pipe beyond moderate. The risk to the pipe can only be reduced to low (by either Option 1 or 2) if the pipe is relocated farther from the slope. The pipe will probably have to be relocated regardless, to allow either Option 1 or 2 to be implemented.

Mid-slope Option 1

The slope failure hazard is created by the decaying lower log-crib wall; therefore, to stabilize the slope, the load placed upon this wall must be supported by other means. The preferred option would be to buttress the entire lower and middle slope region as described in Section 9.3 and shown on Figure 4. The buttressed slope should have an angle no steeper than 1.5H: 1V or 34° and consist of well-graded pitrun or blasted, angular free-draining rock fill. The toe of the slope could either consist of a uniform grade that covers the existing trail (this section of the trail is officially closed), a three-block high Lock-block wall located along the upslope side of the trail, or a GRS wall of similar height.

The buttress must reach the mid-slope area to fully support the slope currently retained by this log-crib wall. Equipment access would be from the south (along the closed trail) by building an access ramp to reach the mid-slope region.

Mid-slope Option 2

Another option to stabilize the mid-slope region is to replace the decaying wall with a GRS wall as described in Section 9.2. However, unless a construction ramp from the toe of the slope can access this mid-slope area, all work may have to be done by hand. The new wall would have to be founded on native, very dense till. The excavation would probably be at least 1.5 m deep by 2 m wide across the entire width of the property. Considering the volume of the excavation and the backfill required, and the lack of equipment access, this option may not be viable to construct.

Further design is required for all mitigative options at this site.

7.14 2017 Westview Drive

Property Description

This is an older house with a closed-in room beneath the sundeck set back 6.2 m from the crest of the ravine. The covered deck is 2.4 m wide, so the set back to the remainder of the structure is 8.6 m. No settlement cracks were noted in the foundation and the occupants did not report any signs of settlement such as doors jamming or cracks in the interior walls. No obvious signs of settlement or slope movement were noted along the slope crest. There is a large cedar tree on the crest suggesting the grade on the slope is original.

The back yard is relatively level and was noticeably wet at the time of the field assessment (i.e. wetter than the adjacent properties). The property is not connected to the municipal storm system. Although no rock pit is evident in the west yard, the wet surface conditions suggest that the roof water is collected into a rock pit that is not functioning properly.

A Dynamic Cone Test (DC-4) about 1 m back from the slope crest found loose soils to 5.8 m depth except for a thin, compact layer near 2.5 m depth. The soils suddenly became dense at 5.8 m depth, which may be the till layer.

Slope Description

The upper slope averages 35° for 9 m below the crest, and then reduces to 31° for the lower 11 m. A hand-dug test pit on the upper slope found loose, disturbed soil comprised of silty sand mixed with topsoil. A large cedar tree near the crest of the slope on the south side of the property suggests the slope grade is original; however, most of the slope is forested with deciduous trees and small conifers. The slope profile resembles a landslide scar and the timber on the slope suggests a landslide may have occurred here several decades ago.

A “Big ‘O’” pipe emerges from the upper slope and runs down to the toe of the slope. There was no water in the pipe despite rainfall at the time of the fieldwork. The “Big ‘O’” pipe has perforations that allow the water to escape along its entire length. The upper slope on this property was wet. If this pipe is collecting the flow

from the footing and roof drains, it is discharging the water onto the slope and increasing the potential hazard.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate	Moderate	Moderate	Moderate

The slope appears to have experienced a slope failure a few decades ago that reduced the overall slope angle. The probability of another landslide at this location is moderate due to the seepage discharge. Such a landslide would likely be limited to the upper 7 m (measured vertically) of loose sand and silt, probably 3 to 6 m wide and extend 2 to 3 m back from the crest. The room below the deck is 6.2 m back from the crest; therefore, the probability of spatial interaction is moderate and the partial risk to this part of the house is also moderate. With more than 8 m setback, the partial risk to the remainder of the house is low.

The house and deck both bear on spread footings. While the covered deck footings may be severely damaged by a landslide, damage to the remainder of the house should be repairable. The specific risk to the room below the deck is moderate while the specific risk to the remainder of the house is low.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

The design earthquake increases the probability of a landslide to high. Since earthquake-induced landslides can be larger than statically-induced slides, the partial risk to the closed-in room beneath the deck also increases to high. The sundeck could be severely damaged by such a landslide but damage to the remainder of the house should be repairable.

The seismic hazard is affected by the high groundwater levels and the potential for liquefaction in the loose sand on these slopes. If the groundwater level could be lowered, the partial and specific risks to the house could reduce to moderate.

Mitigation/Remediation

The least costly means to partially mitigate the hazard at this property is to improve drainage near the slope. The roof and foundation drains should be replaced and should lead into a sump at the top of the slope. The sump should be connected to solid PVC pipe (not Big 'O') that extends to a rock pit or infiltration chamber at the bottom of the slope.

Removing the room below the deck would also reduce the risk by reducing exposure to the hazard. This combination of methods should reduce the specific risk to the house to low under static conditions.

7.15 2041 Westview Drive

Property Description

This older house is located 8.4 m from the crest of the ravine. A small sundeck on the west side of the house extends 2.3 m closer to the crest. The foundation walls have several cracks and rest directly on the native fine, sandy silt, without a footing and proper burial for frost protection. The chimney on the south side of the house has pulled away from the structure.

Remnants of an old timber crib wall were found in the southwest corner of the property, 6.6 m west of the house. The downslope side of this old wall has been filled in and the soil now rests against the wood-panel fence. The soil at this location is damp and has decayed the fence panel. Within this filled area, a large cedar tree suggests that natural grade is probably about 0.6 m deep.

Test Hole 06-14 was drilled near the crest of this slope and found 0.3 m of fill overlying the natural topsoil layer. The native soils consist of loose sandy silt becoming compact below 2.4 m depth. The hole was only sampled to 2.4 m depth but the Dynamic Cone Penetration Tests indicates that firm clayey silt exists below 4.5 m depth and that the surface of the very dense till is at 7.5 m depth.

The property is not connected to the municipal storm system and no rock pit was found. A rock pit probably exists somewhere beneath the back yard but CNV records cannot confirm this.

Slope Description

A 1 m high cobble and mortar wall found along the crest of most of this slope is relatively intact. A 1.5 to 2 m high timber-crib wall situated 3 to 5 m downslope rests on a very steep slope comprised of fill pushed out over the natural slope. This fillslope consists of household and yard debris including wood, metal and furniture. This garbage fill is over-steepened, ranging between 40° and 60° for 7 m down the slope.

The lower slope is 40° for 14 m and comprised of fine-grained colluvial veneer to apron overlying dense till. The slope is over-steepened at the north end, possibly from historic creek erosion; however, the creek is now confined by a berm on the east bank.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Moderate	High	High

The upper slope comprised of fill and debris is significantly over-steepened. As the wood debris decays, this debris pile will create a high probability of a slope failure. The potential failure would likely be 6 to 10 m wide and 2 m deep, consisting mostly of the debris but incorporating some of the natural soils. The cobble and mortar wall would probably be undermined and the fence could be lost, particularly as the landslide scarp retrogresses. However, Test Hole 06-14 found that the back yard is mostly situated on native soil, so the landslide would probably not extend more than 3 to 4 m into the yard.

With more than an 8 m setback to the house, the partial risk to the house is moderate. However, without proper footings, the house is particularly susceptible to damage caused by even small amounts of settlement (as well as frost heave). Therefore, although the house may not be directly damaged by a landslide, the settlement or strain that normally occurs in the soil behind the landslide could cause further cracking of the foundation. As a result, the specific risk to this house is high.

The sundeck is closer to the slope and has a high partial risk, but the deck can be easily replaced.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

The design earthquake creates a high probability of landslide occurrence even if the debris on this slope has not decayed. The potential magnitude of an earthquake-triggered landslide would be larger and the partial risk to the house increases to high. Ground deformation along the crest of the slope would likely still cause significant structural damage to the house. Without proper footings, damage could be severe and the specific risk is very high.

Mitigation/Remediation

Risk mitigation measures require removal of the significant pile of debris dumped over the slope. Further disposal of debris on this slope must cease. Eventually, the cobble and mortar wall and the small timber-crib wall should both be replaced with a GRS wall founded on native soil (see Section 9.2). This combination of measures could effectively reduce the probability of a landslide to moderate under static conditions.

Scheduling this work to coordinate with future development plans may be a point for discussion. If this site is not planned for re-development, consideration should be given to supporting the house on proper footings to improve the vulnerability of the structure.

The roof and foundation drains should be collected into a sump at the top of the slope. The sump should be connected to solid PVC pipe that extends to a rock pit or infiltration chamber at the bottom of the slope. This work should be completed after the debris has been removed from the slope.

7.16 2049 Westview Drive

Property Description

The back yard of this property is supported by a 7 m high, chevron shaped, timber-crib retaining wall. The wall is stepped in two or three tiers with the upper 4 m high tier near-vertical. The area behind the wall is graded with pea gravel that has subsided, suggesting that the entire wall may have shifted downslope.

The covered sundeck at the rear of the house is set back 4.2 m from the top of the wall and shows several signs of distress. The deck posts rest on a shallow strip footing at grade with no burial. Building records show that this footing is tied back to the foundation wall along the west side of the house; however, the footing has tilted outwards considerably and the posts have been replaced with a series of 2x4 studs. The studs rest on the same strip footing causing significant settle along the west side of the deck.

Test Hole 06-15 was drilled 1 m west of the deck footing and found 0.5 m of fill overlying loose sand. The sand is underlain by loose silt at 3.3 m depth, while dense bearing (possibly till) was found at 5.0 m depth. The deck footing appears to lie along the original crest of the ravine and the entire yard to the west consists of fill.

The house is set back 7.2 m from the top of the wall or just 3 m from the original ravine crest. This structure steps down the slope and is 3 stories high with a crawlspace at the back. The foundation walls show no signs of settlement distress.

Slope Description

The timber crib wall is 7 m high and the lower part of the wall is partially buried by concrete and wood debris dumped over the edge and thick vegetation. The slope below the wall is 40° to 43° and forested with large cedar and fir trees. A small, arcuate, oversteepened feature is located 8 m upslope from the floodplain in the area southwest of the wall and may indicate an historic erosional failure. Based on the level of the geologic contact between the till deposit and the Capilano Sediments on the adjacent properties, this lower slope probably consists of till overlain by colluvium.

Slope movement was reported prior to the existing development in 1977 and was thought to be caused by fill on the slope. CNV granted a permit for a rock pit at the base of the slope so presumably there is a pipe buried beneath the retaining wall and the debris.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very High	High	Extreme

The timber cribs show no signs of significant decomposition but several of the cribs have displaced creating openings in the wall. Also, the subsidence immediately behind the wall suggests the entire wall may have shifted downslope. While some movement is natural to generate active earth pressures, the degree of movement in this case seems excessive, which questions the stability of this structure. The ties on the lower part of the wall appear to rest against standing mature timber (the rubble and vegetation on the slope hinders visibility). If so, the stability of the wall could also depend on the stability of these trees.

While failure may not be imminent, in the long-term there is a high probability of a global failure of the wall and upper slope. Blowdown of the trees apparently supporting the lower part of the wall may also trigger a failure. Such failures often extend at least 1 to 2 m into the native soil, creating a relatively large magnitude failure (i.e. greater than 500 m³ in volume). The sundeck would almost certainly be destroyed in the landslide and there is also a high probability of undermining a significant portion of the house, creating a very high partial risk. The degree of undermining could cause extensive damage that may not be repairable; therefore, the specific risk to the house is considered extreme.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

The performance of this timber-crib wall under design earthquake conditions is difficult to predict and depends on the number and condition of the tie-backs. Considering the movement that has occurred under static conditions and without a structural analysis confirming otherwise, it must be assumed that the wall will not withstand a large earthquake and, as such, the probability of a massive slope failure at this location is high under seismic conditions. Furthermore, the landslide scarp has a high probability of spatial interaction with the house and would probably cause extensive (if not irreparable) damage.

Mitigation/Remediation

Mitigation of the hazard will be very difficult and costly because of the limited equipment access. Regardless, the rubble and debris that has been dumped over the wall should be cleared, and the wall inspected by a structural engineer experienced with timber-crib structures to evaluate the integrity and stability of the structure under both static and seismic conditions. A time-frame should be given by the engineer when the structure should be replaced.

