Estimating Hydraulic Conductivity Assisted with Numerical Analysis for Unsaturated Soil - A Case Study

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ABSTRACT: Meteorologically induced pore water pressure changes and associated changes in effective stress often affect the behaviour of geotechnical structures such as slopes. Seasonal fluctuations in pore water pressure can lead to stiffness degradation which is also known to have caused a number of failures across the world. These effects are likely to become more severe in the future as dryer summers and wetter winters are expected to become more frequent climate scenario in many parts of the world. To analyse the behaviour of a slope subjected to atmospheric boundary interactions, a number of parameter may be used including the soil water characteristics curve, saturated and/or unsaturated hydraulic conductivity of soil, and strength parameters. Some of them (e.g., hydraulic conductivity) are very difficult to deduce with high degree of certainty because of natural variability of soils and limitations in testing procedure. This paper outlines how numerical techniques combined with conventional field or laboratory investigation can serve as a useful technique to overcome some of these limitations specially in deducing hydraulic conductivity. The effectiveness of these techniques will be tested using a well-documented case study form the United Kingdom.

KEYWORDS: Pore water pressure, Atmospheric boundary, Climate change, Effective stress, Shear strength, Slopes, Soil water characteristics curve.

1. INTRODUCTION

Slope failures are often triggered by change in pore water pressure (pwp) due to meteorological events such as prolonged rainfalls. Changes in pwp cause changes in effective stresses and may lead to serviceability problems (e.g., excessive swelling near the tow of a slope can cause restrictions on speed limits on a road way or rail track and poor ride quality). In some cases, it may lead to catastrophic failures of structures such as embankments or cut slopes. In addition, the effects of seasonal climatic changes on the pwp can lead to delayed failures of cut slopes in clays because of stiffness degradation (Sivakumar et al., 2007). Conventional design methodology methodologies based on worst possible pwp condition (e.g., full saturation condition) may not guarantee that the structure will remain structural integrity stable/serviceable throughout its intended design life.

Extreme weather conditions with increasing frequency are evident in many parts of the world. For example, the winter of 2000/2001 was the wettest on record in the United Kingdom (UK) and the period of May-July 2007 was wettest for 250 years and caused extensive flooding in many parts of the country (Toll et al., 2008). Singapore recorded its wettest December in 2006 since the record began in 1869 (NEA, 2006). In 2011, Thailand was struck by monsoon and tropical cyclone rains causing extreme flooding in the city of Bangkok. The weather extremes have been forecasted to be even more frequent in the future in many parts of the world including Ireland and the UK (Murphy et al., 2009).

Changes in climate are already having an impact on transport networks of many different countries. Meteorologically induced pwp and seasonal cycling have been responsible for the failure of a number of slopes in recent years (Sivakumar et al., 2007). More than 160 slope failures were reported during the winter of 2000/2001 by the UK Rail and Road authorities (Ridley et al., 2004; Turner, 2001). Similar occurrences have been reported by the Singapore Building and Construction authority (Ng et al., 2007) for the year of 2006/2007.

To better understand the long term effect of climate change on the behaviour of infrastructure slopes, the first logical step is to better understand the interaction between the atmospheric boundary and the vegetation-soil-slope system. In recent years, a number of studies have investigated the effects of different meteorological parameters on the stability of infrastructure slopes. For example, Smethurst et al. (2006), Smethurst et al. (2012), Smethurst et al. (2014), Clarke and Smethurst (2010), Briggs et al. (2013), Bolton and Take (2011) and Potts et al. (1997) investigated different aspects of interaction between meteorological parameters and soil-slope system using laboratory and field investigations.

Davies et al. (2014) and Rouainia et al. (2009) investigated the generation and dissipation of meteorologically induced pwp and its effect on slope stability using coupled hydro-mechanical modelling using SHETRAN (Ewen, 2001) and FLAC-TP flow (Itasca consulting group, 2005). They demonstrated the advantages of using sophisticated modelling approach in analysing the interaction between soil and atmospheric boundary.

Among others, Briggs et al. (2012) investigated the generation of pwp in railway embankments using a one dimensional VADOSE/W (Geo-Slope, 2013) model, Tsaparas and Toll (2002) presented modelling of infiltration and compared with field measurements (6 months) from a residual soil slope in Singapore. In many of the numerical studies (e.g., Davies et al., 2014; Rouainia et al., 2009; Briggs et al., 2012), the analyses were complicated and a number of input parameters (such as leaf area index, root depth) had to be guessed or adjusted. They are often very difficult to deduce objectively.

In any seepage analysis hydraulic conductivity (K), is one of the most important input parameter (for both saturated and unsaturated soils). Estimating an appropriate value even for a saturated soil (K_{sat}) can be difficult. K_{sat} deduced from field and laboratory tests are often different. In some cases the difference can be of orders of magnitudes. Furthermore, K_{sat} deduced from field tests can be affected by local heterogeneity. The implicit assumptions made in the interpretation of the test data may also influence the result, which are often overlooked (Karim and Lo, 2015).

Moreover, K in unsaturated soil (K_{unsat}) varies with soil suction and is difficult and often expensive (requiring specialized skills test equipment) to deduce even in a controlled laboratory environment. It can be extremely difficult to have an objective estimation of K. This paper presents an alternative (observational) approach for the estimation of K_{unsat}.

Also, in this paper, a simplified approach to calculate pwp changes in a soil-vegetation-atmospheric boundary (SVA) system is presented. A simplified flux boundary condition is defined which can represent the combined effect of the atmospheric boundary and vegetation on the pwp behaviour. This way, the use of some of the difficult to deduce parameters (leaf area index, root depth) often used in analyses of SVA are avoided.

