Geotechnical Assessment of Shallow (Surficial) Slope Stability Zoning on the Proposed Paskapoo Slopes Park

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ABSTRACT
The topography of the proposed Paskapoo Slopes Natural Environment Park area exhibits relatively high relief corresponding to natural slopes, ravines and hillsides and has a history of shallow slope instability. To assist the City of Calgary in planning trails and pathways in the park, a geotechnical engineering assessment was carried out to identify shallow (surficial) slope failure mechanisms. This paper describes and discusses the background of the project, geological and geotechnical setting, factors that contribute to shallow slope instability and proposed zoning activities.

RÉSUMÉ
Le nouveau parc environnemental Paskapoo se situe sur un terrain accidenté qui comprend des pentes naturelles, des ravins et des collines qui ont subit de nombreux glissements de terrain au cours des années. Afin d'aider la ville de Calgary dans leur planification des pistes cyclables et des sentiers pédestres pour leurs parcs, une évaluation géotechnique a été menée afin d'identifier les mécanismes responsables pour l'instabilité de ces pentes. Cet article décrit le contexte géologique du projet, explique les paramètres géotechniques, discute des facteurs qui contribuent à l'instabilité des pentes et propose un zonage pour chaque type d'activités sur ces pentes.

1 INTRODUCTION

The proposed Paskapoo Slopes Natural Environment Park is located in southwest Calgary (Figure 1). The study area covers an area of approximately 80 acres. The topography of the study area exhibits relatively high relief corresponding to natural slopes, ravines and hillsides and has a history of shallow slope instability.

The City of Calgary Parks (City) retained Golder Associates Ltd. (Golder) to carry out a geotechnical engineering assessment to identify high, medium and low zones of potential shallow instability of the slopes within the study area. A complete assessment of slope stability and potential failure categories requires an assessment of shallow (surficial) and deep-seated failure mechanisms. The report issued in April 2009 (Golder 2009) presents the shallow (surficial) stability mechanism study and shallow (surficial) slope stability zoning map showing low, medium and high zones of potential shallow slope instability. The results from the study will be used to assist and guide planning of trails and pathways for the park.

2 SHALLOW SLOPE STABILITY CONSIDERATIONS

Three components contribute to the strength of a soil: friction, cohesion and soil suction. A significant effective cohesive component is not likely to be operational in shallow depth of slopes due to a variety of factors including low density and effects of wetting/drying and freeze-thaw cycles. Therefore, soil strength is primarily a function of friction and soil suction. Soil suction occurs in unsaturated soils and increases soil strength relative to saturated conditions. Therefore, slopes consisting of unsaturated soils tend to be more stable than slopes consisting of saturated soils. A saturated soil has no air within voids between soil particles (i.e. the soil pore space is completely filled by water).

Shallow slope stability is controlled by in-situ soil suction and a number of other variables (e.g. surficial soil properties, water content, slope surface gradient, precipitation, infiltration and vegetation cover, etc.). Among other factors, the magnitude of soil suction is dependent on grain size, void ratio and permeability of the soil. Correlations developed between in-situ soil suction and a number of variables, including water content, hydraulic conductivity, soil depth, slope surface gradient, vegetation type and precipitation are summarized in later sections of this paper.

3 DESK STUDY

3.1 Geological Setting and Geotechnical Conditions

The slopes within the study area are primarily north and northeast facing. Approximately 49 % of the study area is forested, 17 % is covered by shrubs, 31 % is grass lands and the remaining 3 % is either wetland or anthropogenic lands.

Development of residential properties within the study area has been taking place since the 1990's and is located at the crest, mid-portion and toe of slopes. To support the design of the local residential developments, geotechnical, hydrological and biophysical inventory analyses have been conducted in some areas. A review of relevant reports shows that slope deposits in the study area predominately include either the upper unit of the Spy Hill Drift (glacial till) on top of tertiary gravel, resting on bedrock, or lacustrine sands and silts overlying glacial till and bedrock. Previous geotechnical investigations by others report that the strength parameters of effective cohesion, c', predominately varies from 0 kPa to 5 kPa and effective friction angle, ϕ', ranges from 27° to 30° for clay till deposits. For silt deposits, c' is 0 kPa and ϕ' ranges from 27° to 30°. No values or discussion of soil suction and its effect on soil strength were provided in these reports.