One option could be to replace the existing timber-crib wall with a GRS wall as described in Section 9.2 and shown on Figure 2. The sundeck should be dismantled before removing the wall because of the room needed for the excavation. The preferred approach would be to replace the wall in sections so that the foundation bearing support for the house is not seriously compromised. However, even sequential construction may not be sufficient to protect the stability of the house. The west side of the foundation may have to be underpinned as described in Section 9.1 before the wall is dismantled.

There is very little access to the back yard for equipment needed to excavate and backfill the slope. Much of the work will have to be done manually unless fences can be removed to allow a mini-excavator to access from the neighbouring property to the south. Regardless, a mini-excavator will have limited reach and the work will still be very challenging.

Access from the bottom of the slope is not possible without removing the standing timber, which includes several mature conifers. The same trees would also have to be removed if a buttress were to be constructed. Ultimately however, a buttress option may have to be considered if a GRS wall cannot be feasibly constructed without threatening the existing house. Either option should be able to reduce the probability of a landslide to moderate under static conditions. Reducing this probability to low requires further consideration during detailed design.

The drainage system for the roof and footing drains will have to be replaced as part of the slope stabilization work. A sump and cleanout should be included to allow the system to be inspected and cleaned out periodically.

7.17 2059 Westview Drive

Property Description

The entire property slopes towards the ravine from Westview Drive. The house is built on a 22° slope and is two stories at the front but steps down the slope with a full basement daylighting at the back. No cracks were visible in the foundation and no separations were found around the doors or windows, indicating that the house may not have suffered much settlement. Footings may be deeper than normal.

There is a sundeck at the rear and a concrete patio deck at basement grade. The sundeck leans to the west and the southern post has been shimmed 7.5 cm. The soil beneath the concrete patio has settled; the slab is now undermined and slopes

noticeably to the west. A 0.6 m high cobble and mortar wall on the north side of the house has two large cracks indicating slope movement.

Dynamic Cone Test DC-11 was conducted adjacent to one of the deck posts and found loose sand to 3.5 m, overlying compact soil. A large cedar tree next to the test hole indicates that the soils are native.

Slope Description

The entire property is on a slope. The house is built on the 22° slope that steepens to 28° below the sundeck and then 40° beginning 7 m west of the sundeck. The slope is forested with large conifers and no seepage was observed.

No till is exposed on the lower slope, but Dynamic Cone Test DC-12 conducted 13 m downslope of the sundeck found 2.4 m of loose sand and silt overlying dense material. The sudden refusal suggests that till is 2.4 m deep at this location and that the lower 5 to 8 m of the slope consists of till.

CNV granted a permit for a rock pit at the base of the slope so presumably there is a pipe buried beneath the slope. However, no sump was found at the back of the house.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

Although most of the lower slope probably consists of till, there is at least 2 m of loose sand and silt on the surface. At 40°, this lower slope is over-steepened and creates a high likelihood of failure. The probability of a slope failure increases if the stormwater connection to the bottom of the slope is broken and water discharges onto the slope.

At 22 to 28°, the upper slope by itself would have a low probability of a landslide but when combined with the lower slope and the thick deposit of loose sand and silt, the probability of a slope failure below the house propagating or retrogressing upslope to the house is high. The most likely scenario would be a landslide initiating 3 to 4 m downslope of the house and then retrogressing upslope.

The settlement of the deck footings is caused by shallow slope movement and is indicative of the marginal stability of the loose soils and the high vulnerability of the deck. Such movement is expected to continue and the probability of even a small, shallow failure damaging the sundeck is high. The house appears to have either deeper footings or a more rigid foundation able to withstand the movement to date. Although the foundation was inspected by a professional engineer (C.A. Boom letter to CNV July 20/77), there are no records of any special foundation

preparation. Therefore, the vulnerability of the house must be considered moderate, which results in a high specific risk.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

The design earthquake creates a high probability of a large landslide with a high probability of spatial interaction with the house, leading to a high partial risk to the house. The level of damage to the house will depend on the depth of the foundation, but it should be assumed that significant damage would result.

Mitigation/Remediation

To reduce the risk to the house to low, the lower slope should be buttressed below the slope break. The engineered slope would be approximately 30° and require approximately 1,000 m³ (bulked) of granular material placed and compacted in lifts. This option is discussed in Section 9.3 and shown on Figure 3. The buttress could be costly, difficult to construct, and would damage the natural vegetative condition of the slope.

Another option to stabilize the mid-slope area would be soil nailing (see Section 9.5). An access ramp would have to be constructed from the base of the slope with the objective of soil nailing the area between the top of the till deposit and the slope break below the house. Both options could reduce the probability of a landslide and the specific risk to the house to low (under static conditions).

A less costly option would be to reduce the vulnerability of the house by improving the foundation of the house. The sundeck should be removed and either cantilevered or founded on footings at least 2 m deep to reduce the potential impacts of the slope movement. The footings along the west side of the house should also be deepened to reduce the vulnerability. Footings at least 2 m deep should improve the factor of safety to a more suitable, minimum level of 1.3. The geotechnically accepted factor of safety of 1.5 (under static conditions) would require the foundation be supported on piles driven into the till.

The stormwater drainage system should be inspected and tested to ensure it is functioning and not discharging water onto the slope. The pipe should be repaired or replaced if necessary. A sump and clean-out should be added at the west side of the house so that the pipe can be inspected in the future.

7.18 2069 Westview Drive

Property Description

The house is built on a 22° slope that steepens immediately below the west edge of the house. The basement fully daylighted to the west and the concrete slab either cantilevers 1.2 m over the slope or has been severely undermined. No cracking was noted in the slab and C.A. Boom Engineering was involved in construction; however, the building records do not indicate that the slab has been designed to cantilever.

A strip footing at the back of the slab (i.e. 1.2 m from the west end of the slab) has no burial and bears directly on loose sand. Dynamic Cone Test DC-12 conducted adjacent to the northwest corner of this footing and found 3.2 m of loose sand and silt overlying compact soil. Large cedar trees adjacent to the house indicate that this slope is the original grade.

A small deck on the north side of the house, adjacent to the northwest corner, has settled and moved downslope. The posts rest on small pre-cast concrete footings bearing at grade without any burial and beyond the slope break. The northern post has settled approximately 10 cm while the southern post has shifted westward 5 to 7 cm.

A Big 'O' pipe emerges from the ground adjacent to the northwest corner of the house and discharges onto the upper slope causing minor erosion. The roof leader at the northwest corner has been disconnected and empties onto the upper slope as well. Farther downslope, a solid ABS pipe was found exposed at the surface and leading downslope. CNV granted a permit for a rock pit at the base of the slope so presumably this pipe leads to the base of the slope.

Slope Description

The 22° slope that the house is built on steepens to 37° at the western edge of the house and actually undermines the concrete deck slab. This slope flattens to 26° 6 m slope distance below the house and then steepens to 29° 10 m farther downslope. The total slope length is 24 m beginning at the west end of the house.

The slope is forested with coniferous trees and appears to be the original grade. No seepage was found and no signs of past landslides were noted.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate	High	Moderate	High

With slopes averaging 26° to 29° and no groundwater discharge, this has more favourable stability conditions than the surrounding areas. However, the 37°

upper slope directly below the west end of the house creates the potential for a small-scale slope hazard. The factor of safety in the stability analysis was less than 1.2, which rates as a moderate probability of a small landslide occurring 5 to 7 m wide by 2 m deep. The probability of a failure increases to high if stormwater is not adequately controlled.

Since the west strip footing has no burial and the house is already over-hanging the slope, the probability of spatial interaction with the house is high and the partial risk is high. Since the damage would probably be limited to the west edge of the house, which may have been designed to cantilever, the vulnerability is thought to be moderate. Damage to the house could be much greater if the west edge of the house was not designed to cantilever the slope.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	Moderate	High

The design earthquake increases the probability of a landslide to high. The probability of spatial interaction with the house, the partial risk, and the specific risk all remain high. Significant slope deformation and structural damage should be anticipated during a large earthquake.

Mitigation/Remediation

The roof, surface and footing drainage measures for the house should be completely reviewed and replaced where necessary. The Big ‘O’ pipe presumably collects the footing drains and probably does not carry much flow. Regardless, the pipe should be connected to the same solid pipe leading to the rock pit at the bottom of the slope. The disconnected roof leaders should be reconnected and the pipe leading down to the base of the slope should be tested or inspected to make sure it is functioning. A sump and cleanout should be installed near the top of the slope so the system can be regularly inspected.

Stabilizing the slope involves the same options as 2059 Westview Drive, and given the proximity of the two structures, the same option should be selected for both. To reduce the risk to the house to low, the entire slope below the house should be buttressed. This engineered slope should be no steeper than 30° and would require roughly 1,000 m³ (bulked) of granular material placed and compacted in lifts. The option is discussed in Section 9.3 and shown on Figure 3. The buttress may be costly and would damage vegetative condition of the slope.

The 37° slope directly below the house could be stabilized with soil nails (described in Section 9.5); however, equipment access to this part of the slope would be challenging.

A less costly option would be to improve the foundation of the house. The west strip footing should be underpinned to deepen the bearing at least 3 m to reduce the potential impacts of the slope movement and improve the factor of safety to a more suitable minimum level of 1.3. The geotechnically accepted factor of safety of 1.5 (under static conditions) would require that the foundation be supported on piles driven into the till. Underpinning would be challenging and may not be feasible without first removing the cantilevered slab for access.

Regardless of the slope mitigation method, if the room at the west side of the house has not been designed to cantilever, it should be removed immediately.

7.19 2101 Westview Drive

Property Description

The house is founded on a series of 45 cm diameter cylindrical columns. A small hand pit dug alongside one of the columns found bearing below 0.6 m depth. A Dynamic Cone Test (DC-7) near the northwest corner of the foundation noted mostly loose sand and silt to 2.6 m depth but with occasional compact seams. Compact to dense soil was found at 3.4 m depth; however, deeper test holes in the general vicinity, such as TH05-2, suggest that till is probably 6 to 10 m deep.

Cook Pickering & Doyle Ltd. (CP&D) conducted the geotechnical investigation and design for this project. Their investigation describes 1 to 1.2 m of fill on site and recommended that the footings bear below this depth. CP&D Test Pit 1 shows 0.9 m of fill over red, silty sand and gravel. Hard, brown clayey silt was found at 2.4 m depth, which agrees well with the compact soils found in DC-7 at 2.6 m.

A CNV internal memo (Dec 21, 1977) states that the CP&D recommendations for bank retention and the sloping of the bank adjacent to the east wall had not been implemented. A CNV letter to the mortgage lender (Jan. 16, 1978) indicates that the original developer, who went bankrupt, failed to meet many bank retention and drainage measures. The mortgage company was informed that they must hire an engineer to supervise this work.

CNV memos indicate that the developer failed to keep the structural designers informed of construction progress. There is no mention of the geotechnical engineers in these memos and it is assumed that they may not have been kept informed either. C.A. Boom Engineering informed CNV that they were taking over inspection of construction and remedial work (letter Jan. 31, 1978). The footings were reportedly approved in a letter to CNV dated February 7, 1978. C.A. Boom Engineering also inspected and approved drainage measures (letter to CNV March 15/78), retaining walls (letter to CNV April 14/78), erosion control measures and cross-bracing (letter to CNV May 15, 1978).

Although there are no signs that the foundations have settled, it would be difficult to discern settlement between independent piers. Several cross-braces have been added since construction, which could indicate settlement, slope movement

problems or structural problems. Regardless, the structural remediation indicates that the structure may not have performed adequately.

The sundeck was added after original construction. The deck posts rest on 20 cm diameter concrete piers located beyond the slope break and bearing at an unknown depth. The deck has transverse bracing (i.e. in the north-south direction) but no lateral or cross-bracing to resist slope movement. The posts have a significant lean but they may have been constructed at this angle.

An ABS drain pipe exits from the base of a concrete retaining wall on the east side of the house and disappears beneath the ground surface. The drain is broken, causing the water to flow over the ground surface beneath the house.

Slope Description

The upper slope is 42° for 6.5 m slope distance and exposes silty sand with some gravel. There are no trees along the crest and this upper slope appears to be over-steepened by fill pushed out during original construction.

The slope reduces to 35° beginning 6.5 m below the crest and the forest is predominantly coniferous. This appears to be the natural slope although the surface includes a thin veneer of silty sand fill that has washed down from above. No seepage or signs of past failures were found. Dynamic Cone Tests indicate that there is compact to dense soil approximately 3 m deep at the crest of the slope. Much of the slope probably consists of compact sand or silt overlain by an apron of silty sandy colluvium. The lower half of the slope probably consists of till also overlain by colluvium.