The effectiveness of the proposed approach is demonstrated by comparing the calculated volumetric water content (θ), near surface suction and deep pwp responses with the measured values from an instrumented research site. The site, hereafter referred to as Craigmore cutting, is located on the Newry- Portadown railway line, adjacent to the A28 at Craigmore, Northern Ireland. The site was instrumented and monitored for more than 3 years (between 2009 and 2012).

2. RESEARCH SITE: CRAIGMORE CUTTING

Details of the research site (i.e., geometry, geology, instrumentation and monitoring) can be found in McLernon (2014). A brief description is presented here.

The slope is a cutting made in heavily over-consolidated glacial till and was constructed in the 1850s. The slope is East facing with 17 m height and a slope angle of approximately 36 degree. Figure 1 presents the plan view and a cross section of the slope along the instrumentation line. The slope became a concern for the Northern Ireland railway authorities due to evidence of shallow surface failures, bent tree trunks and seepage on the face of the slope. Along the length of this cutting, there are near vertical sections where possible failures might have occurred in the past.

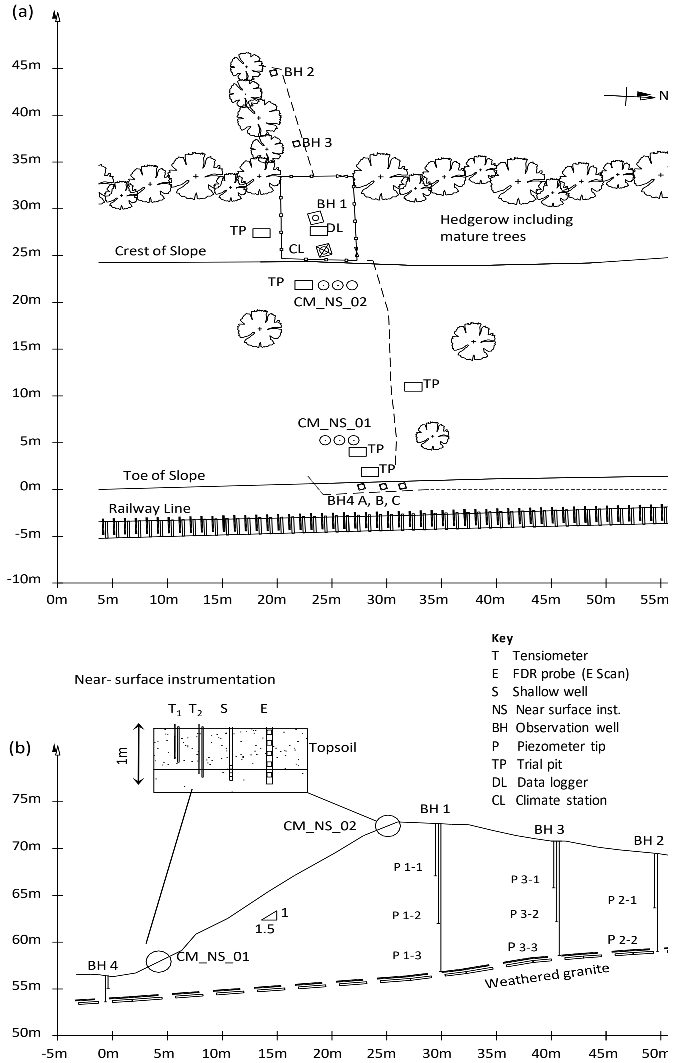


Figure 1 The Craigmore research site plan view and cross-section including instrumentation details (McLernon, 2014)

The ground investigation involved drilling of boreholes, excavation of trial pits, insitu testing (K_{sat} tests using Guelph permeameter and variable head tests) and soil sampling for laboratory testing (moisture content test, particle size analysis, index tests and strength tests). The underlying bedrock at the research site was found to be weathered granite closer to its top surface and shows significantly higher *K* than the layers above.

Bulk samples obtained from the site, contained 20-30% of larger particles (> 20 mm) including gravel and cobbles. The gravimetric moisture content of the insitu soil with were found to be in the range of 10 to 30%. The porosity of the soil ranged between 0.2 and 0.5 with a bulk unit weight of 22.7 kN/m^3 to 22.9 kN/m^3. Particle size distribution graphs for samples collected from different depths the site are presented in Figure 2. Atterberg limit test on the fine fraction revealed liquid limit to be in the range of 29-32% and plastic limit was found to be in varying within 14 to 18%. The consistency of the soil varied from stiff in the upper till layer to very stiff in the lower till layer.

The K_{sat} values at the site were measured over a period of 2 years. Figure 3 presents the deduced values at different depths (from both Guelph permeameter and variable head tests). Differences of up to 4 orders of magnitude can be observed in test results.

The site is covered with vegetation dominantly grass and shrubs with a few mature trees on the face of the cutting.

