Analysis of forest hillslope piezometric records: implications for terrain stability

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Abstract: The groundwater response of a coastal British Columbia site in landslide-prone terrain is assessed from piezometric records. A continuously-recording, instrumentation scheme was installed in the Seymour Watershed, Vancouver, B.C. Instrumentation, consisting of piezometers and tensiometers, was located above a debris slide headscarp area. It was used to describe the groundwater regime in the winter of 1997/98. Electronic piezometers, capable of insertion by driving, were designed and manufactured specifically for use in this project. Data collected from the study site indicate a highly variable distribution of storm-induced positive pore pressures across a small area. A preliminary interpretation of these data shows poor agreement with conventional models of hillslope hydrology.

Introduction

Forest soils on the steep hillslopes of coastal British Columbia have a high capacity for transmission of groundwater flow. Periodically, extreme rainfall events trigger debris slides.

The role of pore water pressures induced by the high levels of precipitation is not well understood. In an effort to mitigate the occurrence of landslides associated with forest development, and to provide input to new tools for analysis of stability, current research has focused on understanding the soil properties and groundwater behaviour (Fannin and Wilkinson, 1995; Sidle et al. 1995; Anderson et al. 1997). A key issue is pore water pressure development in soils, and its spatial and temporal distribution.

The steep, mountainous soils of coastal British Columbia are commonly a blanket (>1 m) or veneer (<1 m) of morainal till or colluvium. The soil matrix comprises a sand or silty sand, and is relatively well-drained. Upper soil profiles are frequently weathered and overlain by an organics layer that includes significant tree roots and forest litter. The underlying bedrock often forms a very low permeability, competent interface with the soil upon which groundwater levels develop.

The coastal region experiences a high total annual precipitation. It is uncommon, however, to witness overland flow on most forested slopes resulting from saturation in excess of the profile, or precipitation exceeding the infiltration capacity of the soils (referred to as Hortonian Flow). Forest soils tend to have a very high capacity for water transmission that can be explained by more rapid non-Darcian flow through macropore networks (Hetherington, 1995). In addition, the humus, or thick organic forest floor layer is highly porous and permeable. Features such as macropores (sometimes termed soil pipes) are known to transmit large volumes of water through the slope, and are difficult to characterize yet they are responsible for the majority of rapid water transmission and often control slope stability. Bevan and Germann (1983) have recognized the complexity that macropores add to the hydrologic properties of a forest soil and outline the difficulties in trying to incorporate these features into traditional predictive models. Macropores can adversely influence the stability of a slope if they clog or terminate, leading to locally elevated pore pressure. Brand et al. (1986) and Pierson (1983) have noted field observations of the effects of pipe flow on slope stability. The effects have also been illustrated experimentally (Pierson, 1983; Sidle et al., 1995).

In this paper we examine the groundwater hydrology of a steep clearcut slope in the Seymour Watershed. Specific objectives of the work were to examine the temporal nature of the groundwater floor across a short headscarp region, and to postulate the factors governing the observed response.

Jamieson Creek study site

The study site is located at the Jamieson Creek landslide, in the Seymour Watershed of the Greater Vancouver Water District. The slope failure occurred in November 1990 and initiated as a debris slide at the upper boundary of a 1984 forest clearcut. The slide debris entrained approximately 5,000 m^3 before entering Jamieson Creek, and thereafter Orchid Creek and the Seymour River, which supplies the

reservoir impounded by the Seymour Dam (Smith and Gerath, 1991).

The area immediately above the headscarp was selected for monitoring because of the rainfall-induced landslide, a headscarp exposure that provides opportunity for visual observation of groundwater seepage, and the relative ease of site access. Further, there is a history of multidisciplinary research in this part of the Seymour Watershed (De Vries and Chow, 1978; Cheng, 1987; Golding, 1987; Acres International, 1993; Wilkinson, 1996) to assist with interpretation of new pore water pressure data.

Surficial soils

Soils at this site comprise ferro-humic podzols and weathered gravelly sand till, or colluvium derived from till, with frequent sub-rounded weathered granodiorite cobbles. Capping the soils is a thick root mat. Grain size analyses have indicated the gravelly sand includes some silt and a trace of clay (Fannin and Wilkinson, 1995). The blanket of soils overlie a competent granodiorite of the Coast Plutonic Complex (Armstrong, 1990).