CNV approved the use of a rock pit at the base of the slope, so presumably a drain pipe runs down the entire length of the slope. No signs of this pipe were found on site.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

At 42° and comprised of fill, the upper slope is over-steepened and creates a high probability of a shallow landslide within the fill pushed out over the slope. With at least 3 m of loose sand beneath the footings and with the outer row of footings located along the edge of the slope, the potential landslide could extend beyond the surficial fill and into the loose sand. This larger magnitude hazard could be approximately 2 m deep, 10 m wide (or more) and extend back 2 to 3 m from the slope crest.

Such a landslide would destroy the sundeck and results in a high partial risk to the west column footings. Even if the footings are 1.2 m deep (as per CP&D's

recommendations) the west column footings would be undermined by such a failure. Structures founded on independent pad footings are typically less rigid than a reinforced concrete foundation wall; therefore, the vulnerability is considered high, which results in a very high specific risk. Potential structural damage could be severe.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

The design earthquake increases the probability of a landslide and the magnitude of the failure. The probability of a failure extending beneath the west footing line is high. Significant slope deformation and structural damage should be anticipated during a large earthquake.

Mitigation/Remediation

A structural analysis of the house and deck should be conducted to determine if the structural problems are caused by slope movement or inadequate design of the beams and cross-bracing. The actual depths of the outside footings should be determined and monitoring devices established to measure future slope movement.

Buttressing of the slope may not be viable because of the slope height and the location of the potential instability. Supporting only the lower slope would not improve the stability or the risk to the house. Instead, the buttress would have to cover the entire slope height, which may not be feasible.

If equipment could access the upper slope, the upper 8 to 10 m of the slope could be stabilized with soil nails (described in Section 9.5). However, access from the bottom of the ravine would require a filled ramp and a similar level of work as the buttress option. Both options could reduce the probability of a landslide to low and the specific risk to the house to moderate (under static conditions).

A more viable means to reduce the risk to the structure is to deepen the foundation and improve the lateral reinforcement to allow the structure to withstand the potential slope failure. Underpinning or deepening the footings along the western edge of the building to bear on till would improve the stability of the house or reduce the probability of damage to the house. The vulnerability of the house could be reduced to low and the specific risk to moderate (under static conditions). No test hole was drilled on this site due to its inaccessibility but the nearest test holes suggest till could be as shallow as 6 m or as deep as 10 m. Therefore, the foundations would have to be underpinned by drilling piles beneath each corner of each footing. Piles would also be needed for any additional columns or supports deemed necessary from the structural analysis. East-west oriented grade beams would be needed to provide lateral stability to the piles

against slope movement. With poor accessibility and height restrictions, only small equipment could be used. The piles would also require lateral support to resist slope movement such as reinforced concrete grade beams.

The sundeck should be removed. If replaced, the new deck should be founded on piles seated in the till and cross-braced to resist lateral slope movement. Alternatively, a smaller deck could be cantilevered.

The broken ABS drain pipe should be replaced. The drainage system should be tested to ensure that the pipe beneath the slope is not broken causing water to discharge into the slope. A sump and clean-out should be added near the crest of the slope so that the pipe can be inspected in the future.

7.20 2103 Westview Drive

Property Description

The house is very similar to 2101 Westview Drive and was constructed as part of the same development. The structure is founded on a series of 45 cm wide square columns. A small hand pit dug alongside the northwest column found the footing at 0.45 m depth bearing on loose sand. Dynamic Cone Test DC-8 adjacent to this northwest column found loose sand and silt to 2.9 m depth, overlying compact to dense soil. Dynamic Cone Test DC-7 near the southwest corner of the foundation found mostly loose sand and silt to 2.6 m depth with occasional compact seams. Compact to dense soil was found at 3.4 m depth and could be the till layer; however, deeper test holes in the general vicinity suggest that till is probably 6 to 10 m deep.

CP&D were the geotechnical engineers for this project and their investigation describes 1 to 1.2 m of fill on site and recommended that the footings bear below this depth. CP&D Test Pit 2 shows brown silt at 1.5 m and then dense grey fine sand at 2.4 m.

The shallow hand-dug test pit at the northwest corner of the structure proves that the footings are not as deep as CP&D recommended. CNV memos indicate that the developer failed to keep the structural designers informed of construction progress. There is no mention of the geotechnical engineers in these memos and it is presumed that they may not have been kept informed either.

A CNV internal memo (Dec 21, 1977) states that the CP&D recommendations for bank retention and the sloping of the bank adjacent to the east wall had not been implemented. A CNV letter to the mortgage lender (Jan. 16, 1978) indicates that the original developer, who went bankrupt, failed to meet many bank retention and drainage measures. The mortgage company was informed that they must hire an engineer to supervise this work.

CNV memos indicate that the developer failed to keep the structural designers informed of construction progress. There is no mention of the geotechnical engineers in these memos and it is assumed that they may not have been kept

informed either. C.A. Boom Engineering informed CNV that they were taking over inspection of construction and remedial work (letter Jan. 31, 1978). The footings were reportedly approved in a letter to CNV dated February 7, 1978. C.A. Boom Engineering also inspected and approved drainage measures (letter to CNV March 15/78), retaining walls (letter to CNV April 14/78), erosion control measures and cross-bracing (letter to CNV May 15, 1978).

There are many indications that the building has settled or moved laterally due to possible slope movement. Several new posts have been added and rest on pre-cast concrete footings bearing on the ground surface without any burial. These posts are not properly attached to the beams and several of the older footings have been shimmed. Separation between column footings and a concrete wall along the west foundation line indicates more than 15 mm of lateral movement.

The original sundeck was fairly small and cantilevered out using horizontal beams. The deck was subsequently enlarged and is supported by diagonal posts braced back to the vertical posts along the west foundation line. This added cantilever load could be causing some of the displacements noted in the foundations.

Slope Description

The upper slope is 45° for 7 m slope distance and exposes silty sand with some gravel. Construction debris, including some chain-link fencing, supports the upper slope and creates the over-steepened conditions. There are no conifers along the crest and an old alder was topped when the sundeck was expanded. This upper slope appears to be over-steepened by fill placed during original construction rather than natural conditions.

The slope reduces to 35° beginning 7 m below the crest and the trees in this area are predominantly coniferous. This appears to be the natural slope although the surface includes a thin veneer of silty sand fill that has washed down from above. No seepage or signs of past failures were found. Dynamic Cone Tests indicate that there is dense soil approximately 3 m deep at the crest of the slope. Much of the slope probably consists of dense sand or silt overlain by an apron of silty sandy colluvium. The lower half of the slope probably consists of till also overlain by colluvium.

CNV approved the use of a rock pit at the base of the slope. A sump box at the crest of the slope appears to collect the roof drains into a solid ABS pipe that is buried on the slope.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

At 45° and comprised of fill, the upper slope is over-steepened and creates a high probability of a shallow landslide within the fill pushed out over the slope. The potential landslide could extend beyond the surficial fill and into the loose sand, which is more than 2.5 m deep. This larger magnitude hazard could be approximately 2 m deep, 10 m wide or more, and extend back 2 to 3 m from the slope crest.

Such a landslide creates a high partial risk to the western footings, which were not constructed as deep as CP&D recommended. Structures founded on independent pad footings are typically less rigid than a reinforced concrete foundation wall; therefore, the vulnerability is considered high resulting in a very high specific risk. Potential structural damage could be severe.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

The design earthquake increases the probability of a landslide and the magnitude of the failure. The probability of a failure undermining the west side of the foundations is high. Significant slope deformation and structural damage should be anticipated during a large earthquake.

Mitigation/Remediation

A structural analysis of the house should be conducted to determine if the structural problems are caused by slope movement or inadequate design of the beams and cross-bracing. The numerous posts and footings that have been added since original construction should be upgraded to meet the building code requirements and the footings buried at least 0.6 m (or preferably to the firm bearing layer at 1.2 m depth identified by CP&D). Monitoring devices should be established to measure future slope movement.

Buttressing of the slope may not be viable because of the slope height and the location of the potential instability. Supporting only the lower slope would not improve the stability or the risk to the house. Instead, the buttress would have to cover the entire slope height, which may not be feasible.

If equipment could access the upper slope, the upper 8 to 10 m of the slope could be stabilized with soil nails (described in Section 9.5). However, access from the bottom of the ravine would require a filled ramp and a similar level of work as the buttress option. Both options could reduce the probability of a landslide to low and the specific risk to the house to moderate (under static conditions).

A more viable means to reduce the risk to the structure is to deepen the foundation and improve the lateral reinforcement to allow the structure to withstand the potential slope failure. Underpinning or deepening the footings

along the western edge of the building to bear on till would improve the stability of the house or reduce the probability of damage to the house. The vulnerability of the house could be reduced to low and the specific risk to moderate (under static conditions). No test hole was drilled on this site due to its inaccessibility but the nearest test holes suggest till could be as shallow as 6 m or as deep as 10 m. Therefore, the foundations would have to be underpinned by drilling piles beneath each corner of each footing. Piles would also be needed for any additional columns or supports deemed necessary from the structural analysis. East-west oriented grade beams would be needed to provide lateral stability to the piles against slope movement. With poor accessibility and height restrictions, only small equipment could be used. The piles would also require lateral support to resist slope movement such as reinforced concrete grade beams.

The drainage system should be inspected or tested to ensure that the pipe on the slope is not broken causing water to discharge onto the slope. A sump and clean-out should be added near the crest of the slope so that the pipe can be inspected in the future.

7.21 2117 Westview Drive

Property Description

The house is built on the upper slope and set back approximately 25 m from the ravine crest. The house is three-stories at the back with a two-storey sundeck. The middle post supporting the two decks has visibly settled causing the deck to sag in the middle. The upper deck is also visibly separating from the house.

The property slopes at 30° below the house for approximately 8 m and is supported by a cast-in-place, reinforced concrete retaining wall 2 m high. The wall is covered with brambles but appears to be in good condition.

A flat bench on the west (downslope) side of the retaining wall is 12 m wide and was reportedly once a tennis court. The ground has an old asphalt pavement surface. A sump or clean-out exists adjacent to the north end of the wall and probably collects the roof leaders from the house above.

Slope Description

The upper slope of the ravine is 48° for 7 m and supported by construction debris, including some chain-link fencing. There are no conifers along the crest and the area appears to have been pushed out to create the level area apparently once used for the tennis court. Dynamic Cone Test DC-9 was conducted 1.5 m back from the crest of the slope and found 1.7 m of loose to very loose soil overlying dense material.

The slope reduces to 35° beginning 7 m below the crest and the forest is predominantly coniferous. This appears to be the natural slope although the surface includes a veneer of silty sand fill that has washed down from above. No seepage or signs of past failures were found. Much of the slope probably consists

of dense sand or silt overlain by an apron of silty sandy colluvium. The lower half of the slope probably consists of till also overlain by colluvium.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

At 48° and comprised of fill, the upper slope is over-steepened and creates a high probability of a shallow landslide within the fill pushed out over the slope. The potential landslide could extend beyond the surficial fill and into the loose sand, which is 1.7 m deep. This larger magnitude hazard could be approximately 2 m deep, 10 m wide (or more) and extend back 2 to 3 m from the slope crest.

The probability of a larger landslide capable of impacting on the retaining wall 12 m back from the slope is low. The slope above the retaining wall is 30° with a low probability of failure; therefore, as long as this retaining wall remains stable, the probability of a slope failure directly impacting on the house is low. The structural stability of the retaining wall is beyond the scope of this assessment.

Movement of the sundeck could be caused by settlement in the sloping fill behind the concrete retaining wall. However, considering that the middle sundeck post has settled more than the other two, the settlement is more likely caused by decomposition of the post. The top of the concrete pad footing is not visible and the wooden post extends below the ground surface. Moisture in the ground is probably causing the post to decay, resulting in the settlement. Regardless, this is not a slope hazard.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Although the slope becomes more unstable under design earthquake conditions, the probability of spatial interaction with the house remains very low. The seismic stability of the reinforced concrete wall below the house is a structural matter and beyond the scope of this assessment. However, if the wall moves significantly or fails, the house could be severely damaged. Also, if the sloping backfill behind the wall was not properly compacted during construction, excessive ground deformation could damage the house.

Mitigation/Remediation

The owners should replace the middle sundeck post and should ensure the other wooden posts do not extend below the ground surface.

A structural assessment of the retaining wall below the house is recommended. The study should also include testing the density of the backfill behind the wall to evaluate the seismic stability of the wall.