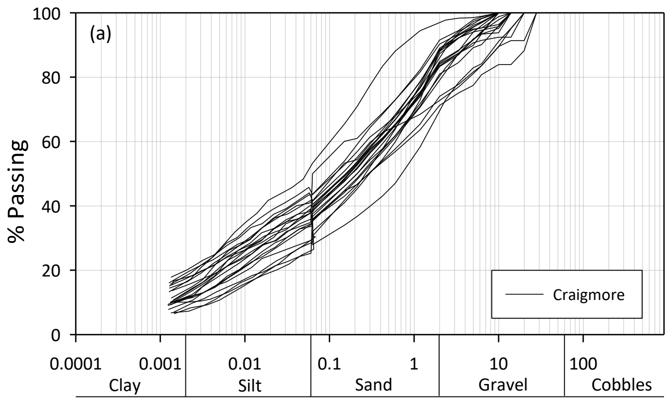


Figure 2 Particle size distribution for samples collected from different depths at Craigmore cutting (McLernon, 2014)

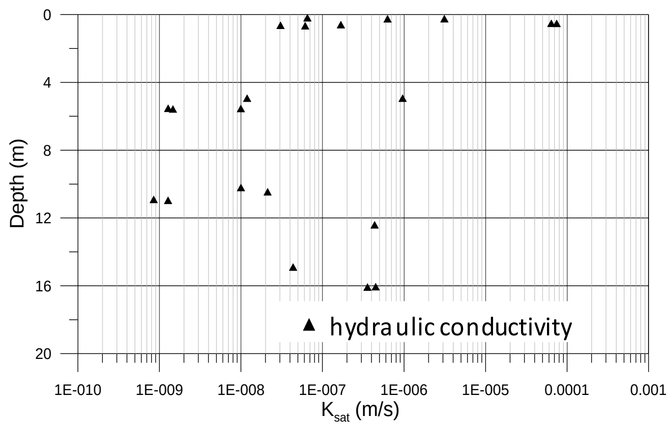


Figure 3 Saturated hydraulic conductivity determined from different field tests (Carse, 2014)

Instrumentation included near surface soil moisture probes to measure moisture changes above the phreatic surface, near surface tensiometers (standard water filled) to measure soil suction, piezometers to measure pwp at greater depths, and a weather station to record local meteorological parameters.

Pwp was monitored at multiple depths over a period of 3 years in borehole BH1 (crest location). Additional monitoring points at the bedrock till interface (BH2-2) and BH4A at toe location were recorded for approximately 1 year. This was supplemented by manual dips at BH2-1 BH3-1, BH3-2 and BH3-3 to the rear of the slope.

3. NUMERICAL ANALYSIS

The analysis discussed here is conducted using SEEP/W (Geo-Slope, 2013a) - a finite element program capable of analysing groundwater seepage and pwp distribution within a porous media such as a soil in a saturated or an unsaturated state. The pwp distribution from such analysis (provided that the movements in the soil were not large or fast enough to cause changes in the water pressure) can be used as input for a stability analysis to assess the safety factor of the slope, or in a stress-strain analysis to assess the serviceability conditions (such as deformations).

For a complete description of seepage behaviour of a soil, SEEP/W (Geo-Slope, 2013a) requires the knowledge of soil water characteristics curve (SWCC) and a K_{unsat} function (i.e., variation of K with suction).

3.1 Geometry and Mesh

The discretised geometry used for the analyses is presented in Figure 4. The geometry was extended by approximately 75 m on the left and 90 m on the right of the cutting to avoid boundary effects. Pwp and other variables usually change rapidly close to the exposed soil surface. To avoid numerical ill-conditioning, smaller size elements (0.125 m thickness) were used in that zone and larger sized elements were used (1 m) at greater depths. A total of 5118 nodes and 4859 elements (3 nodded triangular and 4 nodded rectangular) were used to discretize the geometry.

3.2 A Simplified Flux Boundary Condition

To model the interaction between atmosphere and vegetation-soil system, an equivalent flux boundary condition (net surface flux – *NSF*) is defined here and is used as input to the model. *NSF* can represents the combined effect of meteorological parameters and vegetation on the pwp regime of soil (net effect of rainfall, runoff and evapotranspiration).

In absence of any other source or sink, rainwater may enter the soil through the ground surface and leave as a result of evapotranspiration and interflow. From the water balance equation (Blight, 2003),

$$\sum R - RO - ET - S + RE = 0 \tag{1}$$

where, R is the rainfall, RO is the runoff, ET is the actual evapotranspiration, S is the change in stored water within the soil mass and RE is the net recharge from surrounding soils. Assuming in a soil mass, the net effect of interflow $RE \approx 0$, we can consider S to be equal to *NSF*. Thus,

$$SF = \sum R - RO - ET \tag{2}$$

To calculate ET a reference value (ET_r) is calculated using the Penman-Monteith equation (Zotarelli et al., 2013). ET was then deduced using the following relationships,

$$ET = ET_r \qquad \text{for } 0 \leq SMD \leq RAW \tag{3}$$

$$ET = ET_r \times \frac{TAW - SMD}{TAW - RAW} \qquad \text{for } SMD \geq RAW \tag{4}$$

where, SMD is the soil moisture deficit, RAW is readily available water, and TAW is the total available water.

Table 1 Parameters used for the calculation of evapotranspiration

Parameter	Value
Psychrometric constant (kPa/^{0}C)	0.000665×atm.
Solar constant	0.082
Latitude (rad)	0.946614
Albido or canopy reflection coefficient	0.23
Stefan-Boltzman constant (Mj/K^4/M^2/day)	4.903×10^{-9}
Elevation above sea level (m)	70

The meteorological data needed for the calculation of ET_r i.e., temperature, dew point, and wind speed were collected from the weather station installed at the research site (see Appendix A). Other parameters required are presented in Table 1.

It is to be noted that, RO was not measured at the research site during the period under consideration. It was estimated using a two tank soil water storage model (SWSM) (McLernon, 2014). The model calculates how much water from a particular intensity of rainfall infiltrates the soil based on the available storage capacity and permeability of soil. The amount of water that cannot infiltrate, is treated as RO. That means, even if the soil has enough storage capacity, if the rainfall intensity is more than the soil's capacity to allow water in (permeability), the excess water will flow as runoff. Depending on the amount of rainfall, ET and runoff, *NSF* can assume a positive or a negative value. A positive value will mean water is infiltrating into the ground, whereas, a negative value will indicate ET is dominant and water is leaving the soil matrix.