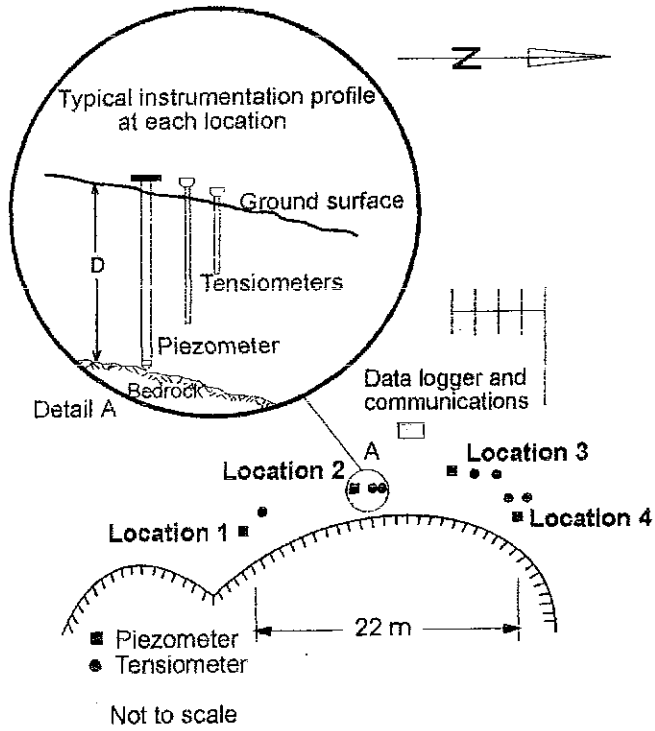
Hand-auger borings and soundings with a rod and hammer were used to define the thickness of the soil profile and shape of the soil-bedrock interface above the headscarp of the landslide. Instrument "nests" were established at four locations in soils that were 1.4 to 2.0 m thick.

Soil density at the site is low due to the high percentage of organics in the upper profile, and a high degree of weathering. Bulk and dry unit weights were established by sampling intact, relatively undisturbed blocks from a sidescarp location near the top of the slide. Samples were taken from a depth of 1 m, near the bedrock surface, to minimize the organic content. Blocks were trimmed, wrapped in cellophane, and sealed with wax before leaving the site. A bulk unit weight of 11.5 kN/m^3 and dry unit weight of 6.3 kN/m^3 were recorded. Results agree with values reported by De Vries and Chow (1978) for soils tested in the Jamieson Creek drainage. The low values are not uncommon for soils with a high organic content, as reported by Harr (1977).

Field instrumentation

An array of instruments was placed above the headscarp to monitor the variation of pore water pressures with time and precipitation. Instrumentation consisted of 4 piezometers, 7 tensiometers, a rain gauge, a barometric pressure gauge and an automatic data-acquisition system (see Fig. 1). The system is capable of continuous monitoring and remote downloading of data. An overview of the instrumentation is provided below, with emphasis on the design and operation of the customized piezometers.

Fig. 1. Instrumentation layout: schematic view.



Piezometers

Project requirements demanded an inexpensive, robust, low-maintenance, automated piezometer that is easy to install and results in little disturbance to the soil. After careful consideration, it was determined that no commercially available piezometers were well-suited to the project requirements.

Particular concern addressed installation on a remote mountain side. Typically, a borehole that is larger than the piezometer is advanced to the depth of interest, the piezometer is then inserted and the hole finally backfilled. Such a technique has several drawbacks on steep slopes overlain by thin soils. It is difficult to advance the hole in rocky soils, and the resulting installation is likely to have considerably disturbed the zone of interest. A push-in type piezometer is preferable, but the necessary equipment to install such units is not well-suited to steep slopes. A small hole could be augered manually, but pushing the piezometer tip into an undisturbed area (beyond the augered hole) would be difficult and likely involve the use of a manual impact hammer. The high accelerations caused by hammer impacts have potential to damage the commercially available push-in type piezometers. As a result, a custom piezometer system was designed to withstand the impact of driving caused by a hammer type installation (Fig. 2a).

The custom piezometer system comprises a tip mounted on a pipe (Fig. 2b), a separate pressure transducer section (Fig. 2c), an inner tube (Fig. 2d) and a protective cover which mounts on top of the pipe (Fig. 2e). The piezometric tip is made of stainless steel and has a 60 deg.

Fig. 2. Piezometer system.