7.22 2121 Westview Drive

Property Description

The house is two stories with a partial basement and sits on a 22° slope, set back more than 30 m from the crest of the steep ravine slope. This upper slope is landscaped to form several benches. Test Hole 06-19 was drilled on this slope and found 0.45 to 1.0 m of loose sand fill overlying loose, native sand. Compact silt was found at 2.1 m depth and dense soil (possibly till) was found at 6 m depth. The fill appears to be the same as the natural soil and was probably from the original house excavation.

Slope Description

The upper slope directly below the house is 22° for 34 m and then steepens to 38° into the ravine. The ravine slope appears to be natural and is forested with conifers and large maple trees. The lower slope was not assessed in detail because of the considerable house set back.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

The upper slope directly below the house has a low probability of landslide occurrence. The lower slope has a high probability of landslide occurrence, but the probability of a slide impacting on the house is very low. Therefore, the greatest landslide risk is created by the upper slope where both the partial risk and specific risk are low.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Low	Moderate	Low

Although the ravine slope becomes more unstable under design earthquake conditions, the probability of spatial interaction with the house remains very low. The greater risk is created by the upper slope. At 22°, this upper slope has a low probability of failure during an earthquake and a low partial risk.

Mitigation/Remediation

No mitigative work is recommended at this stage.

7.23 625 West 22nd Street

Property Description

The house was constructed during 2006 and Fieber Rock Engineering Services (Fieber) were retained as the geotechnical engineer. The foundation was excavated about 1.5 m below the ground surface at the west edge and bears on compact sand and sandy silt. The house is set back only 3 m from the crest of the slope while the driveway is supported by a 4 m high concrete retaining wall located 2 m from the slope crest.

A rock pit was reportedly constructed near the crest of the slope and was approved by Fieber (April 6, 2006). A sump in the back yard is located close to the crest of the slope with a discharge pipe heading westward towards the slope. No disturbance was found on the slope, so presumably the rock pit is located on the level ground near the crest.

Slope Description

A short boulder-stack wall lines the crest of the slope adjacent to the house. The upper slope varies from 30° to 35° but is only 7 m long and leads onto a 19 m wide bench sloping at 15° to 20°. This upper slope is naturally forested with conifers and large deciduous trees and appears to be well drained. Overall, this upper slope is less steep than the adjacent slope to the south and shows no signs of past failures.

The lower slope is steeper, ranging between 40° and 49° and an extensive exposure of very dense till was found near the slope break, indicating that the steeper terrain is probably entirely till overlain by colluvium.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Low	Low	Low	Very Low

The upper slope is less steep than most of the ravine due to a wide bench on top of the till deposit. The probability of a landslide occurring in the upper Capilano sediments on this bench is low. Also, if a landslide occurs on the upper slope, it would probably be fairly small because of the limited slope height and extend less than 2 m back from the crest. The house is set back approximately 3 m, creating a moderate probability of spatial interaction and a low partial risk. This development was constructed under the guidance of a geotechnical engineer who had the foundations deepened to approximately 1.5 m. The deepened footings

and more rigid foundation reduce the probability of a landslide undermining the foundations and results in a low vulnerability and a very low specific risk to the house.

The most likely cause of a slope failure on this property will be from the discharge of collected stormwater. Placement of a rock pit at the crest of the gully slope is not recommended. The surficial sand overlies silt and then clay; therefore, the infiltrating water will flow laterally along the silt and clay layer and discharge on the slope. Piping in the silt or a small slump in the clay is possible. If left unchecked, the potential instability could grow and retrogress to the point where it could impact on the house.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate	Moderate	Low	Low

Under design earthquake conditions, the probability of a landslide increases to moderate with a moderate probability of spatial interaction with the house and a moderate partial risk. The slope may experience significant ground deformation with some impact on the house; however, the 1.5 m high reinforced concrete foundation walls improve the rigidity of the foundation and reduce the vulnerability, resulting in a low specific risk.

Mitigation/Remediation

The rock pit or roof water infiltration pit should be relocated to the bottom of the ravine slope. Or as a minimum, the stormwater drainage should be carefully monitored and the slope inspected regularly during the winter to ensure problems do not develop. If a seepage zone is observed downslope of the rock pit, the rock pit should be relocated.

7.24 626 West 22nd Street

Property Description

The house is constructed on steel pipe piles filled with concrete. The piles were designed and inspected by Robinson Dames & Moore (geotechnical engineers) and J. Novacek & Associates Ltd. (structural engineers). The pile lengths range from 5 m on the west edge of the building to 11.5 m along the east edge. All piles were reportedly driven to bear on very dense till except for one timber pile supporting the driveway. Reports indicate that this pile created high vibrations during driving and was seated in the overlying sand or silt, reducing the load capacity of the suspended driveway slab.

The piles are arranged in three rows with lateral support provided by concrete grade beams oriented east-west. The sundeck is cantilevered and braced back to

the piled foundation. The ground beneath the house is bare with several old stumps indicating original ground elevations.

The house is situated on the slope, which has an average angle of 23°. The slope crest follows the east property boundary and the uppermost few metres slope at 40°. There is a partial timber retaining wall supporting part of this uppermost slope but it is in poor condition and the slope is raveling.

The house was inspected by Golder Associates Ltd. (Golder) in 1992. They noted that the house had not suffered any distress but recommended that the bare ground beneath house be covered for erosion control (report May 19/92).

Slope Description

As described above, the house is situated on a 23° slope. The slope steepens to 30° about 5 m below the west side of the foundation and to more than 40° about 15 m below the house. This steepened slope appears to consist of till and the slope break is at roughly the same elevation as the pile tips, which are reportedly bearing on till.

CNV granted permission for a rock pit at the bottom of the slope. Presumably, the roof leaders are collected into a solid pipe buried beneath the slope. This has not been confirmed.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Low	Moderate	Low	Low

Since the lower slope consists of very dense till, the slope hazard is predominantly limited to the upper half of the slope. With an overall slope angle of less than 30°, the probability of a large landslide is low.

If a landslide does occur, the probability of spatial interaction with the house foundation is high since the house is located on the slope, resulting in a moderate partial risk to the house. The piles are driven to bear on till; therefore, the vulnerability is low and the specific risk is also low. Bearing support should not be affected and the house should not be impacted by settlement. The main concern would be the lateral loads on the piles created by the slope movement. The grade beams connecting the piles are presumably designed to provide this lateral support.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate	Moderate	Low	Low

Under design earthquake conditions, the probability of a landslide increases to moderate with a high probability of spatial interaction with the house (i.e. the ground beneath the house will likely move). This creates a moderate partial risk. The ability of the piled foundation to withstand this movement depends on the structural design and particularly the strength of the concrete grade beams providing lateral support to the piles. The vulnerability of the piled foundation is assumed to be low under seismic conditions because of the grade beams, resulting in a low specific risk. A lateral pile analysis would be required to fully assess the behaviour of the piled foundation during an earthquake, but is beyond the scope of this assessment.

Mitigation/Remediation

Golder's recommendation to cover the bare ground beneath the house for erosion control should still be implemented. Golder recommended shotcrete or a thin layer of concrete, but a hard surface like concrete can concentrate surface water onto the slope below. There are better erosion control products available that should accomplish similar benefits at less cost. A permanent erosion control mat such as North American Green P300 would be adequate but can be damaged by both human and animal traffic. Since the area beneath the house is fully accessible and used for storage, a cellular confinement system, such as *Geo-Cell* supplied by Nilex or *Geoweb* supplied by Armtex, is recommended. These cellular membranes are filled with granular soil to reinforce the surface and provide erosion control while allowing natural moisture infiltration.

The old timber retaining wall along the east side of the house should be removed and the over-steepened slope should be retained by a short GRS wall (see Section 9.2).

7.25 622 West 22nd Street

Property Description

This older house is located to the east (upslope) and north of the pile-supported house. The basement daylights on the west side of the house and is set back 2.4 m from the fence and 4.0 m from the crest of the slope. There is a small crack in the foundation wall but no other cracks were reported in the stucco or interior plaster. The patio stones are relatively old but do not show any signs of settlement.

A cobble and mortar retaining wall in the back yard has one crack with 10 mm of horizontal displacement in the east-west direction, which could be caused by minor slope movement. Such movement is normal, considering the proximity to the slope.

The front yard is relatively level and located directly east of the pile-supported house. An old timber-crib retaining wall along the west property line has decayed causing the slope to ravel but with no potential impact on the house.

Test Hole 06-18 was drilled in the patio along the west side of the house and found 0.75 m of loose sand fill overlying native loose sand (delineated only by the original topsoil layer). Compact silty sand and sandy silt were found at 1.2 m depth. Samples were only collected to 4 m depth but a DCPT found compact soils overlying dense till at 11.8 m depth.

Although CNV records are unclear, the roof and footing drains probably drain to a rock pit at the base of the slope. This was not able to be confirmed.

Slope Description

The house is located at the crest of the same slope as the house at 626 West 22nd Street. The slope is 30° near the crest, flattening to between 22° and 25° directly north of this adjacent house. The slope is forested with mixed conifers and deciduous trees and a thick understory.

The slope steepens to 40° near the base of the slope with exposures of very dense till. Seepage discharges from the slope at this slope break. The elevation of this till exposure and slope break agrees closely with the depth of till in Test Hole 06-18.

The slope was assessed by Robinson Dames & Moore as part of the development at 626 West 22nd Street (report Apr. 27, 1984). The study found that fill was pushed out over slope crest but “no evidence of large-scale instability was observed.”

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Low	Low	Moderate	Low

With very dense till on the lower slope and the middle and upper slope generally no steeper than 25°, the probability of a significant landslide occurring at this location is low and, with 4 m setback from the crest, the partial risk to the house is also low. The structure has moderate vulnerability (damage to the house should be reparable), resulting in a low specific risk. The sundeck is closer to the crest of the slope and could be more easily damaged by slope movement.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate	Moderate	Moderate	Moderate

Under design earthquake conditions, the probability of a landslide increases to moderate. An earthquake-induced landslide could extend at least 2 m back from

the slope crest, creating a moderate partial risk to the house. With moderate vulnerability, the result is a moderate specific risk.

Mitigation/Remediation

The stormwater connection to the rockpit should be investigated and replaced if necessary. If the roof and footing drains do not lead to a rock pit at the base of the slope (or the system is not found to be functioning properly), either a connection should be made to the municipal system or to a new infiltration chamber at the base of the slope. A sump and clean-out should be added near the crest of the slope so that the pipe can be inspected in the future.

The retaining wall along the west side of the front yard needs to be replaced as discussed for 626 West 22nd Street. This issue mostly affects the neighbouring property to the west.

7.26 625 West 23rd Street

Property Description

This two-storey house is built on a relatively level grade and is set back 6.5 m to the northeast from the crest of the ravine where a large landslide occurred in 2004. The back yard is level and west fence line follows the headscarp of the landslide. The owner reports no damages inside the house and no significant cracks were noted in the foundation walls. The sidewalk around the southeast side of the house was built in 2006; therefore, it would not be expected to reflect any movement. The only sign of movement within the fenced yard is 5 to 10 cm of subsidence up to 2 m from the headscarp.

Test Hole 06-17 was drilled within the subsidence zone between the house and the crest of the slope to determine if this part of the failure scarp had been backfilled. The test hole found 0.75 m of fill comprised of topsoil mixed with sand, overlying native compact sand, indicating that the grade between the house and the slope is mostly natural.

Test Hole 06-16 was drilled farther south close to the crest of the slope. The test hole found loose sand becoming compact at 2.9 m depth and overlying compact sandy silt and silty fine sand at 4.1 m depth. The DCPT found very dense soil (probably till) at 6.8 m depth.

A small garden shed built near the end of West 23rd Street is located at the very crest of the slope and is slightly undermined.

Slope Description

The slope was severely impacted by a large landslide that occurred on March 6, 2004. The landslide was triggered when a watermain ruptured along Westview Drive near West 23rd Street. The water flowed westward along West 23rd Street and then southward across this property's driveway and over the bank. The

landslide was assessed by Kerr Wood Leidal (report March 12, 2004) who concluded that the event had caused the house set back to decrease from approximately 7.5 m to 5.5 m at the nearest point.

The design stabilization measures included buttressing the slope with engineered fill reinforced with geogrid. The design drawing shows several drain pipes installed through the engineered fill to the surface of the natural slope. There is also a series of “Geo-ridge sediment control devices” installed down the middle of the fill area and several willow-wattle contour drains.