3.3 Other Boundary Conditions

Based on the field investigation, drainage was allowed on the left and right hand sides of the fractured bedrock layers (modelled as potential seepage face). The ballasted surface under the rail track was modelled with a zero pwp boundary condition. *NSF* was applied at the exposed slope surface.

3.4 Material Models

All soil types were modelled using the "saturated/unsaturated" option. That is, the soil could remain in a saturated or an unsaturated state during an analysis, or it could change state depending on the analyses parameters and boundary conditions.

Site investigation showed 3 distinct material types namely, weathered upper till layer, lower till layer and a weathered (fractured) bedrock layer. The soil near the exposed slope surface for both the upper and lower till layers showed higher K probably due to the presence of plant roots and other organic matter. Two additional

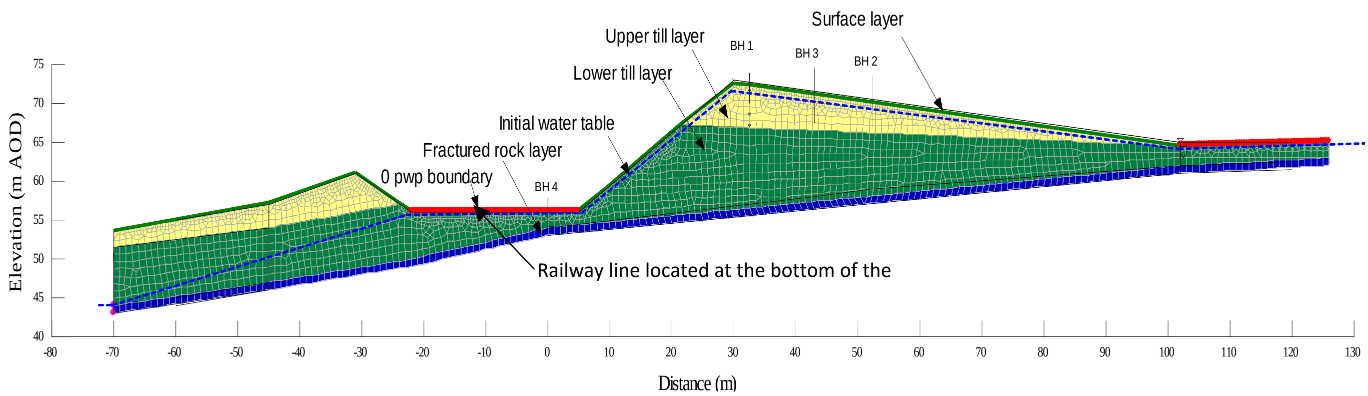


Figure 4 Discretized geometry used for the Craigmore cutting analyses

materials were created to model this near surface soil. The thickness of the near surface layers were taken as 0.4 m (thickness of A and B horizons from the field investigation) and the K of these layers were assumed to be 10 times than the corresponding layer below (Toll et al. 2012). The input parameters necessary for describing the material behaviour are discussed next.

3.4.1 SWCC

The SWCCs for the upper and lower till layers and the weathered bedrock layer was taken from McLernon (2014). There was inadequate information available on the SWCC of the near surface material layers. They were modelled using the same SWCC as of the layers below. The SWCCs for different soil layers are presented in Figure 5.

3.4.2 Estimation of Hydraulic Conductivity

For modelling flow through an unsaturated soil, a K_{unsat} function needs to be defined. This function can be estimated from laboratory or field tests. In this investigation, however, test K_{unsat} data was not available. For these situations, SEEP/W (Geo-Slope, 2013a) allows the choice different functions (Fredlund and Xing, 1994; Green and Corey, 1971; Van-Genuchten, 1980) that uses correlations with K_{sat} and SWCC. The Van-Genuchten (1980) function was used in this study.

$$\mathrm{k_{unsat}} = \mathrm{k_{sat}} \frac{[(1-(a\Psi^{n-1})(1+(a\Psi^{n})^{-m})]^2}{(1+(a\Psi)^n)^{\frac{m}{2}}} \tag{5}$$

where, a, n and m are curve fitting parameters and Ψ is the suction range. K_{sat}, for a particular soil type, can be deduced using laboratory and/or field tests.

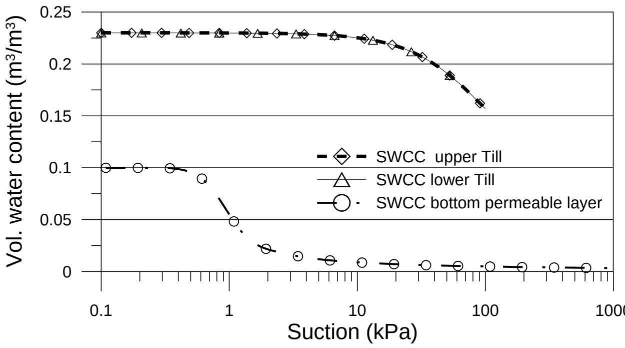


Figure 5 SWCCs used for material models used in Craigmore cutting analyses (McLernon, 2014)

Table 2 Initial estimates of K_{sat}

Property	Value (m/s)
K_{sat} upper till	1.75×10^{-7}
K_{sat} lower till	1.75×10^{-8}
K_{sat} weathered bedrock	7.0×10^{-7}

As shown in Figure 3, there were up to 4 orders of magnitude differences in K_{sat} values at different depths. This makes an objective estimation of K_{sat} very difficult. An alternative and objective approach is discussed here.