Groundwater conditions within the study area generally consist of a perched water table above the bedrock surface and groundwater flow in the bedrock. The perched groundwater table existing in the upper deposits was reported to be generally 3 m to 5 m below existing grades and daylights at variable locations on the slope.

3.2 Aerial Photography Mosaics

Photo mosaics of aerial photography were produced to assist in the characterization of the widespread nature and extent of the study area. Smaller map images within the study area were combined into one large overall view to show landform changes. The study area boundary was also projected on to each figure.

Representative photo mosaics of aerial photography included available aerial photographs flown between 1955 and 2007. Observations from the aerial photograph mosaics were generally focused on landform changes (vegetation cover and topography) of the study area.

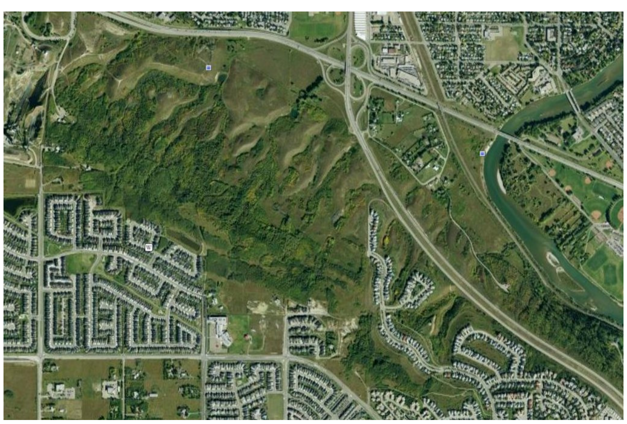

Figure 1. Site Plan

3.3 Slope Surface Gradient

Slope geometry and surface gradient vary significantly over the study area. The average slope surface gradient generally varies between 10 % - 60 % (10H:1V to 1.7H:1V) with some areas as steep as 100 % (1H:1V). Higher slope surface gradients exist locally in some areas as a result of previous failures or surficial erosion. Slope surface gradients of 15 % (6.7H:1V) increment intervals were generated for the study area. These give an idea of the landform characteristics and form the basis of the zoning map.

4 SITE RECONNAISSANCE

A site reconnaissance comprising a geotechnical component and a vegetation survey was conducted and included detailed visual observations and photographs of landforms and features related to slope instability. Features included the geometry of slopes, slope surficial soil conditions, vegetation cover, surface runoff and seepage conditions, location of existing structures, cracks and areas of instability (e.g. Figure 2) and potential impact of existing pathways on the slopes within the study area. Piles of timber, soils and construction debris observed in some areas during the site visit were also photographed and recorded on file.

The site visit also included the component of a vegetative cover survey of the area. The interpretation of soil and moisture characteristics from the aerial photos was supplemented with ground "truthing". Three main categories, which consist of trees, shrubs and grasses, were further subdivided into 12 vegetation communities based on differences in vegetation patterns.

In general, the type of vegetation community is expected to have varying degrees of influence on soil moisture profiles, and thus on shallow slope stability. The moisture regime of the tree dominant communities is mesic (moist), and the moisture regimes of the shrub and grassland dominant communities are submesic (dry) to subexiric (very dry). Hydrophytic (i.e. water-loving) vegetations exist in two wetlands, suggesting moisture conditions are sufficiently wet to support the growth of these plants throughout the majority of a year.

In some areas, the abundance of disturbance adapted species indicated recent surficial movement of the soils. Disturbance-adapted species can colonize quickly and generally do not develop strong root systems. These species are less likely to strengthen surficial soils of slopes, in comparison to the existence of native species (i.e. native grasslands) with deeper root systems.