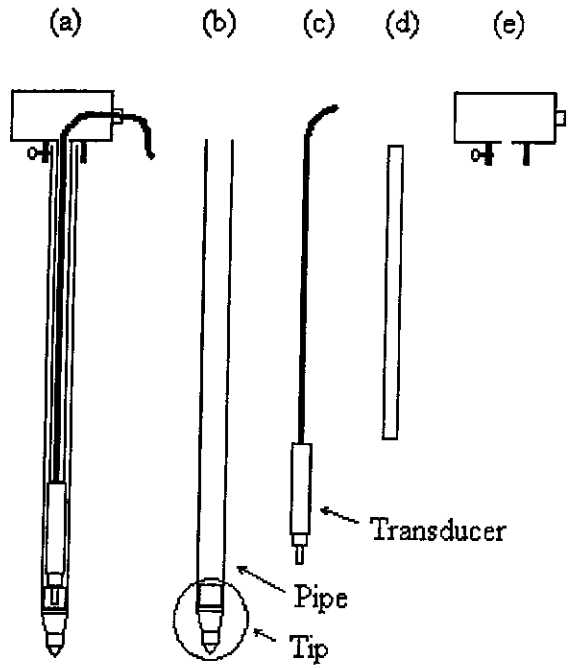
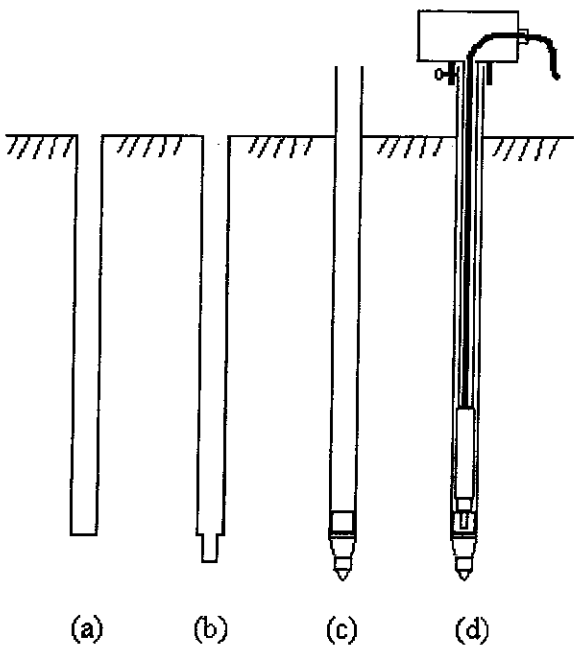


Fig. 3. Piezometer installation.



conical point similar to that of a cone penetrometer. A 20 mm long cylindrical porous polyethylene filter protects a small glycerin-filled internal tubular cavity. The cavity leads to one end of a Swagelock quick-connect fitting mounted inside the body of the tip. The upper shoulder of the tip screw-mounts to the end of a steel pipe that continues up to the ground surface.

The pressure transducer section incorporates the upper Swagelock fitting, an electronic pressure transducer, and a housing with amplifier circuitry (for the transducer). The Swagelock quick connector is a miniature QM series constructed of stainless steel and fitted with O-ring seals. It was modified for a direct push-fit connection and has a built-in spring loaded shutoff valve (on both ends used) to ensure that the transducer and tip remain saturated during installation. The pressure transducer is a Sensym model 19C calibrated in the range -100 kPa to +10 kPa. The amplifier housing is attached to the back of the transducer and has special cable seals for the electrical cable that exits from the top end.

The combination of the inner tube and protective cover was used to keep the tip and pressure transducer firmly connected through the spring loaded Swagelock fitting. In deep installations, it may be preferable to weight the transducer section which would act to keep the Swagelock connected, thus avoiding the tube altogether. The electrical wire exits from the transducer housing up through the center of the inner tube and into the protective cover. The cover has a screw lock mechanism for securing the tube and preventing ingress of foreign material.

The principle of operation is as follows: pore water pressure acting on the filter is transmitted through the glycerin that fills the cavity between the filter and the transducer. Glycerin is miscible with water and was chosen for its high air entry tension characteristics to prevent loss of saturation. The electrical signal from the transducer is then amplified and relayed through a cable to the data logging equipment.