The design shows a slope of 1.7H: 1V or 30° but the measured slope angle is 37°. Other differences between the design and observed conditions include fewer drain pipes extending from the fill and only one visible geogrid layer (although the others may simply be buried). The slope is vegetated with mostly grasses and brambles such as blackberry and only a few small trees. The willow-wattles have been in place for more than 2 years and have not sprouted.

The base of the fill is designed to be supported by a “vegetated geogrid and stacked rock toe.” The field assessment found boulders sloping at 25°, but no geogrid (again, the geogrid may be entirely buried). Significant seepage was noted discharging from this slope break. The elevation of the slope break is quite close to the elevation where Test Hole 06-16 encountered very dense till, indicating that the landslide occurred entirely within the Capilano Sediments above the till layer, as would be expected. The groundwater seepage is occurring within the sandy silt layers directly overlying the till.

Below the boulder armouring, the slope steepens again to about 30° but is more natural and forested. This lower slope does not appear to have been involved in this landslide.

The slope below the west end of West 23rd Street is less steep because a large diameter water pipe is buried beneath the right-of-way. The backfilled area creates a slope of 30° to 31°. The natural slope immediately south and below the garden shed is steeper and ranges between 31 and 33° with some over-steepening at the crest. This slope is mostly forested with conifers and shows no signs of past failures.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Low	Low	Moderate	Low

Although the landslide was stabilized, the upper slope is still very steep and does not have any trees or large shrubs to provide root support. Without adequate root support, the loose sand surface has a high probability of erosion despite the drainage measures. Shallow erosion or surface raveling was evident on site.

The probability of a landslide depends largely on the geogrid reinforcement: how many layers were actually installed, the type of geogrid and the length into the slope. With inadequate geogrid reinforcement, the probability of a landslide could be moderate (i.e. factor of safety less than 1.3) or even high. If the geogrid was installed in accordance with the design, the probability of a landslide should be low (factor of safety 1.4). The design objective for slope stabilization measures is usually a minimum factor of safety of 1.5, which could have been achieved if the actual slope was 30°, as per the design.

The 2004 landslide was triggered by a broken watermain, and the volume of water involved undoubtedly affected the magnitude of the failure. A natural landslide on this slope should be smaller, probably in the range of 10 m wide and 2 to 3 m deep. The scarp would probably follow the 2004 landslide scarp or perhaps extend 1 to 2 m farther back. With the nearest corner of the house 6.5 m back, the probability of a failure directly impacting on the house is low, although if left destabilized for any period of time, the landslide could retrogress and partially damage the house. The house is located immediately behind a 2H: 1V line projected up from the armoured toe, which is often considered the minimum setback for such slopes.

The slope at the end of West 23rd Street is 30 to 31° and has a low probability of failure. However, the slope below the garden shed has a moderate probability of a small landslide and even a minor slump could cause the garden shed to slide down the ravine slope.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
Moderate	Moderate	Moderate	Moderate

Under design earthquake conditions, the probability of a landslide is at least moderate and could be higher if the installed geogrid does not match the design. Earthquake-induced landslides can be larger than statically-induced slides; therefore, the probability of a slide directly impacting on the house also increases to moderate, resulting in a moderate specific risk.

Mitigation/Remediation

Since Kerr Wood Leidal designed and inspected the slope stabilization work, they should review the as-built conditions and confirm if the geogrid reinforcement is sufficient for a minimum factor of safety of 1.5. As a minimum, their construction records should be reviewed and proper as-built drawings prepared for the CNV's records.

The garden shed should be moved away from the slope crest.

7.27 632 West 23rd Street

Property Description

The house is two stories with the lower level daylighting along the crest of the ravine. Most of the house footings are 3 to 4 m from the slope crest but the closest footing is 2 m from the slope crest and the sundeck post footings are within 1.5 m. No significant cracks were noted in the foundation walls but most of the foundation walls were not visible.

A mature fir tree adjacent to the sundeck appears to be partially buried, indicating that the edge of the slope has been filled. Repeated attempts to conduct a Dynamic Cone Test (DC-5) along the crest of the slope encountered refusal near 1.5 m depth. Refusal probably occurred on tree roots suggesting that the fill is 1 to 1.5 m thick. The overlying soils are loose to very loose.

The concrete sidewalk leans out towards the slope but is not badly cracked. Some minor separations and vertical off-sets were noted at the sidewalk joints indicating small-scale slope movement but nothing significant.

There are no records of a rock pit on this property or of a connection to the municipal storm main.

Slope Description

The property has slopes to the west and south. The slope below the south side of the house faces the water main right-of-way and gradually increases in height from east to west. This slope is 40° and forested. The understorey is very thick and visibility was very limited; however, no signs of movement or past failures were observed.

The west slope is higher and a greater concern. The upper slope is uniform 39° and appears to have been filled. The surface of the slope is covered with polyethylene sheets and snow-fencing, possibly for erosion control. Dynamic Cone Test DC-5 indicates the surficial soils are loose to very loose.

The slope flattens slightly to 37° 10 m below the crest and groundwater discharge was observed at this point. Surface exposures consist of some surficial gravelly sand, silt and clay. Another Dynamic Cone Test (DC-6) at this location found 4 m of very loose to loose soil and did not encounter till. The seepage is probably occurring along the contact between the silty sand/sandy silt and the underlying silt and clay, so most of this slope probably consists of silt and clay.

The slope flattens to 25° approximately 20 m below the crest and this lower slope receives significant groundwater discharge. The flattened slope is caused by landslide debris or colluvium that has deposited from above. Based on the test holes to the south of this property, the underlying slope probably consists of till at this elevation but is covered by the landslide debris.

Landslide Hazard & Risks

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	Very High	Moderate	Very High

A small landslide (30 m wide by 20 m high by 0.5 m thick) occurred in December 1999 and was assessed by EBA Engineering (EBA report May 2/00). The landslide reportedly occurred in native sands and silts due to excessive groundwater discharge. The GVRD pipe was not considered a possible cause but was found to be at risk from future landslides (i.e. within the deposition zone). The house was deemed not to be in immediate danger but lacked sufficient setback for long-term stability. The only recommendation was to consider surficial stabilization measures such as “biotechnical and more conventional soil engineering methods”.

The location of this landslide was not described in EBA’s report and was not readily apparent on the slope because most of the slope has been heavily disturbed by past slumps and fill placement. The stabilization work referred to in EBA’s report was not found on site except for perhaps the snow-fencing and polyethylene sheeting placed over the upper slope, which provides only minimal erosion control. If the landslide occurred here, the house should certainly have been considered at risk.

Regardless, with most of the slope 37° or steeper and with significant groundwater discharge at mid-slope and signs of fill placement over the slope, the probability of a landslide is high. Since most of the house is set back only 2 to 3 m from the crest, the probability of spatial interaction with the house is also high, resulting in a very high partial risk. The house foundation is built into the slope; therefore, the vulnerability is moderate. Any landslide reaching the slope crest would likely destroy the sundeck and possibly undermine the outside footings. Damage would probably be very costly but repairable.

Seismic Slope Hazard

<u>Probability of a Landslide</u>	<u>Partial Risk to House</u>	<u>Vulnerability of House</u>	<u>Specific Risk to House</u>
High	High	High	Very High

The landslide risks increase under design earthquake conditions. The probability of a landslide occurring under seismic conditions is high and the slide would probably have a direct impact on the house. The potential magnitude of the failure increases as well, thereby increasing the potential damage to the house. The result is a high probability that the house could be destroyed or damage could be irreparable during a large earthquake.

Mitigation/Remediation

Mitigating the landslide hazard on a slope that is steep, with poor access, and a house very near the crest is difficult and costly. Underpinning of the foundation would be costly because bearing would have to reach the till layer 10 to 13 m deep. Drilled piles along the outside of the footings would be the only option but equipment access would allow only portable equipment across the south and west sides of the house. The piles would not reduce the probability of a landslide but merely the potential for damage to the structure. The piles would require sufficient internal reinforcement and thick grade beams to withstand the significant lateral loads that would be placed on the piles during a landslide. A structural analysis would be required to determine if suitable lateral stability is feasible.

Another alternative would be to buttress the slope. Working from the bottom of the slope, all loose colluvium and landslide debris would have to be removed from the lower slope and then the area filled with open-graded rock fill and armoured with boulders because of the groundwater discharge. A 2H: 1V (or 27°) slope covering the lower 2/3rds of the slope with a 3 m wide bench at the top of the buttress (see Section 9.3) would improve the factor of safety to 1.3 (reducing the partial and specific risks to the house to moderate under static conditions). A factor of safety of 1.5 would require a buttress over the entire slope with an even flatter slope angle.

A combination of a buttress over the lower 2/3rds of the slope, soil nailing (see Section 9.5) of the upper slope and installation of subhorizontal drains (see Section 9.4) within the groundwater discharge zone could be as effective as a buttress over the full slope. This combination of options is shown conceptually on Figure 6.

A cost benefit analysis should be undertaken for all options. A final option is to avoid the hazard by removing the old house and building a new house near the northeast corner of the property using appropriate set backs. A minimum 10 m set back is recommended unless other specific measures are taken to reduce the landslide risk.

Until such measures are taken, the owners should be made aware of the hazards and risks. The slope conditions should be monitored throughout each winter to provide advanced notice of a failure, where possible. However, advanced notice is not always possible since failures can develop rapidly. The decision to occupy this house must be made with full knowledge of the risks.

8.0 LANDSLIDE RISK MITIGATION

The different approaches to mitigate the landslide risk can be grouped as follows:

- i. Measures to reduce the hazard or probability of a landslide occurring;
- ii. Measures to reduce the probability of spatial impact with the structure;
- iii. Measures to reduce the vulnerability of the structure.

Which approach is most appropriate depends on the individual circumstances and will vary for each property.

8.1 Measures to Reduce the Hazard

Measures to reduce the probability of a landslide occurring mainly curtail or control the specific landslide triggers, and include:

- i. Flattening of the slope angle by either pulling back over-steepened sections or placing a fill buttress on the lower slope (see Section 9.3).
- ii. Reinforcing the slope using GRS walls (see Section 9.2) or soil nailing (see Section 9.5).
- iii. Improving subsurface drainage to lower the groundwater table near the slope (see Section 9.4).
- iv. Controlling stormwater, including roof water, in infiltration chambers at the bottom of the slope or into the storm main and ensuring connections are sound.
- v. Avoiding or removing in-ground sprinkler systems within 30 m of the slope crest.
- vi. Avoiding or removing ponds within 30 m of the slope.
- vii. Avoiding or removing fill placed on the slope or within 3 m of the slope unless the slope is specifically assessed by a geotechnical engineer and the fill is designed so as not to impact on the natural slope stability.
- viii. Ensuring all retaining walls (including landscape walls) within 3 m of the slope crest are designed by a geotechnical engineer.
- ix. Removing household garbage, metal and wood debris, found on the slope.
- x. Removing yard waste and fill from the slope wherever it is suppressing the natural vegetation.
- xi. Preparing and implementing a landscape plan using natural species with strong root networks.

8.2 Measures to Reduce Probability of Spatial Interaction

Reducing the probability of spatial interaction essentially means avoiding the hazard. For new developments, structures should be sited beyond the estimated reach of the landslide. All new structures should have a minimum factor of safety of 1.5 against interaction with a slope failure. For Mosquito Creek, this setback depends on the slope angle and the thickness of the Capilano Sediments in the area of the development. Each site should be specifically assessed by a professional engineer or geoscientist. For planning purposes, the minimum

setback should default to 10 m from the crest of the ravine unless specific measures are designed to mitigate the risk.

For existing structures, the options are limited except for moving the structure farther from the slope. This may be a viable option for the sewer main but would be costly for an existing house. With the rapid increase in property values, some of the properties with older homes may be planned for redevelopment, at which time siting of the new structure becomes critical.

8.3 Measures to Reduce Vulnerability

For most houses, reducing vulnerability means improving the rigidity of the foundation and underpinning the footings. Underpinning is discussed in detail in Section 9.1.

9.0 CONCEPTUAL DESIGNS

The following sections describe mitigative methods that have been suggested for several properties in Section 7. Typical cross-sections are included illustrating how these methods would improve slope stability or reduce the risk to the structure. While the cross-sections may apply to a specific property, they are conceptual only and require further detailed design work. The design of any mitigative options must be conducted by a professional engineer and will depend on the specific objectives and site conditions.

9.1 Underpinning of Footings

Underpinning involves extending the footing to a greater depth on a suitable bearing layer. The main advantage of underpinning occurs when the foundation is located close to or even on a slope subject to shallow or thin failures. The foundation can be stabilized by bearing on denser, more stable soils such as till. Deeper foundations are also less susceptible to damage caused by slow, shallow slope movement such as creep that normally occurs on most steep slopes.