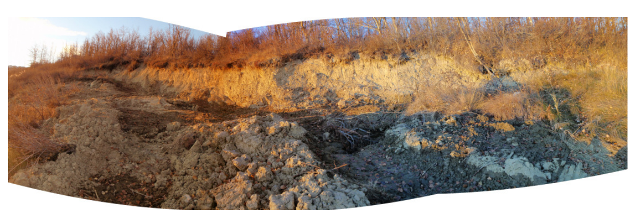

Figure 2. Slumped ground

5 GEOTECHNICAL SITE INVESTIGATION

The geotechnical site investigation included a total of 10 manually hand-augered holes that were drilled at various locations. A 50 mm diameter hand-auger was used to minimize the disturbance footprint at the investigated location as well as overall disturbance of the ground surface within the study area. The penetration depth achievable was between 0.3 m and 2.4 m for manual augering. Soil suction measurement was taken with depth in each hole and recorded (Figure 3). All boreholes were backfilled with native soils extracted from the boreholes.

Two hand-dug test pits were excavated to facilitate a more detailed examination and assessment of ground stratigraphy and for quality soil sampling. The pits were manually dug within a 1 m by 1 m square on ground surface and advanced down to 0.8 m to 0.9 m below existing ground surface. Soil suction was also measured with depth. The test pits were backfilled with native soils, hand-compacted and trimmed to the previous surface elevation.

In-situ soil suction measurements were taken using a Quickdraw Soil Moisture Probe (series 2900) manufactured by SoilMoisture Equipment Corporation of Santa Barbara, CA, USA. The soil moisture probe was inserted into pre-bored holes (Figure 3). It generally took 25 to 50 minutes to achieve stable instrument equilibrium conditions, depending on soil conditions and penetration depth. Soil samples were taken at corresponding depths for determination of natural water content and to establish a natural water content versus soil suction correlation. Groundwater levels in existing piezometers (installed previously by others) that were located within the study area were read to obtain updated groundwater levels.

Soil suction measurements showed suctions ranging between 8 kPa and 36 kPa within a depth of 1.5 m below existing slope surface. For sandy silt soils, the soil suctions ranged between 14 kPa and 40 kPa within a depth of 1.5 m below the existing slope surface.

Laboratory grain-size distribution, water content, and Atterberg Limits tests were carried out on the soil samples. The result show that the water content ranged between 11 % and 35 %, liquid limit varied from 36 % to 50 %, plastic limit ranged from 19 % to 27 %, and plasticity index, I_p, varied from 17 to 26.

Figure 3. In-situ suction measurement

6 FACTORS INFLUENCING IN-SITU SOIL SUCTION AND CORRELATIONS DEVELOPED

Correlations were developed between in-situ soil suction and a number of variables, including water content, hydraulic conductivity, soil depth, slope surface gradient, vegetation type and precipitation.

6.1 Effect of Water Content, Void Ratio and Permeability

To facilitate characterization of the potential for slope instability, the natural water contents were analyzed in conjunction with the soil suction measured in surficial soils. The data tended to show a trend of decreasing soil suction with increasing water content.

Areas of the slopes where soils are more likely to retain moisture are expected to have a lower value of soil suction. If a portion of a slope has undergone surficial instability, the permeability and void ratio of these soils are expected to be greater than natural/undisturbed surficial soils. Disturbance or failure allows a greater degree of connectivity between pores in the soil as well as larger pore sizes and hence, faster equilibration of negative pore pressures and less capacity to maintain high suction even in dry periods. This implies that areas with a history of previous slope instability are more prone to future shallow instabilities.

6.2 Effect of Slope Surface Gradient

Steeper slopes with a greater slope surface gradient have a lower factor of safety against slope instability than flatter slopes. Slope surface gradients were computed based on 3TM survey data provided by the City.

Slope surface gradients were calculated and plotted against suction. The data tends to show a trend of decreasing suction with increasing slope surface gradient for silty clay. There was no clear trend of suction with increasing slope surface gradient for sandy silt.

It is expected that a steeper slope is less stable than a flatter slope, for the same soils. Surface runoff is expected to be greater on a steeper slope than on a flatter slope. However, surface runoff may cause surficial soil erosion, especially for loose sandy materials with no vegetation cover. There appears to be little correlation between slope surface gradient and soil suction.

6.3 Effect of Soil Depth

Profiles of soil suction with depth show generally a trend of decreasing suction with increasing depth below the ground surface.

Based on data from previous reports, groundwater at this site is generally 3 m to 5 m below existing ground surface. Evaporation effects will be higher at shallow depths. Suction is expected to decrease to zero at surfaces with a shallow groundwater table.