To install the piezometer, a 33 mm diameter hole, which matches the diameter of the pipe and shoulder of the tip was hand augered to a depth equal to the desired elevation of shoulder itself (Fig. 3a). A 22 mm pilot hole, sized to accommodate the diameter of the filter, was advanced beyond that point, a distance shorter than that from shoulder to tip (Fig. 3b). The piezometer was inserted to rest the tip at the bottom of the pilot hole, and then driven with a hammer to seat it in undisturbed soil above the bedrock (Fig. 3c). Next, the glycerin-saturated transducer section was lowered down the pipe and made to firmly engage the Swagelock fitting by supplying a downward force with the inner tube, and the tube then secured with the screw lock on the protective cover (Fig. 3d).

This robust push-in piezometer system obviates the need to excavate and backfill around the unit. The Swagelock fitting not only allows for installation of the piezometer tip independently of the transducer section

(thereby allowing hard driving without damaging the transducer) but also permits the transducer section to be easily removed for future recalibration or long term maintenance. In addition, such a system is cost-effective if continuous monitoring is not required in multiple installations (only one transducer section would be needed to monitor all installations). Most parts are made of stainless steel to provide corrosion protection and extra steps were taken to environmentally protect the covers from low temperatures.

Tensiometers

Vacuum style tensiometers supplied by the Soil Moisture Equipment Corporation were installed to complement piezometric observations with measures of negative and positive pore pressures. Standard lengths of 450, 600, and 1200 mm were used. A pressure transducer, identical to that on the piezometer, was mounted on the gauge port of the tube to automate the measurement of pore water pressure.

Rain gauge

There are several hydrometric stations throughout the Seymour Watershed. The precipitation data reported in this study are from a rain gauge located a map distance 4.5 km from, and at an elevation 500 m lower than the instrumentation at the headscarp.

Barometric pressure

Pore pressures are directly affected by changes in atmospheric pressure. This influence was accounted for by recording atmospheric pressure at the site synchronously with pore pressure.

Data recording equipment

A Lakewood Systems Ltd. UL16 datalogger with 16 analog input channels and 64K byte memory was used to record the data at a specified time interval. With all channels in use and a 20 min. data interval, the logger stores approximately 1 month of data. The resolution of all transducers used in the study is the equivalent of 0.7 cm of water. The transducers and data logging system are powered by a 2.6 Ahr gel cell battery, that has power for about 1 year of operation.

With only seasonal access to the Jamieson Creek site available, a number of communication systems were evaluated for data transfer from site. A conventional Very High Frequency (VHF) radio telemetry system was chosen based on universal applicability, cost-effectiveness, and reliability. A small 5 watt VHF radio with a Kantronics radio modem connects to a 6 element Yagi antenna that relays data from the datalogger to a site within city limits. The telemetry system is powered by a 100 Ahr gel cell battery (reserve capacity for 1 month) and charged by a 75 watt solar panel.

Field observations

A time series plot of tensiometer and piezometer recordings, along with hourly precipitation, is shown for a late October 1997 storm (Fig. 4) together with a similar plot (Fig. 5) for the month of February 1998 (without the tensiometers, but including atmospheric pressures). Data were recorded at 20 minute intervals: the recording intervals were deemed short enough to capture the rapid rise and fall of pore pressures, while long enough to avoid exceeding the memory capacity prior to data downloading. Atmospheric pressure was recorded on-site throughout the study period to allow for accurate correction of pore water pressures. Shifts in barometric pressure are directly reflected in pore pressures, and can change by as much as 3 kPa (the equivalent of 30 cm of water) over a month.

Recorded piezometric data correlate well with the tensiometer data for the storm event (Fig. 4). The unit code, for example P1-137, refers to a piezometer installed at Location 1 to a depth of 137 cm below ground surface. Pulses of positive pore pressure were registered by the piezometers shortly after the tensiometers registered close to zero suction, suggesting that once the soil has been wetted throughout, positive pore pressure can build up. The piezometer responses tended to react in unison to larger precipitation events, with a rapid rise and fall in pressure (Fig. 5). An exception to the rapid piezometric response is unit P4-203, which appears to drain much more slowly than the other units.

Fig. 4. October 1997 storm response.