To underpin a strip footing, a structural engineer must first determine how far the footing load can bridge, which depends on the height of the foundation wall and the amount of steel reinforcement. Underpinning proceeds in sequences by excavating beneath the footing in sections. Each section of excavation is blind formed, reinforced, and poured with high-early strength concrete to set quickly. The adjacent section is not excavated until the concrete from the first section reaches sufficient strength. More than one underpin panel may be prepared at one time as long as they are not adjacent to one another.

To underpin a pad or column footing, the load on the column must first be supported on temporary footings to either or both sides. Small posts can simply be removed and replaced with deeper footings while larger columns must be underpinned in segments similar to a strip footing.

Another option for underpinning is to drill small diameter piles, micro-piles, or pin piles down to bear on the very dense till. These piles can be drilled alongside the existing footings and then tied into the footing with dowels and a reinforced grade beam. The pile spacing and diameter depends on the load on the walls and the distance the walls can span and would have to be designed by a structural engineer.

When a landslide impacts on a structure underpinned by piles, the lateral load exerted on these piles by the earth movement can be significant. The pile tip will be seated in till or other stable material but the top of the piles must also be restrained laterally by grade beams. A lateral pile analysis is required as part of the structural pile design.

Underpinning does not reduce the probability of a landslide occurring but reduces the potential impacts on the structure, as illustrated in Figure 1.

9.2 Retaining Walls

The preferred type of retaining wall for this slope is a Geosynthetic Reinforced Slope (GRS) wall. A GRS wall is constructed using geogrid or high-strength geotextile reinforcement placed in horizontal layers. The geosynthetic acts not as tie-backs but as soil reinforcement such that the entire reinforced mass serves as a gravity wall.

Although the reinforcement can be left bare, some type of facing is preferred to help form the front face during construction and for esthetics. The wall can have a wire-mesh facing similar to a gabion, or a concrete block facing. While Lock-blocks were initially used for facing, they are too large and heavy for most of these lots. Since many of the walls will have to be constructed by hand or with very small equipment, either wire-mesh or small concrete blocks are recommended for facing, depending on the purpose.

The wire-mesh facing is typically just to create the face. The slope stabilization is created by the geogrid or high-strength geotextile while the facing is almost sacrificial. The wire-mesh facing is best suited where the face will be planted to create a natural look. The facing is either sloped back at a specified angle or stepped back. The advantage of stepping the wall facing is that shrubs can be planted on the steps to create a "green" wall.

Many different small concrete blocks now exist on the market, such as Allan Blocks or Keystone Blocks. The principles are similar and, like the wire-mesh facing, the reinforcement is created by the geogrid or high-strength geotextile.

The main benefit of GRS walls over more traditional masonry, reinforced concrete, and rock and mortar walls is the ability for the GRS wall to accommodate slope movement or settlement. The soil near the slope surface often creeps or moves without failing. Such movement will easily cause cracking in rock and mortar walls and even reinforced concrete walls if there is inadequate steel reinforcement. The

layers of geogrid help bridge the movement so that even if the block facings shift or move, the reinforced earth behind the facing remains stable.

Another benefit of GRS walls is the cost. Such walls are considerably less expensive to build than reinforced concrete, and are easier and faster to build than rock and mortar walls.

Conceptual designs for GRS walls in a couple of different situations are shown on Figure 2. These are conceptual designs only. The actual designs will depend on site conditions and each wall must be individually engineered.

9.3 Slope Buttressing

Slope buttressing improves the slope stability by reducing the slope angle and adding mass to the toe of the potential landslide to resist movement. The key to this method is to ensure that the fill supports the toe of the landslide and that the buttress is thick enough to be effective. Within Mosquito Creek, the lower slope consists of very dense till that has been prone to erosion from the creek, but since the creek channel has been stabilized, landslides within the till are fairly rare or quite small. The potential landslides with a magnitude capable of directly impacting houses or underground services are located within the Capilano Sediments on the upper one half to two thirds of the ravine slope; therefore, the buttress must cover a large portion of the slope.

Buttressing the upper and middle slope regions is challenging because the buttress must begin at the bottom of the slope and build upwards. The fill must be placed in lifts and must be wide enough to allow heavy equipment to operate. Access ramps will be needed for the equipment to exit off the top of the buttress once it is completed. Ultimately, the height and width of the buttress must be designed for each property based on the existing slope configuration, the proximity of the element at risk, and the elevation of the till deposit. Figure 3 provides a conceptual design for buttresses at two properties, 2059 and 2069 Westview Drive, as examples. A buttress option is also given on Figure 4 for 2015 Westview Drive.

The buttresses must be constructed of free-draining material so as not to hinder the natural drainage on the slope. Materials can range from free-draining pitrun sand and gravel to angular blasted rock fill. The final design slope angle depends partly on the material used; a steeper angle can usually be permitted for angular rock fill than for pitrun. All materials must be placed and compacted in lifts to a minimum 95% standard Proctor maximum density in order to provide sufficient shear strength. The final slope can be graded by the excavator and even dressed with topsoil and planted.

Despite seeding and planting of the buttress slope, the main disadvantage of this option is its impact on the natural setting. All trees and vegetation within the buttress area must be removed. Where the slope has been severely disturbed and currently consists of small deciduous trees, the impact on the natural environment may be minor. However, where the slope is forested with large

conifers or even large maples, the visual and environmental impacts will last for several decades. Also, considering the proximity to Mosquito Creek, approvals or authorization for the work may be required under the Fisheries Act.

9.4 Subsurface Drainage

Stability of the Capilano Sediments is greatly affected by the groundwater levels in the unconfined aquifer near the base of this unit. Installation of sub-horizontal drains above the clay layer could lower the groundwater level near the slope and improve stability. Drains are installed by drilling on the slope and inserting slotted PVC pipe, often with a geotextile sleeve.

The effectiveness of this method depends largely on the spacing of the drains and the permeability of the surrounding soil. Sub-horizontal drains are expensive to install and require maintenance, including periodic cleaning of the drains. The drains can become plugged with sediment over time, reducing their effectiveness.

Further design work would be required to evaluate the applicability of this stabilization method to the ground conditions in the Mosquito Creek ravine.

9.5 Soil Nailing

Soil nailing, soil doweling and installation of micro-piles are all methods of inserting internal reinforcement into the soil. Soil nails are steel bars driven or drilled and grouted into the ground to enable the soil mass to act as a coherent reinforced-soil structure. A new method of installing soil nails was developed using technology from the British Military. A 38 mm diameter steel rod is driven up to 6 m into the ground using compressed air. The apparatus is typically mounted on a tracked excavator, which improves accessibility. Without the need for grouting, the anchors can be installed quicker and achieve design strength almost immediately.

Soil nails and pin piles can be installed horizontally, vertically, or perpendicular to the slope, as shown on Figure 5. Unlike tie-backs, soil nailing is a passive system of reinforcement, meaning that the nails are not post-tensioned. The reinforcement must be installed at closely spaced intervals and the ground surface is coated with shotcrete reinforced with wire mesh. Recent applications have used geogrid reinforcement at the surface. Because of the tight nail spacing, this is not a method for broad-scale stabilization. However, soil nailing can be effective at reinforcing and stabilizing a particular slide mass or for stabilizing the slope directly below a particular structure.

In the past, soil nailing has mostly been used for stabilizing temporary excavations because of concerns regarding corrosion of the steel nails. However, the development of corrosion resistant nails and coated nails have increased their use on permanent slopes. Micropiles and pin piles function in a similar manner to soil nails but typically consist of cast-in-place reinforced concrete piles instead of steel soil nails. Recycled plastic pins have been used more recently.

Equipment access is a significant limitation for the use soil nails along the Mosquito Creek ravine. Stabilization is primarily needed on the upper slope; however, equipment access along the crest of the slope is severely hindered by the existing houses. If access can be provided for a tracked excavator, the soil nail launcher could be used to reach over the crest and drive nails into the upper bank. Otherwise, access must be achieved by constructing a filled ramp from the base of the slope.

Drainage is another issue. The facing of the soil nail reinforced slope is typically covered with wire-mesh reinforced shotcrete. Shotcrete would probably be aesthetically undesirable in the park setting. More importantly, where there is groundwater discharging from the slope in the area to be stabilized, the pore pressure of the water trapped beneath the shotcrete could cause problems. Newer applications of soil nailing have used a “green facing” that utilizes geogrid and vegetation. Drainage could be provided by driving hollow nails horizontally in the seepage zone at the base of the Capilano Sediments, as shown on Figure 5.

9.6 Bioengineering

Bioengineering uses vegetation and root support to reinforce the surficial soils or to contain eroded soils. Methods include wattle fences, live pole drains, and modified brush layers. These methods are inexpensive and can be effective at reducing surface erosion or even stabilizing small raveling failures and can be used in conjunction with other mitigative methods. For example, live pole drains can be installed on the lower slope below subhorizontal drains or below an area of soil nailing in order to collect and control the groundwater discharge. However, bioengineering should not be relied upon as the primary means of stabilization where the element at risk is significant.

10.0 LIMITATIONS

This study is intended for use by the CNV as a planning tool only and should be read in conjunction with the preliminary landslide risk analysis for the ravine. The study delineates the relative hazards and risks on the east slope of the Mosquito Creek ravine based on the proximity of the adjacent structures and services and the type of foundation, but does not include any assessment of the structural integrity of these structures or services.

The study is based predominantly on field reconnaissance with limited subsurface investigation. Restricted site access limited the methods of investigation on many of the properties. General observations are made on the existing slope gradients, shape, morphology and the general stability. Information on the subsurface soil, groundwater and bedrock conditions are gathered from drill-holes, hand-dug test holes, in-situ testing and soil exposures. Sub-surface conditions other than those identified may exist and could impact on slope stability, requiring a review of the recommendations contained in this report, with amendments made as needed. The classification and identification of the type and condition of the geological units present in and adjacent to the development are judgmental in nature. Variations (even over short distances) are inherent and are a function of natural processes.

Westrek does not represent or warrant that the conditions listed in the report are exact and the user should recognize that variations may exist.

The east bank of the Mosquito Creek ravine is steep and has a history of landslides. As such, inherent risks exist and landslides can occur even where the likelihood of instability has been identified as very low or low. CNV and all property owners must operate with an understanding of this risk. Many of the potentially unstable conditions are the direct result of actions taken by the property owners. Failure to modify their actions and remedy past actions could cause landslides that affect their property, their neighbours' property, and public property.

Factual data and interpretation contained within this report were prepared specifically for CNV with whom Westrek has entered a contract. No representations of any kind are made to any third parties with whom Westrek has not entered a contract.

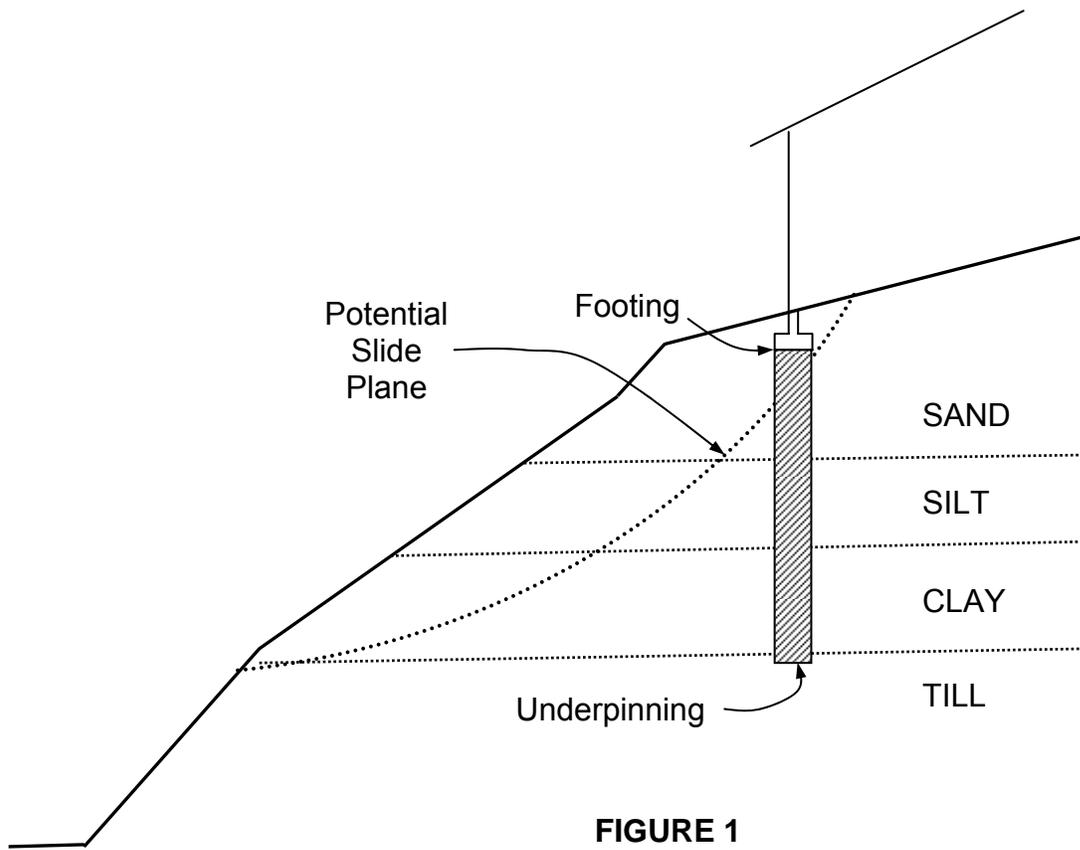


FIGURE 1
CONCEPTUAL DESIGN FOR
UNDERPINNING OF FOUNDATION
(Not to Scale)

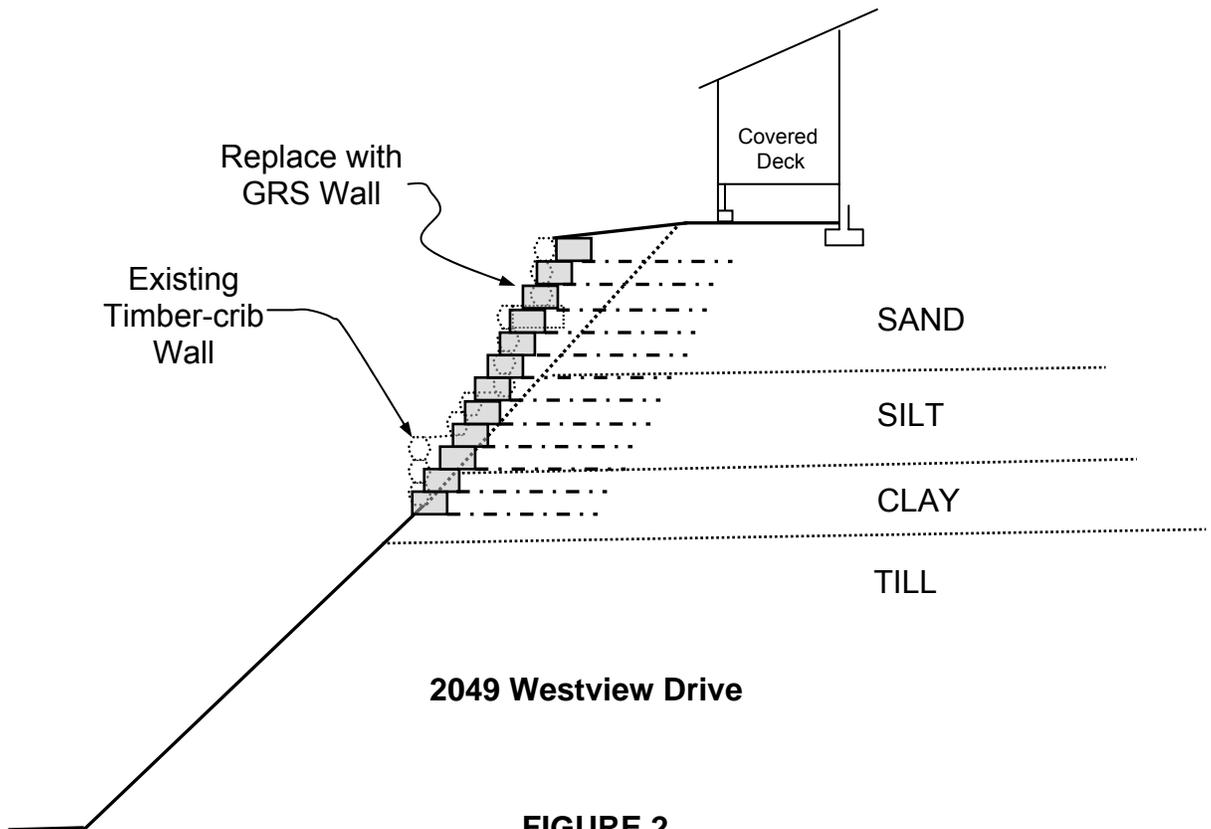
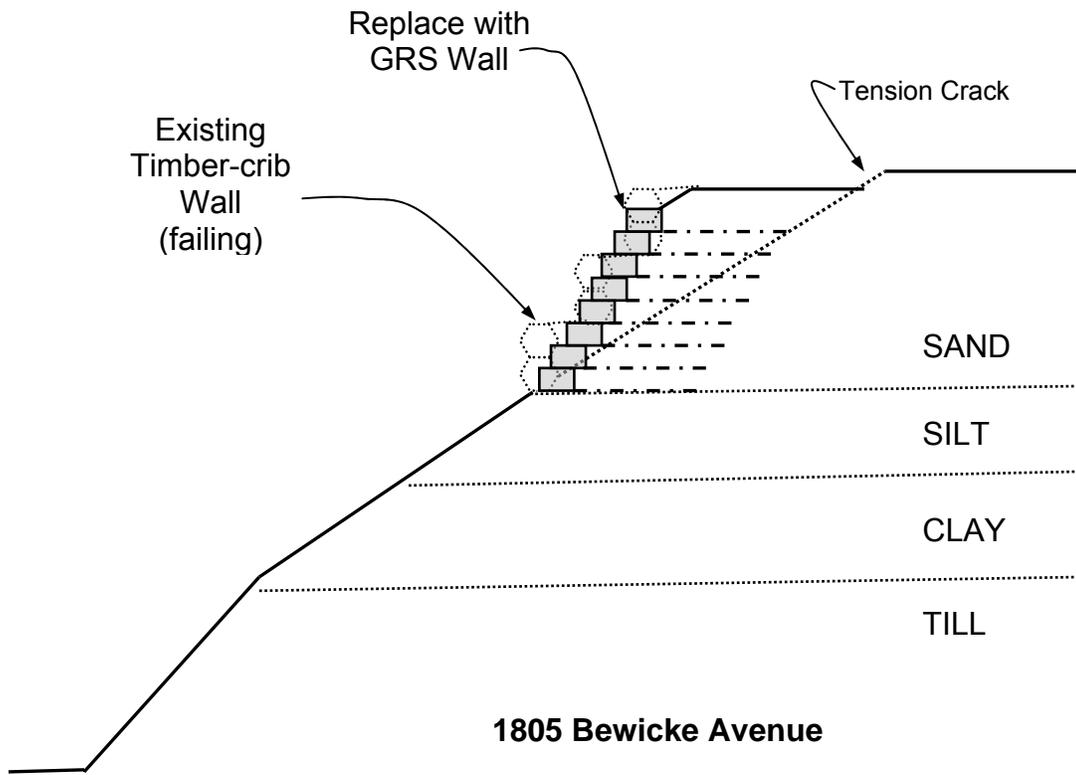
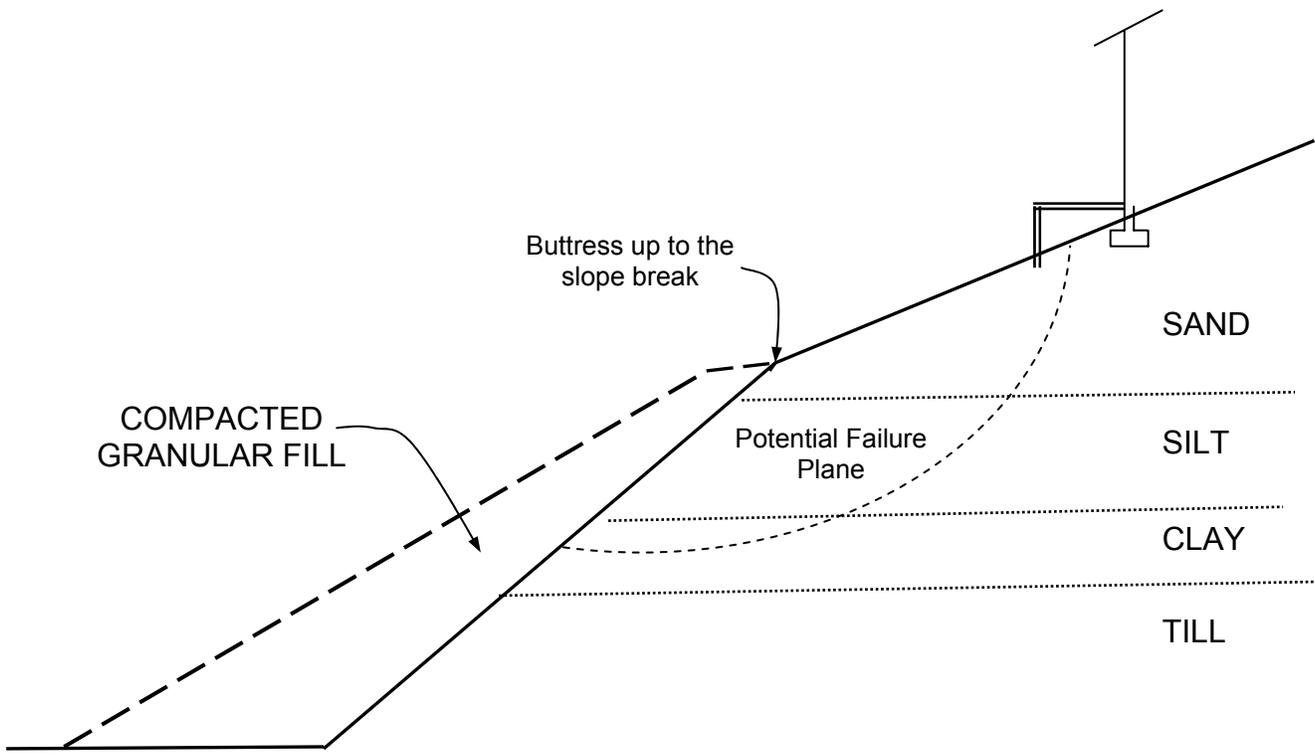
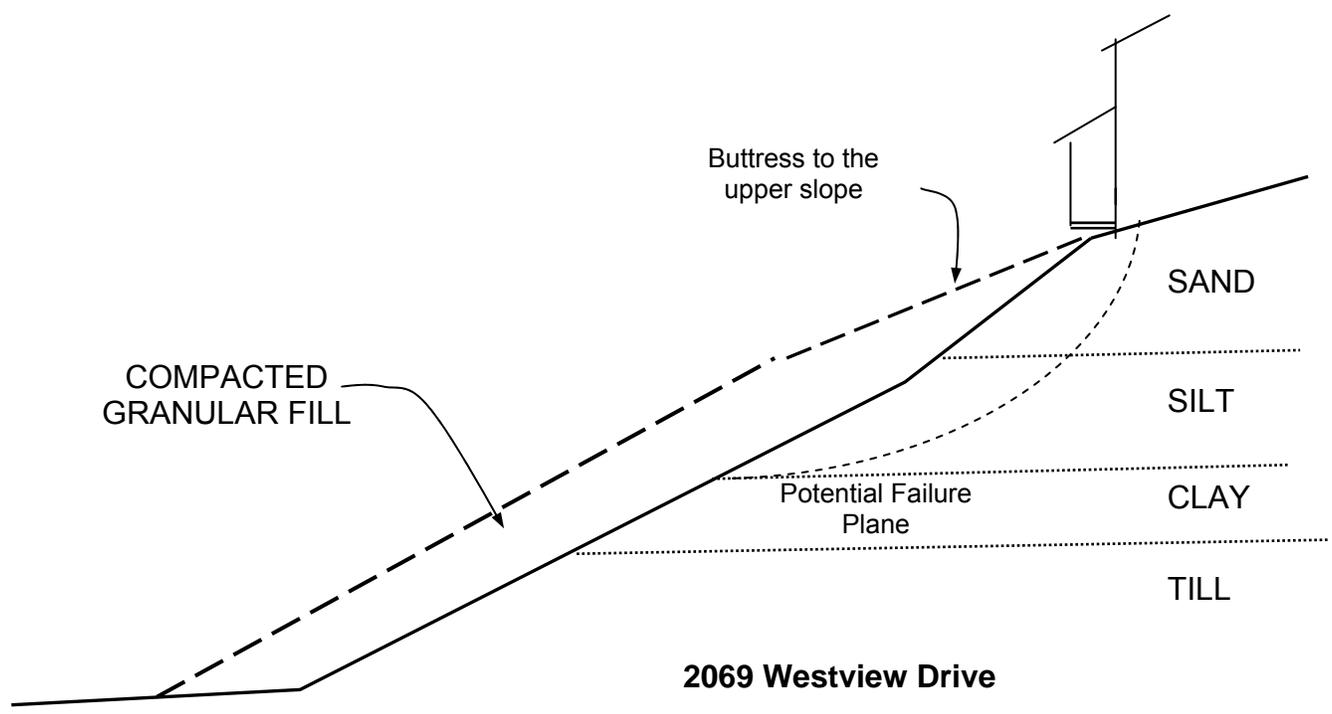


FIGURE 2
CONCEPTUAL DESIGNS OF
GEOSYNTHETIC REINFORCED SOIL
(GRS) WALLS
 (Not to Scale)

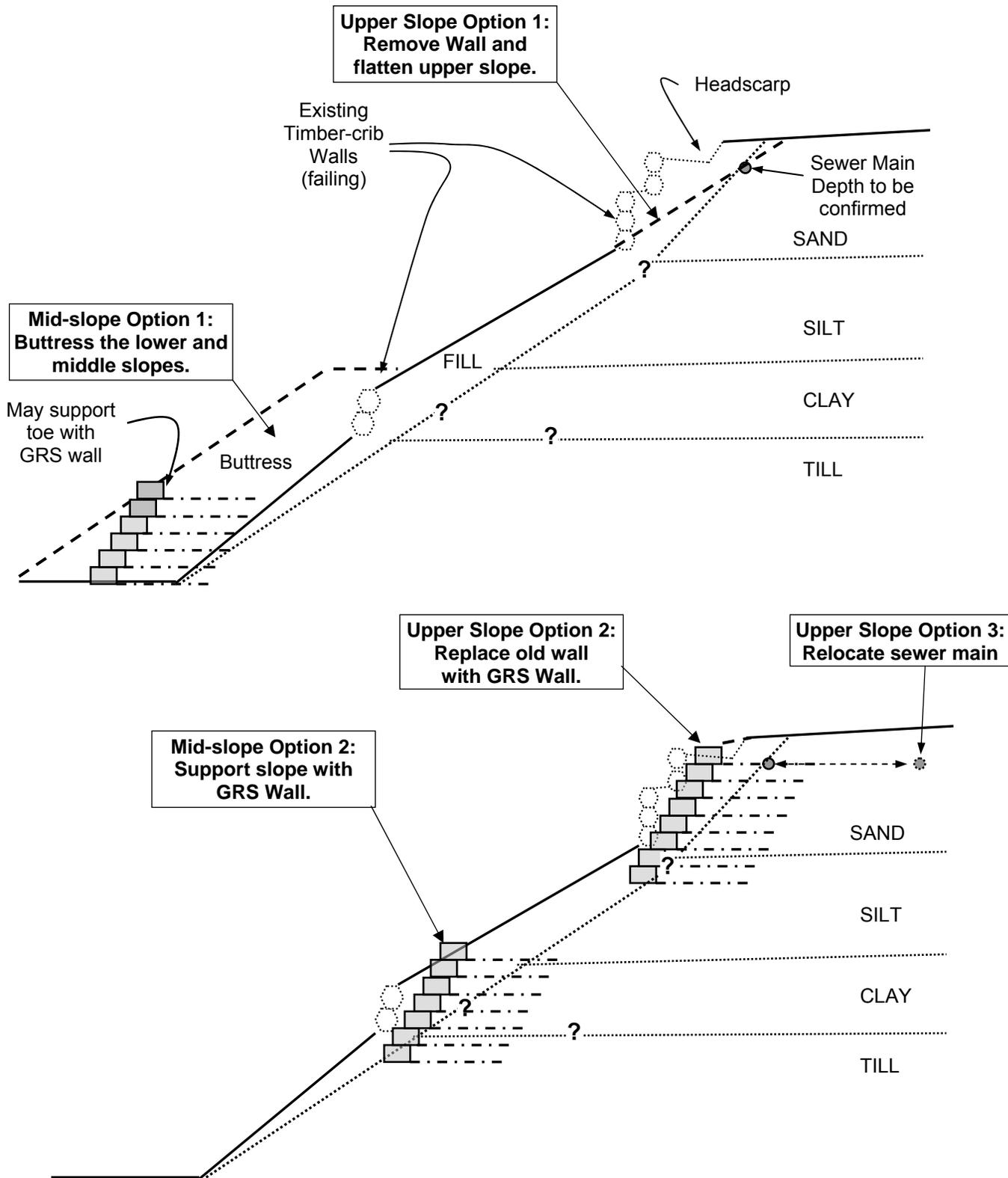


2059 Westview Drive



2069 Westview Drive

**FIGURE 3
CONCEPTUAL DESIGNS OF
SLOPE BUTTRESSES**
Scale 1:200



**FIGURE 4
CONCEPTUAL DESIGNS OF
MITIGATION OPTIONS FOR
2015 WESTVIEW DRIVE**

Scale 1:200 (approx.)

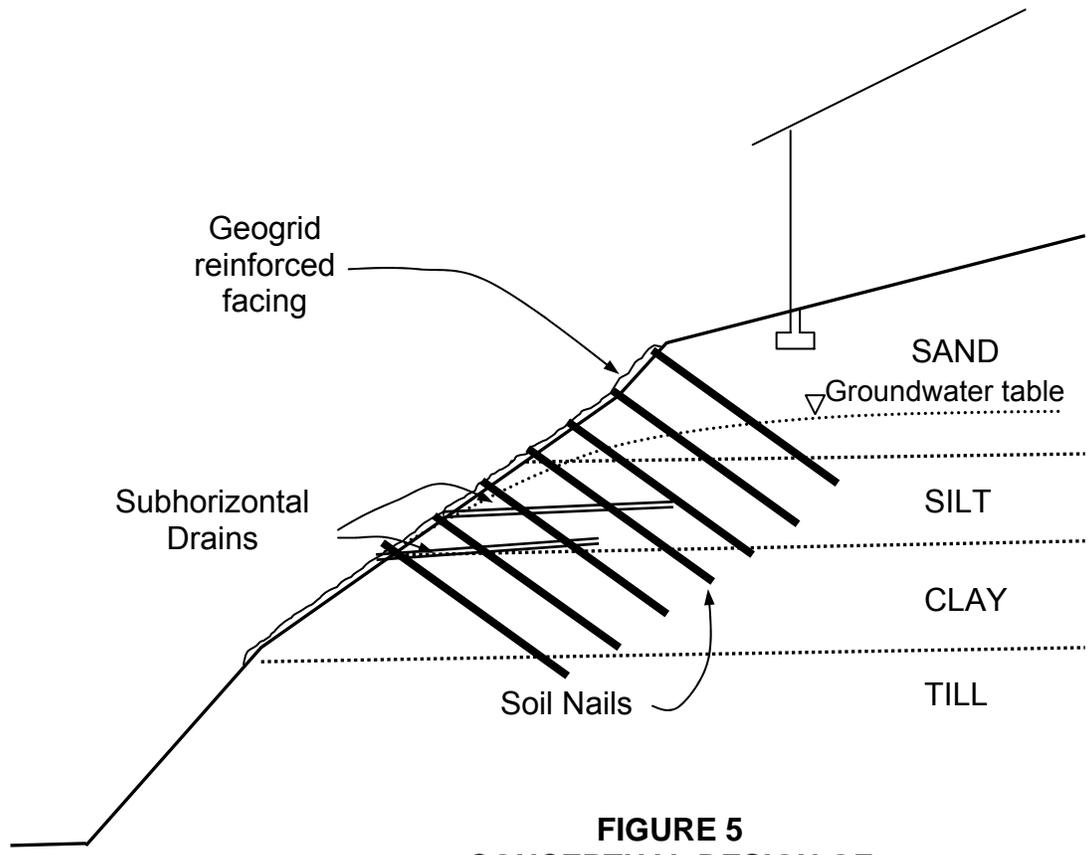


FIGURE 5
CONCEPTUAL DESIGN OF
SOIL NAIL REINFORCEMENT &
SUB-HORIZONTAL DRAINS
(Not to Scale)

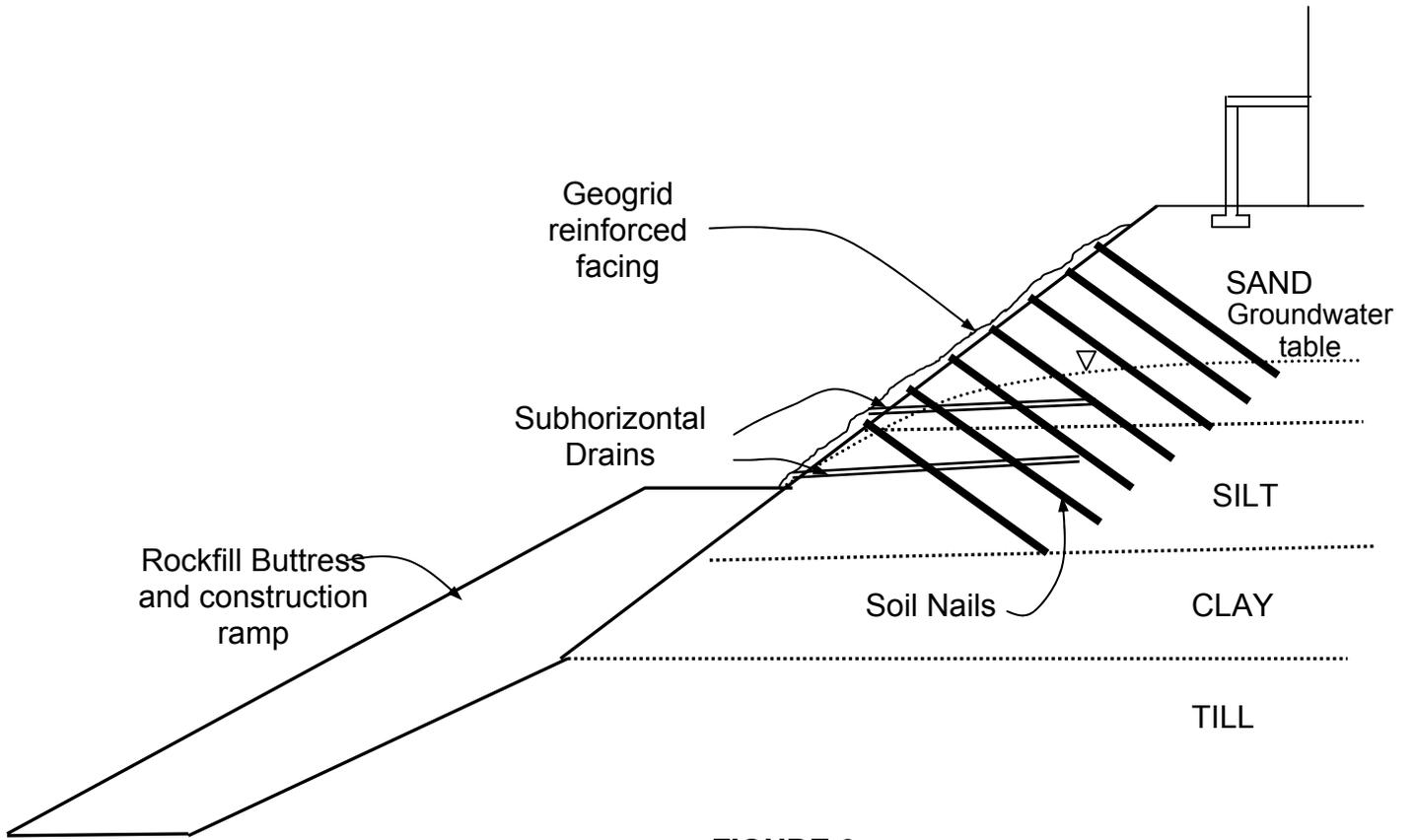


FIGURE 6
CONCEPTUAL DESIGNS OF
MITIGATION OPTIONS FOR
632 WEST 23RD STREET

Scale 1:200 (approx.)

Appendix A.

Background Summary.

Appendix B.

Summary Risk Tables.

Appendix C.

Bore-hole Logs.