Originally proposed by Lo et al. (2008), this method was used to estimate K_{sat} for vertical drain improved soils. They used numerical analysis of field settlement data to estimate an equivalent K_{sat}. The engineering approximation was that in a consolidation analysis around a vertical drain the combined effect of different K in undisturbed and smear zone on flow of water can be captured by an equivalent value. The effectiveness of the method in different problem domains has been demonstrated by Karim et al. (2010), Karim et al. (2014), Lo et al. (2013) and Manivannan et al. (2011). In this paper, the method is extended to work in the unsaturated flow domain.

The assumption made here is that the effect of local heterogeneity and presences of cracks and fissures in the soil can be captured by an equivalent number. Equivalent K_{sat} has been estimated by numerically analysing the first 6 months of field measured pwp data. Piezometer readings from two locations, i.e., BH1.1 (5.6 m BGL) and BH1.3 (16.0 m BGL) were used for this purpose. Few trial analyses were conducted with K_{sat} being systematically varied until a good match was found.

In principle this process is not very different from conventional techniques used to deduce K_{sat}. Interpretation of many of the field tests also involve a number of assumptions and back-fitting of field observations. For example, in a Guelph Permeameter test, the flow of water into soil is observed and collected data are interpreted using saturated-unsaturated flow theories to estimate K_{sat}.

It is to be noted that, the calculation of *NSF* involves the estimation of *RO* using a two tank SWSM and which is also dependent on K. Thus, an iterative process was adopted for the estimation of K_{sat} and *NSF*. The step by step procedure is outlined below.

1. The first step in the process was to make an initial estimation of K_{sat}. It is difficult to objectively estimate a value for K_{sat} as the numbers scattered over a large range. From Figure 3 educated guesses were made. The chosen values of K_{sat} were 1.75×10^{-7} m/s for the upper till, 1.75×10^{-8} m/s for the lower till layer. Value of 7×10^{-7} m/s (McLernon, 2014) for was chosen for the weathered bedrock layer. After Toll et al. (2014) the K_{sat} values for soils in A and B horizon (top 0.4 m in this case from field observations) were assumed as 1 order of magnitude bigger than values of the layers below.
2. Following this, *RO* was estimated using the two tank SWSM model and daily *NSF* was calculated using Eq. (2).
3. The deduced *NSF* was then used as an input flux boundary condition in a first trial numerical analysis. Results were compared against the field observations at 2 different depths (BH1.1 - 5.6 m BGL and BH1.3 - 16 m BGL) as presented in Figures 6 and 7. It can be seen in the figures, the calculated pwps are not in good agreement with the field observations, especially at greater depths.
4. In the next step, K_{sat} values were systematically varied until a good match between the observed and calculated pwps were found. For every chosen K_{sat}, the calculation for surface *RO* and *NSF* was repeated. Analysis results using best matched (equivalent) K_{sat}, are also presented in Figures 6 and 7. The best matched values of K_{sat} were found to be, 1.875E-9 m/s for the lower till layer and 2.025E-7 m/s for the upper till layer. They are approximately 10 times smaller and 1.15 times larger than their respective first trial values.

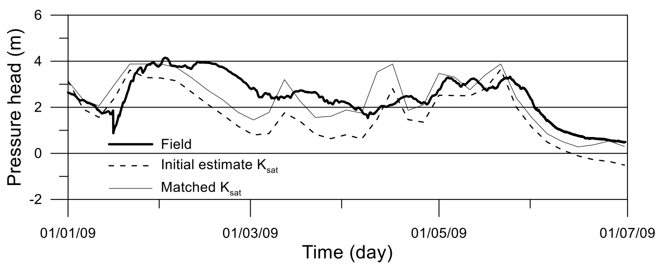


Figure 6 K_{sat} estimation trial plots for Craigmore cutting at BH1.1

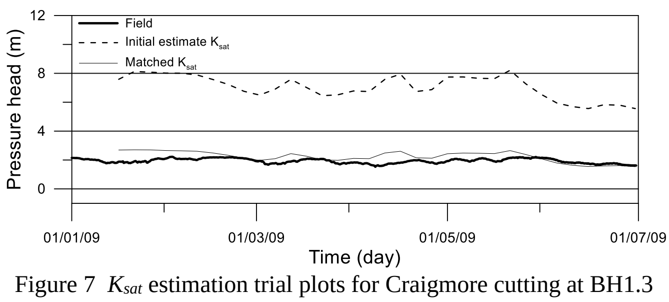


Figure 7 K_{sat} estimation trial plots for Craigmore cutting at BH1.3

The best match K_{sat} was used for further analysis of the problem. Using best match K_{sat}, *NSF* values were calculated for the entire monitoring duration of 3 years (January 2009 to December 2011). Recorded rainfall, calculated *ET* and *RO* along with *NSF* values for the best match K_{sat} scenario are presented in Figure 8.

For comparison purpose, two different analyses were conducted. One with first trial K_{sat} and corresponding *NSF* values (Analysis 1) and the other with the best matched K_{sat} and corresponding *NSF* (Analysis 2).