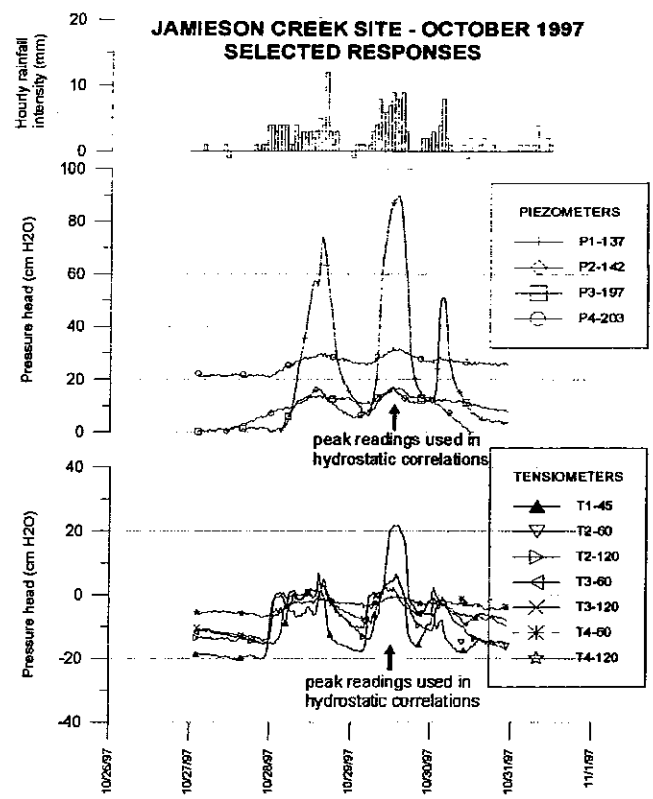
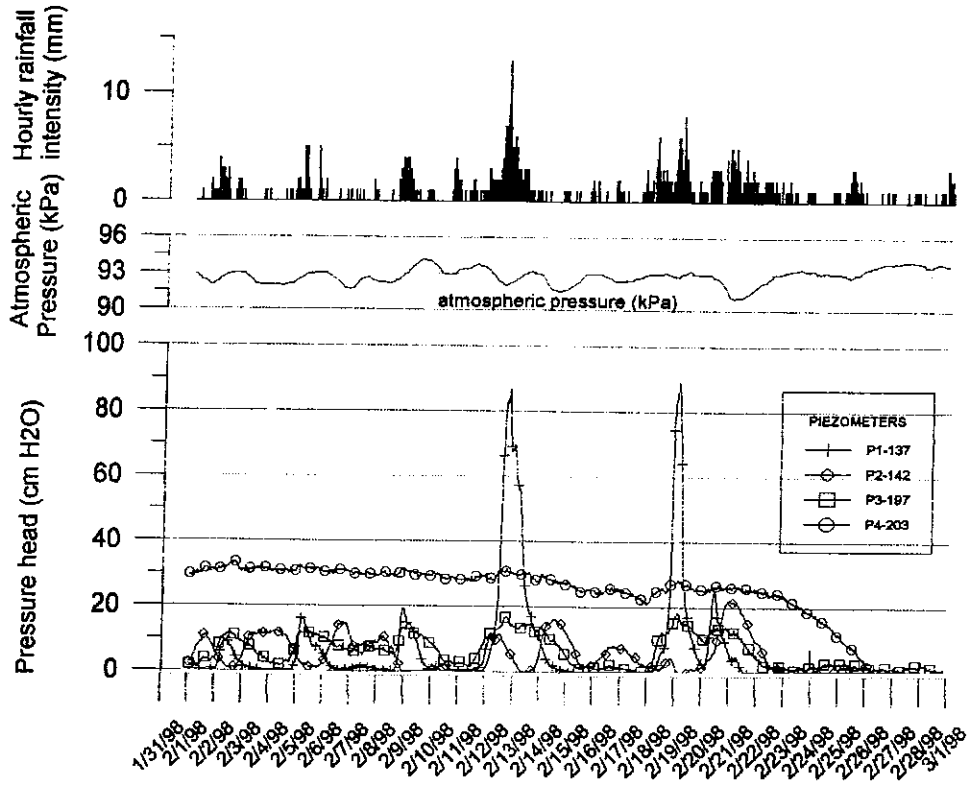


Fig. 5. Time series data: February 1998



The sensitivity of the soil pore water response to storms was not found to be consistent between all of the piezometer units. Units P1-137 and P3-197 react to larger storm events, while P2-142 and P4-203 are more sensitive and seem to respond to almost all precipitation events. The range in magnitudes of response over the entire recording period is considerable. P1-137 attained values to +94.9 cm, while P2-142, P3-197 and P4-203 recorded maximum values of +18.4 cm, +31.6 cm and +32.6 cm respectively.