6.4 Effect of Precipitation

It is difficult to correlate precipitation data due to uncertainty in the consistency of rainfall events between the airport and the different locations where suction measurements were made. There is also the issue of the timing of suction measurements in relation to rainfall events. Nonetheless, the trend of precipitation and soil suction were observed as part of the research program jointly undertaken by Golder and the University of Calgary in 2001. The results showed that suction dropped soon after the end of May/beginning of June (the typical wettest period) and rose again over the following three months, achieving peak values at the end of August/beginning of September (during the typical driest period). The range of soil suction over the 7-month interval (from May to December) is significant, ranging in some cases from a minimum of 10 kPa in May to a maximum of 50 kPa in August/September.

The effect of precipitation is intrinsically linked to the effect of infiltration and in turn to soil water content. Infiltration of water into an unsaturated soil (i.e. advance of the "wetting front") will effectively diminish the value of negative pore pressure (or suction) in the soil. If infiltration due to precipitation is sufficiently high as to saturate the soil, soil suction would diminish to zero.

The reduction of suction caused by infiltration reduces the shear strength of surficial soils, which in turn reduces shallow slope stability. Evaporation of moisture within surficial soils results in development of negative pore pressures (suction) and increases the shear strength of the soils. This, in turn, increases slope stability. As a result, slopes that were stable in dry seasons, often slump or fail in wet seasons (e.g. snow melting, rainfall infiltration).

6.5 Effect of Vegetation

Infiltration contributes to recharging the shallow slope soils with water. In treed lands, precipitation is partially shed off by trees and infiltration is thus reduced. Tree roots also strengthen (reinforce) surficial soils, slow runoff and reduce peak flows. It is expected that treed lands increase the stability of surficial soils.

Grassed slopes are generally more responsive to evaporation and infiltration. Lowering of the water content by evaporation increases the value of in-situ soil suction and soil strength. Conversely, infiltration increases water content and can diminish soil suction.

6.6 Relationship between Soil Shear Strength and Soil-Water Characteristic Curve

Grain size distributions were measured for the main soil types and the results for selective soils are presented in Figure 4.

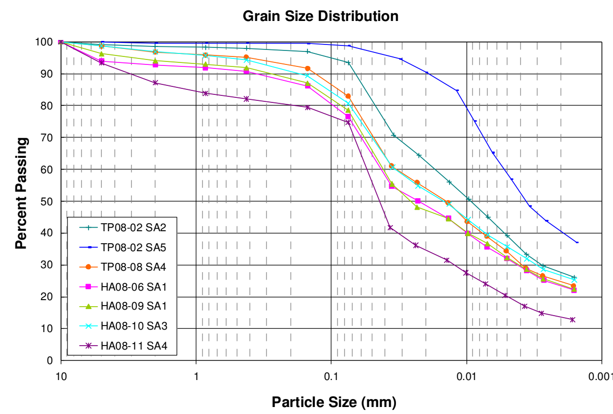

Figure 4. Measured grain-size distribution curves

The suction strength is a function of the soil suction and the volumetric water content of the soil. The soil-water characteristic curves, SWCCs, shown in Figure 5 were estimated (Fredlund et. al. 1996) from the grain-size distribution curves shown in Figure 4. Each SWCC starts at a suction value approaching 0 kPa and ends with a suction of 1,000,000 kPa. The air entry value for the soils appears to be around 20 kPa. The dry density of the soil samples was estimated to be either 1550 or 1600 kg/m^3. These dry densities correspond to initial void ratios of 0.774 and 0.688, respectively, and initial saturated porosities of 43.6% and 40.7%. The specific gravity of the soil was assumed to be either 2.75 or 2.70.

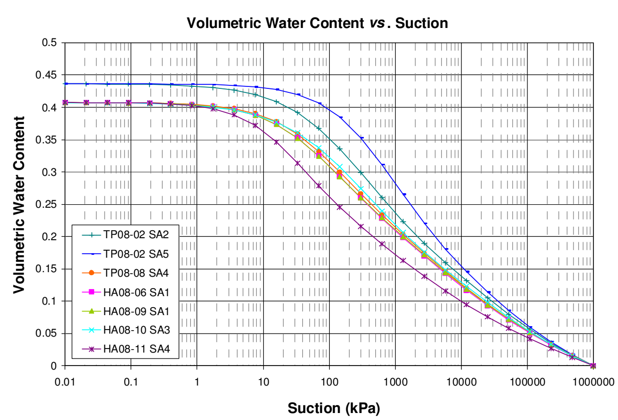

Figure 5. Estimated Soil-Water Characteristic Curves (SWCCs)

The unsaturated soil behaviour is related to net stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$, in which u_a is pore-air pressure and u_w is pore-water pressure. The shear strength of an unsaturated soil, τ_f, can be described as follows (*Fredlund et al. 1996*):

$$\tau_f = [c' + (\sigma_n - u_a) \tan\varphi'] + [(u_a - u_w)\, \Theta^{k} \tan\varphi'] \qquad [1]$$

where: c' is the effective cohesion, φ' is the effective angle of internal friction, σ_n is the normal stress on the failure plane, κ is a fitting parameter dependent mainly on the plasticity of the soil, and Θ is the normalized water content (i.e., $\Theta = \theta_w / \theta_s$ where θ_w is volumetric water content and θ_s is the saturated volumetric water content).

κ can be estimated based on the empirical relationship proposed by Vanapalli and Fredlund, (2000) for the relationship between the fitting parameter, κ, and the plasticity index of the soil.

$$\kappa = I_p^{2} + 0.0975\, I_p + 1 \qquad [2]$$

Each shear strength envelope is nonlinear and was generated using Equation [1] with a κ value of 2.4 (Fredlund et al. 1996). The *SVSlope* software from *SoilVision Systems Ltd* can also be used to generate the shear strength envelopes. One of the estimated shear strength envelopes (i.e., shear strength versus matric suction), is shown in Figure 6.

For a plasticity index, I_p, of 21, a κ factor of 2.4 was selected for application with Equation [1]. The saturated shear strength parameters, c' and φ' for the silty clay soils used in this study were 5 kPa and 27˚, respectively.

The shear strength equation for an unsaturated soil can also be written in a linear, approximate form as described by *Fredlund et al.* (1978):

$$\tau_f = [c' + (\sigma_n - u_a) \tan\varphi'] + [(u_a - u_w) \tan\varphi^{b}] \qquad [3]$$

where: φ^b is the increase in shear strength with respect to matric suction.

Therefore, φ^b can be expressed as follows:

$$\tan\varphi^{b} = \Theta^{k} \tan\varphi' \qquad [4]$$

Shear strength originating from the suction in the soil can be described as follows (*Fredlund and Rahardjo, 1993*):

$$s = (u_a - u_w) \tan\varphi^{b} \qquad [5]$$

The estimated φ^b values for silty clay soils ranged from 9.0˚ to 18.3˚ with an average value of 12.0˚. The estimated φ^b value of 12.0˚ is considered to be a conservative value for the slope stability assessment. The measured soil suction values ranged between 8 kPa and 36 kPa. Therefore, the shear strength arising from soil suction was estimated (by Equation 5) to be between 2 kPa and 8 kPa.

Similarly, the estimated average φ^b for sandy silt soils is 8°. The corresponding shear strength arising from soil suction was estimated (by Equation 5) to be between 2 kPa and 6 kPa.

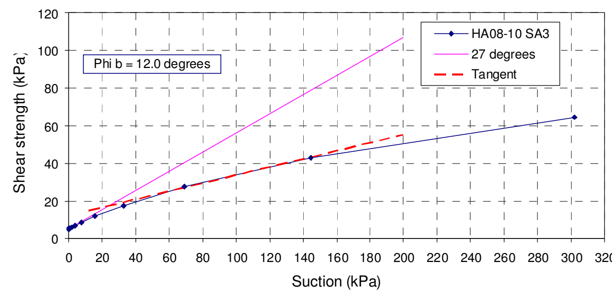

Figure 6. Shear strength estimations based on the saturated shear strength values and the Soil-Water Characteristic Curves, SWCCs (Sample HA08-10-SA3)

7 IN-SITU SOIL SUCTION AND CORRELATIONS SUMMARY

The failure envelope of an unsaturated soil is non-linear due to the non-linear Soil-Water Characteristic Curve (SWCC). At low matric suction (high water content), the soil is at or near saturation condition and behaves as a saturated soil.

Soil suction generally decreases with increasing depth below the ground surface, and decreases to zero at the surface of the groundwater table.

Current soil suction measurements indicate that, for silty clay, soil suction ranged between 8 kPa and 36 kPa within a depth of 1.5 m below existing slope surface. For sandy silt, soil suction ranged between 14 kPa and 40 kPa within a depth of 1.5 m below existing slope surface.

Soil suction drops in wetter season (e.g. May and June in Calgary) and rises again over the following months, achieving peak values at the end of August or beginning of September (during the driest period). Shallow slope instability is more prone to occur in wet seasons.

Slopes that are stable in dry season may not remain stable in wet season (e.g. snow melting, rainfall infiltration).

Areas of slopes where soils are more likely to retain moisture are expected to have a lower value of soil suction and to be less stable.

Areas of previous slope instability are more prone to develop future shallow instabilities.

The occurrence of surface runoff and surficial soil erosion are expected to be higher on a steeper slope than on a flatter slope.

A steeper slope is less stable than a flatter slope, for a given soil type with other factors being similar.

Treed and grassed slopes tend to be more stable than bare slopes (i.e. no to little vegetation cover).

For the soil samples retrieved, the surficial soil shear strength change with a change in matric suction was estimated as φ^b = 12° for silty clay soils and φ^b = 8° for sandy silt soils. Strength arising from soil suction was estimated between 2 kPa and 8 kPa for silty clay soils, and between 2 kPa and 6 kPa for sandy silt soils.

The above findings have been incorporated in assessing the potential shallow slope instability zoning in proposed Paskapoo Slopes Park, as discussed in the following section.

8 SHALLOW SLOPE STABILITY ZONING

Based on a review of the information collected during the site reconnaissance and the correlations derived between in-situ suction and water content, slope surface gradient, soil type, soil depth, precipitation, SWCC and hydraulic conductivity function, the study area was divided into High, Moderate and Low zones from a potential shallow slope instability perspective. A simplified colour code using red, yellow and green was adopted for the ranking categories. These colors correspond respectively to High, Moderate and Low Zones of potential shallow slope instability.

High Zones are defined as areas with slope surface gradient greater than 60 % (1.7H:1V) or with signs of active erosion (slumped ground, surficial soil erosion, erosional gully, seepage, ponded water and tension cracks) during the October and November 2008 site reconnaissance.

Moderate Zones are defined as areas with slope surface gradient between 30 % (3.3H:1V) and 60 % (1.7H:1V) and with no signs of active erosion during our October and November 2008 site reconnaissance.

Low Zones are defined as areas with slope surface gradient less than 30 % (3.3H:1V) and with no signs of active erosion during our October and November 2008 site reconnaissance.

8.1 High Zones

A high (red) designation represents that slopes are only marginally stable from a potential shallow slope instability perspective or have experienced shallow slope failures or slumps. The red areas comprise very steep slopes, generally greater than 60 % (1.7H:1V), or slopes with signs of active erosion (e.g. slumped ground, surficial soil erosion, erosional gully, seepage, ponded water and tension cracks) observed during the October and November 2008 site reconnaissance. These slopes are erosion prone, erosion-impacted along paths, easily gullied by overland drainage, and are generally destabilized at seepage points. Surficial soils noted within the high zones include lacustrine silt and silty sand, clay till and fill, which comprise the majority of the soil exposures. Seventeen High Zones of potential shallow slope instability were mapped within the study area.

8.2 Moderate Zones

A Moderate Zone (yellow) indicates that the slope is currently stable but may become unstable if disturbed. Other factors that could lead to slope instability include elevated groundwater elevations, heavy precipitation over prolonged periods, slope surface soil erosion and surface loading conditions on or near the crest of the slope that decrease geotechnical stability. The slope surface gradients of these areas are typically between 30 % (3.3H:1V) and 60 % (1.7H:1V) and with no signs of instability at the time of visit. Surficial soils observed within the Moderate Zones include primarily lacustrine silt and sand, clay till and fill.

Elevated groundwater elevations and heavy precipitation over prolonged periods will result in loss of suction and a decrease in effective stress. This leads to a decrease in soil strength and subsequently the factor of safety of slope stability decreases. Slope surface soil erosion caused by runoff may change (i.e. increase or decrease) the slope surface gradient. These changes will affect commensurately the factor of safety for surficial slope stability. Inappropriate surface loading conditions on the crest or mid-slope areas (refer to as slope surcharge loading) would increase the driving force to the slope and decrease overall slope stability.

The impact on stability caused by elevated groundwater table depends on the magnitude of increases in pore water pressure associated with a higher groundwater table. A rise in groundwater also destroys the suction strength contributions to slope stability. Steeper slopes in the moderate zone with a higher groundwater table could lead to surficial instability and active erosion. Such areas would then be classified in the high zone.

Changes of groundwater level can be monitored using piezometers. Frequent groundwater level monitoring is recommended, especially in late spring (snow melt) and summer (rainfall infiltration).

8.3 Low Zones

A Low Zone (green) shows that the slopes are generally stable and with no signs of instability at the time of visit. Slope surface gradients are shallower than the previous two categories and are typically less than 30 % (3.3H:1V). The Low Zone includes natural slopes and regraded slopes. The majority of these slopes comprise seeded, planted, treed and managed ecosystems.

9 RECOMMENDED PLANNING CONSIDERATIONS

Recommended planning considerations for High, Moderate and Low Zones of potential shallow slope instability include management of existing pathways, planning new pathways development, seepage management, revegetation, and earthworks with requirements from geotechnical engineering input.

9.1 High Zones

The slopes designated as High Zones are considered to be unstable or marginally stable from a potential shallow slope instability perspective, or currently showing signs of shallow instability. Consequently, development of new pathways should be not allowed if the City wants to minimize maintenance and repair of the pathways. In addition, consideration should be given to closing existing pathways if apparent impact by slope instability is imminent or failure has encroached on pathway.

Within the grassed areas, the addition of deep rooted, drought-resistant tree or shrub species is recommended. It is anticipated that deep-rooted trees will strengthen surficial soil stability. It is recommended that tree planting operations be carried out using hand-operated equipment, with vehicular traffic and soil disturbance to be minimized. Watering of the planted trees/shrubs should be limited to the tree/shrub well only. However, it should be recognized that disturbance caused by tree/shrub planting and subsequent watering may lead to further slope instability.

Within the treed areas, the recommendations include preserving existing trees, seepage management and reducing overland drainage or runoff from reaching the slope. Species of trees that grow in wetter terrain may be planted near the toe to reduce available water and soil moisture.

Signs of slope deterioration should be monitored on a regular basis, which include but not limited to slumped ground, surficial soil erosion, loss of vegetation cover, erosional gully, seepage, ponded water and cracks.

Groundwater level monitoring is recommended to the slopes immediately above Sarcee Trail in areas in the high zone.

Areas with seepage, ponded water, surficial soil erosion and erosional gully, as well as areas construction rubbles and debris on mid-slope areas observed during the site visit in 2008 are recommended with rehabilitation.

Review by a geotechnical engineer is required for rehabilitation. Recommendations for specific areas should be on a case-by-case basis.

9.2 Moderate Zones

Development of new pathways within the Moderate Zones should be subject to review by a geotechnical engineer. Cut slopes, sliver fills, base preparation and drainage installation should also be reviewed by a geotechnical engineer. Existing pathways of limited usage may remain open, however, an annual inspection may be warranted to detect early signs of deterioration.

The rehabilitation of the Moderate Zones could consist of the addition of deep-rooted trees and shrubs. Soil disturbance and watering should be minimized similar to the recommendations for High Zones. It is anticipated that careful rehabilitation techniques will have a minimal impact on slope stability in the short-term.

Groundwater level monitoring is recommended to the slopes immediately above Sarcee Trail in areas in the moderate zone.

9.3 Low Zones

Development of pathways within the Low Zones need not be engineered. Current pathways may remain and additional ones may be opened. No preferred vegetation type is recommended.

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