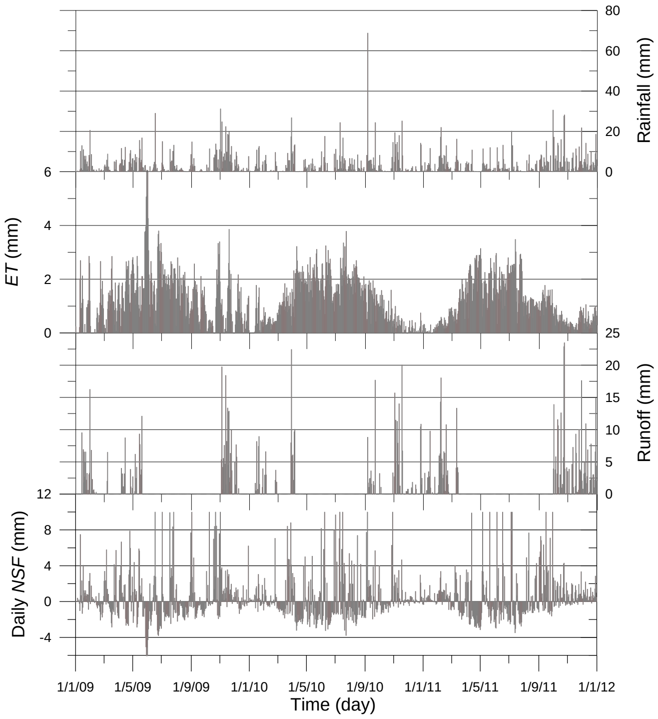


Figure 8 Recorded rainfall, calculated *ET*, surface runoff and *NSF* (Analysis 2) for Craigmore research site (2009-2011)

4. RESULTS AND DISCUSSION

4.1 Deep PWP Response

Figures 9 to 11 present the field measured pressure heads at different depths (5.6 m, 10.7 m and 16.0 m) at BH1.1 along with the calculated values form the two analyses. At shallower depth (5.6 m) Analysis 1 under calculated the pressure head and at greater depths (10.7 and 16.0 m BGL) it consistently over calculated throughout the analysis period of 3 years. At BH1.2, the overestimation was by up to 4 m of pressure head during the months of November 2010 to February 2011. For the case of BH1.3 the difference between the calculated and observed pressure heads varied between 4 and 6 m.

Calculations from Analysis 2 (with matched K_{sat}), on the other hand, were much closer to the field observations. It captured the crest and troughs of the pressure head variation with good accuracy including the seasonal/inter-seasonal fluctuations. The maximum difference in peak pressure head between the field observation and calculation was approximately 2 m at BH1.2. At other depths calculation accuracy was better (difference less than 1 m at BH1.3).

It is interesting to note that, in Analysis 1, K_{sat} values were approximately 1.5 times lower in the upper till layer (than corresponding matched value) and it resulted in under calculation of pressure head. The opposite was the case for the lower till layer (values were 10 times higher than matched value). The lower *K* in the upper till layer reduced the capacity of water to infiltrate fast enough before the stored water in the active zone (top 0.4 m approximately) got removed by evapotranspiration or drainage. In the lower till layer, on the other hand, because of higher K_{sat} (relative to matched value) water could get into the soil but the fractured rock layer (acted as a drainage) could not remove the water quick enough resulting in higher than measured pressure head.

The drainage condition at the bedrock interface played an important role in the pwp dynamics. The fractured bedrock layer was modelled using a K_{sat} value obtained from a limited number of field tests, an assumed thickness and SWCC. The assumption on the SWCC should not significantly affect the calculation accuracy as the soil there is likely to remain saturated for the entire duration of modelling. If a different thickness and/or K_{sat} value for the fractured bedrock layer was used, it will affect the pwp dynamics and the matched K_{sat} values will be different.

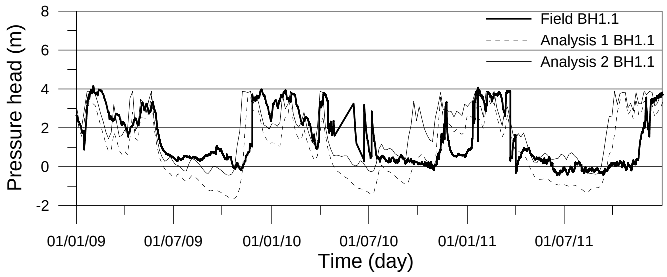


Figure 9 Measured and calculated pwp heads for BH1.1 from two different analyses

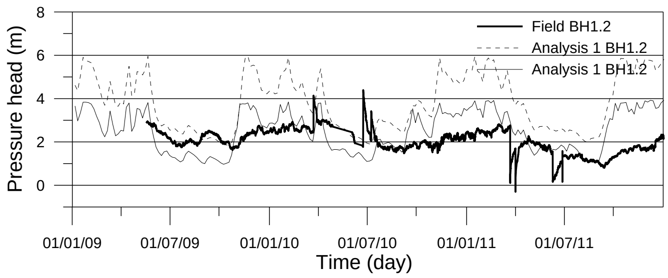


Figure 10 Measured and calculated pwp head for BH1.2 from two different analyses

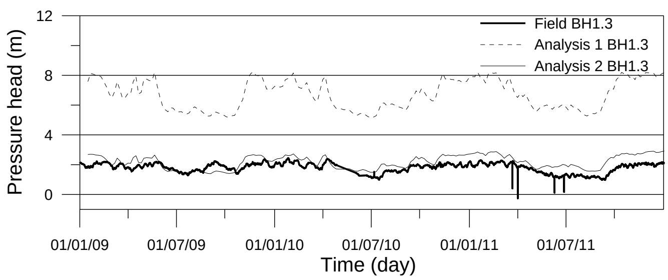


Figure 11 Measured and calculated pwp head for BH1.3 from two different analyses

4.2 Near Surface Suction Response

In Figures 12 and 13, measured and calculated suctions at 0.8 m BGL at the toe and crest location (respectively) are presented. From the field observations, the toe location remained saturated or in a near saturation state throughout the monitoring period (1.5 years). However, both Analysis 1 and 2 calculated suction generating (up to 15 kPa magnitude) during the spring and summer months.

From the field observation, the crest location remained in a near saturated state for approximately half of a year (October to March). After March 2011, suction started to build up slowly and peak suction of 40 kPa was observed in September 2011. Both analyses, on the other hand, calculated the build-up of suction much earlier and the peaks and troughs of the suction trend were much more pronounced. There were nominal differences between the two analyses results. The peak suction magnitude was captured with reasonable accuracy.

The differences between the calculated and observed suction can be attributed to the assumptions related SWCC and to some extent estimation of *K* in the surface layer. The SWCC for the surface layers were considered to be the same as of the corresponding layers below. These predictions can be improved by using a better estimation of SWCC and including both wetting and drying SWCC in the analyses.

4.3 Volumetric water content response

Figure 14 presents the calculated and measured volumetric water content from July 2010 to December 2011 at 0.9 m depth at the crest location. There was minimal difference between the two different analyses results. Both analyses underestimated the maximum and minimum water content which occurred during winter and summer months, respectively. This can be attributed to the choice of SWCC. To better capture the volumetric water content profiles, SWCC needs to be estimated using extensive field or laboratory tests.

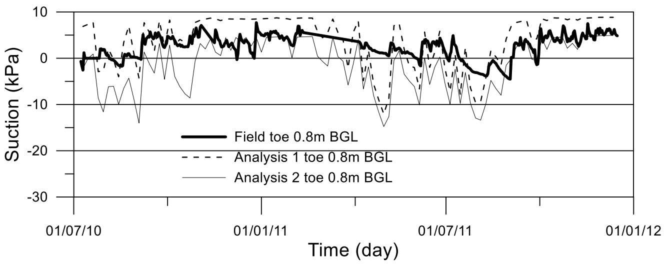


Figure 12 Measured and calculated suctions at the toe location 0.8 m BGL

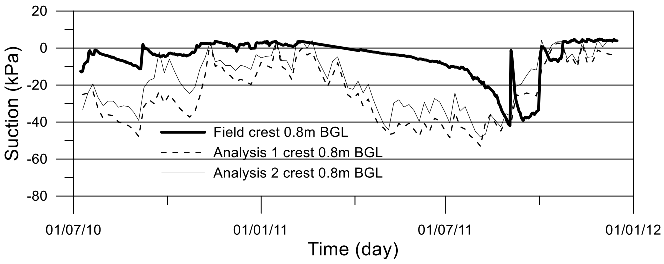


Figure 13 Measured and calculated soil suctions at the crest location 0.8 m BGL

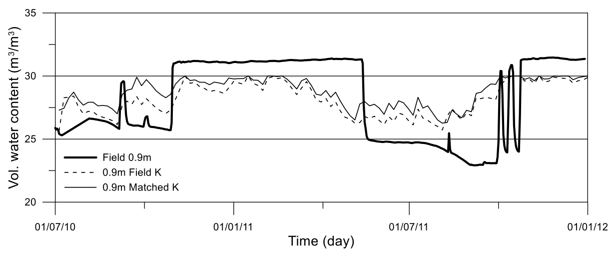


Figure 14 Measured and calculated VWC at 0.9 m depth at the crest location

4.4 Spatial Distribution of PWP and Temporal Variation of Factor of Safety

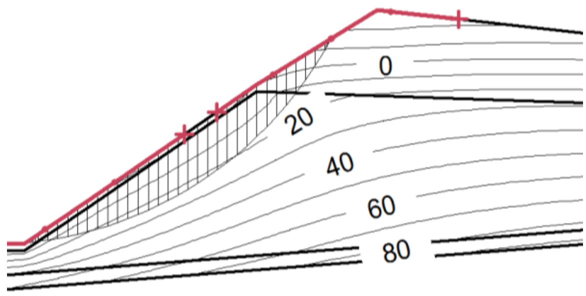
Distribution of pwp for the slope for a selected date of 1 January 2010 (mid-Winter) are presented in Figures 15(a) and 15(b) for Analyses 1 and 2, respectively. Significant differences can be observed between the contour plots. Analysis 1, conducted with an initial estimate of K_{sat} calculated significantly higher pwp. Analysis 2, on the other hand, calculated significantly lower pwp. There was a small suction bulb (approximately 8 kPa) generated and was carried through the winter in Analysis 2.

It is interesting to note the differences in pwp distribution caused by choice of K. Analysis 1 carried out with a lower value of K for the lower till layer (approximately 10 times) reduced the drainage of water into the fractured rock layer and as a result, there was a higher buildup of pwp. Furthermore, slightly higher values of K for the upper till and surface layer allowed more water to enter and be enter and to be stored there during rainfall periods and consequently increased the supply of water to be infiltrated into the lower till layers. The opposite was the case for Analysis 2. Thus, the differences in the pwp distribution were dominantly controlled by the balance of the water entering and leaving the lower till soil layer.

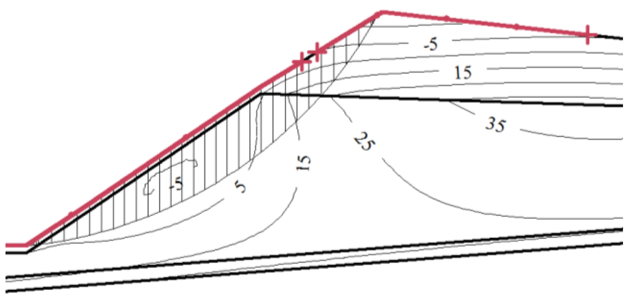
Using the calculated pwp distributions (from both Analysis 1 and 2), 2 sets of limit equilibrium (Morgenstern-Price) analyses were conducted using a numerical program SLOPE/W (Geo-Slope, 2013b). The soil strength parameters used for the slope stability analyses are presented in Table 3 and were taken from McLernon (2014). The calculated factor of safety (FOS) at different points in time (mid winter and mid summer for 3 years) are presented in Figure 15(c). Calculated FOS from Analysis 1 was consistently below 1 during the winter months which can be treated as unrealistic considering the fact that the slope has been in service for more than 150 years and has only shown some shallow surficial failures. For the case of Analysis 2, the calculated factor of safeties varied between 1.1 and 1.5. This can be treated as a more realistic number.

Table 3: Soil properties used for the limit equilibrium analyses (McLernon, 2014)

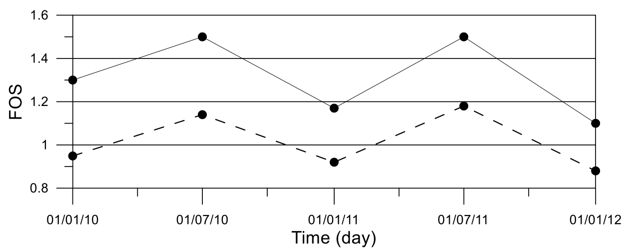
	Unit wt. (kN/m^3)	C (kPa)	φ (degree)
Surface layers	20	8	31
Upper till	22	8	31
Lower till	22	8	31
Bedrock	22	5000	50



(a)



(b)



(c)

Figure 15 Pwp distribution (contour labels are in kPa) in Craigmore cutting on 1 January 2014: (a) Analysis 1, (b) Analysis 2, and (c) FOS changes with time in the two analyses

None of the analyses were able to produce any indication of the shallow failures observed on the slope. In reality, shallow failures can occur due to a number of reasons including stiffness degradation because of pwp cycles, loss of strength of soil because of decaying plant roots, local scouring of soils due to heavy rainfall and so forth. The simple limit equilibrium analysis was not adequate to capture such complicated features.

5. CONCLUSIONS

This paper discusses an alternative and objective approach of estimating hydraulic conductivity for seepage analysis in the unsaturated domain. A simplified approach in modelling the meteorologically induced pwp variations has also been discussed. The effect of atmospheric boundary and vegetation on the pwp regime of a cut slope was modelled using a calculated equivalent flux boundary condition which represented the infiltration due to rainfall and also the water uptake due to evapotranspiration.

Near surface suction, deep pwps and volumetric water content measurement from an instrumented research site were used for assessing the validity of the approach. The analysis using the initial estimation of K_{sat} produced reasonably good results for the near surface layers. However, it failed to capture the deeper pwp variations with sufficient accuracy. The analysis conducted using the equivalent K values produced better pwp predictions at all the different depths under consideration throughout the monitoring period of 3 years.

To demonstrate the influence of the parameter K_{sat} on the predicted pwp distribution and related stability two sets of limit equilibrium analyses were conducted. The analysis conducted with the initial estimate of K_{sat} resulted in low factor of safety. The stability calculation from the matched K_{sat} analysis was more realistic. This emphasizes the importance of having a proper estimation of K and its influence on behaviour of soil slopes.

6. ACKNOWLEDGEMENTS

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8. APPENDIX

Appendix A: Additional Parameters Needed for Calculating NSF

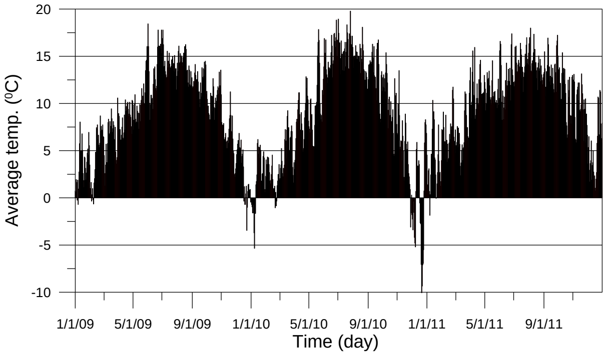

Figure A1 Average daily temperature level at the Craigmore research site (2009-2011)

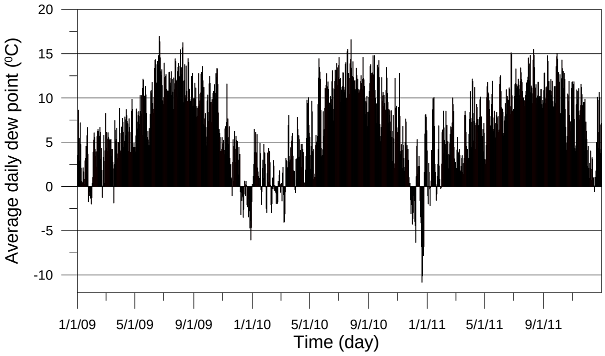

Figure A2 Average daily dew point at the Craigmore research site (2009-2011)

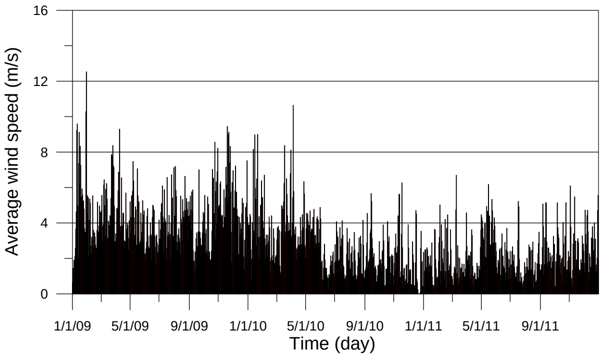

Figure A3 Average daily wind speed 2 m above the ground level the Craigmore research site (2009-2011)