Discussion

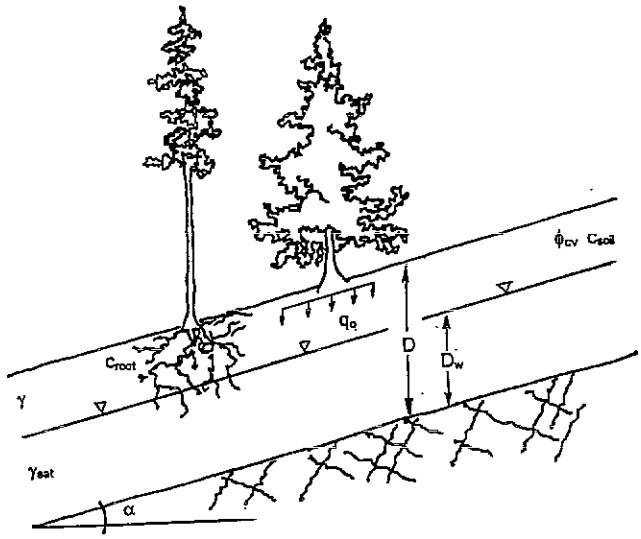
In a hydrologically complex zone such as the headscarp region, designing a piezometric monitoring scheme to study the localized pore pressures presents a considerable challenge, as piezometers are only capable of recording information about pore pressures at a very finite location in the soil profile. The layout used at the Jamieson site was intended to capture pore pressure build-up around suspected areas of groundwater concentration, namely near soil pipes and seepage zones. The difficulty with the application is that the piezometer tip is driven into the soil behind the headscarp, where it may not intersect the actual subsurface drainage zones. Furthermore, the fact that the units were positioned within 5 m of the headscarp is also a consideration. Release of the slide mass created a new hydrologic boundary condition at the headscarp that may have drawn down the storm induced upslope potentiometric surface. This new boundary condition may have also altered the natural flow configuration to one where convergence and draining through larger macropores provides the path of least resistance. The outcome of the rerouting could potentially be a lowering of pore pressures in the region immediately behind the scarp (where the piezometers are located). This hydrologic condition was understood prior to establishment of the instrumentation site. Recalling the objective, the intentions were not to attempt to characterize the pre-slide conditions, but rather the "post-slide" hydrologic conditions at this complex location.

The piezometric response to storms

The field data shown, together with more detailed observations (Jaakkola, 1998), indicate the soil responds to precipitation events within hours, and non-uniformly. More specifically:

- Groundwater flow passes through the site in a spatially non-uniform distribution, generating positive pore pressures that vary greatly across a distance of only 22 m. The maximum groundwater pressure head observed at the four headscarp instrumentation "nests" varied with location from +30 cm to +94.9 cm for the same November 1997 storm event. This distribution challenges the use of slope stability analyses based on the infinite slope equation (Hammond et al., 1992) where groundwater is assumed to flow parallel to the

Fig. 6. Infinite slope stability (after Hammond et al. 1992).



surface at a uniform depth across a planar slope, see Fig. 6.

- Piezometric responses generally occur when sustained precipitation intensities greater than 3 mm/hour are exceeded. The response at Locations 1, 2, and 3 (Fig. 5) rises and falls with precipitation intensity. In contrast, (Location 4) maintains elevated pore pressures for days after precipitation (although the instrumentation is only 6 m from the headscarp).

Summary remarks

The use of models for prediction of hydrologic processes and slope stability has become increasingly common at watershed scales. Modelling is gradually being accepted in terrain stability assessments of watersheds, alongside the increasing use of Geographic Information Systems (GIS). Many models operate within GIS frameworks, using digital elevation models (DEM) created from digital elevation data, which are readily available through government ministries for large areas of the province of B.C. at scales as large as 1:20,000. Output from models can assist specialists delineate areas of potential instability, and provide an objective, quantitative analysis of terrain stability to complement the qualitative field and office-based assessment of common current practice.

The common model used to describe groundwater flow, in a planar soil layer overlying a relatively impermeable bedrock, assumes for simplicity a piezometric surface parallel to the ground surface (Montgomery and Dietrich, 1996; Pack, 1997) as shown in Fig. 6. The assumption of parallel flow is widely adopted in such translational slope stability analyses (Hammond et al, 1992), and imposes a linear distribution of pore water pressure with depth. None of the field data are consistent with such a linear distribution (Jaakkola, 1998; Fannin and Jaakkola, 1999).

References

Acres International Limited. 1993. GVWD watershed ecological inventory pilot study (Jamieson-Orchid-Elbow drainage) (final report). Acres International Limited, Vancouver, B.C. Report prepared for Greater Vancouver Water District, Burnaby B.C.

Anderson, S.P., Dietrich, W.E., Montgomery, D.R., Torres, R., Conrad, M.E., Loague, K. 1997. Subsurface flow paths in a steep, unchanneled catchment. Water Resources Research, **33**: 2637-2653.

Armstrong, J.E. 1990. Vancouver Geology. *Edited by* C. Roots and C. Staargaard. Geological Association of Canada Cordilleran Section, Vancouver, B.C.

Beven, K., and Germann, P. 1983. Macropores and water flow in soils. Water Resources Research, **18**: 1311-1325.

Brand, E.W., Dale, M.J., and Nash, J.M. 1986. Soil pipes and stability in Hong Kong. Quarterly Journal of Geology, London, **19**: 301-303.

Cheng J.D. 1987. Root zone drainage from a humid soil in the west coast of Canada. Proceedings of the XIXth General Assembly of the International Union of Geodesy & Geophysics, Forest Hydrology and Watershed Management, *edited by* R.H. Swanson, P.Y. Bernier, & P.D. Woodward. Aug. 9-22, 1987, Vancouver Symposium, IAHS Publication No. 167. Wallingford, England, pp. 377-386.

De Vries, J., and Chow, T.L. 1978. Hydrologic behaviour of a forested mountain soil in Coastal British Columbia. Water Resources Research, **14**: 935-942.

Fannin, R.J. and Wilkinson, J.M.T. 1995. An analysis of the Jamieson Creek landslide. Proceedings of the 48th Canadian Geotechnical Conference, Vancouver, B.C. 25-27 Sept. 1995, pp. 635-642.

Fannin, R.J. and Jaakkola, J. Hydrological response of hillslope soils above a debris slide headscarp. A paper submitted to the Canadian Geotechnical Journal (in review).

Golding, D.L. 1987. Changes in streamflow peaks following timber harvest of a coastal British Columbia watershed. Proceedings of the XIXth General Assembly of the International Union of Geodesy & Geophysics, Forest Hydrology and Watershed Management, *edited by* R.H. Swanson, P.Y. Bernier, & P.D. Woodward. Aug. 9-22, 1987, Vancouver Symposium, IAHS Publication No. 167, Wallingford, England, pp. 509-538.

Hammond, C.J., Hall, D., Miller, S., and Swetik, P. 1992. Level 1 Stability Analysis (LISA) documentation for Version 2.0. General Technical Report INT-285, US Dept. of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

Harr, R.D. 1977. Water flux in soil and subsoil on a steep forested slope. Journal of Hydrology, **33**: 37-58.

Hetherington, E.D. 1995. Subsurface flow rates over bedrock on step slopes in Carnation Creek Experimental Watershed. Proceedings, Mountain Hydrology: Peaks and valleys in research applications, *edited by* B.T. Guy and J. Barnard, Canadian Water Resources Association, Vancouver, BC.

Jaakkola, J. 1998. Forest groundwater hydrology: implications for terrain stability in coastal British Columbia. M.A.Sc. thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC.

Montgomery, D.R., and Dietrich, W.E. 1996. A physically based model for the topographic control on shallow landsliding. Water Resources Research, **30**: 1153-1171.

Pack, R.T. 1997. New developments in terrain stability mapping in BC. Proceedings of the 11th Vancouver Geotechnical Society Symposium - Forestry Geotechnique and Resource Engineering. *edited by* S. Cullum-Kenyon, BiTech Publications, Richmond, BC. pp. 3-16.

Pierson, T.C. 1983. Soil pipes and slope stability. Quarterly Journal of Geology, London, **16**: 1-11.

Sidle, R.C., Kitahara, H. Terajima, T. and Nakai, Y. 1995. Experimental studies of the effects of pipeflow in throughflow partitioning. Journal of Hydrology, **165**: 207-219.

Smith, D. and Gerath, R.F. 1991. Geotechnical assessment of 1990-1991 landslide events in Greater Vancouver Water District watersheds. Thurber Engineering Limited, report prepared for the Greater Vancouver Water District, Burnaby, BC.

Wilkinson, J.M.T. 1996. Landslide initiation: a unified geostatistical and probabilistic modeling technique for terrain stability assessment. M.A.Sc. thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC.