ANALYSIS OF SOIL SUCTION CHANGES IN EXPANSIVE REGINA CLAY

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ABSTRACT

The prediction of seasonal soil suction changes is critical to the analysis of volume change in unsaturated, expansive soils. A one-dimensional moisture flow model was developed to study the boundary flux and suction conditions in a soil profile at a test site in Regina, Saskatchewan. The test site was part of an extensive study related to ground movements and associated distresses caused to underground water mains. A parametric study was performed to study the effects of net radiation, wind speed, precipitation, soil properties and initial suction conditions on the amount of actual evaporation, net infiltration, and variation of soil suction and depth of suction change in the soil profile for a period from 1 November 2005 to 31 October 2006.

RÉSUMÉ

La prédiction de changements saisonniers de succion de sol est critique à l'analyse de changement de volume dans aux sols non saturés et expansifs. Un modèle de flux d'humidité dans une dimension a été développé pour étudier le flux de frontière et les conditions de succion dans un profil de sol à un site de test dans Regina, Saskatchewan.. Le site de test faisait partie d'une étude vaste apparentée aux mouvements de sol et les détresses associées a causé aux tuyaux souterrains. Une étude paramétrique a été exécutée pour étudier les effets de rayonnement net, la vitesse de vent, la précipitation, les propriétés de sol et les conditions de succion initiales sur la quantité de véritable évaporation, l'infiltration nette, et la variation de succion de sol et la profondeur de changement de succion dans le profil de sol pour une période du 1 novembre, 2005 au 31 octobre, 2006.

1 INTRODUCTION

The City of Regina was developed on a post-glacial lake deposit called Regina Clay. The deposit is highly plastic, unsaturated, expansive clay that exhibits large volume changes as the soil water content changes. As a result of the volume changes, light infrastructures buried in the expansive soils such as water mains are often subjected to severe distress during their service life. Recently, the rate of water main breakage has increased in older areas (Hu and Hubble 2005). A study is currently being conducted by the NRC Center for Sustainable Infrastructure Research in Regina to investigate the causes of failures of the water mains. Climate induced soil volume change was determined to be one of the critical factors behind the water main failures. To better understand the behaviour of the water mains during their service, a section of water main was instrumented and installed in an older area of Regina. A series of sensors were also buried in the backfill and in the native soil around the trench to monitor the working environment of the water main.

The prediction of changes in soil suction is critical in the analysis of volume change in unsaturated, expansive soils. Therefore, a part of the study on the water main failures is to model the boundary flux and the suction conditions in the soils. In this study, a one-dimensional moisture flow model was used together with detailed climatic information and vegetation collected at a weather station in the city. Soil properties and initial suction conditions for the modeling were obtained from laboratory tests. A range of net infiltration at ground surface, suction and water content changes of the clay soils were selected for the climatic conditions over a period of one year from 1 November 2005 to 31 October 2006.

2 SITE OVERVIEW

The study site is located in the Emerald Park, a well developed residential area in the south central Regina. The park area and front yards of the houses are grass covered. Various mature deciduous and coniferous trees with up to 560 mm trunk diameters and 12 m height (Figure 1) have grown in the park as well as in front of the residential houses. Water mains of 0.15 m diameter were at approximately 1.8 m depth under the pavement. Houses and big trees may have significant impact on the radiation, wind speed and air temperature at the test location.

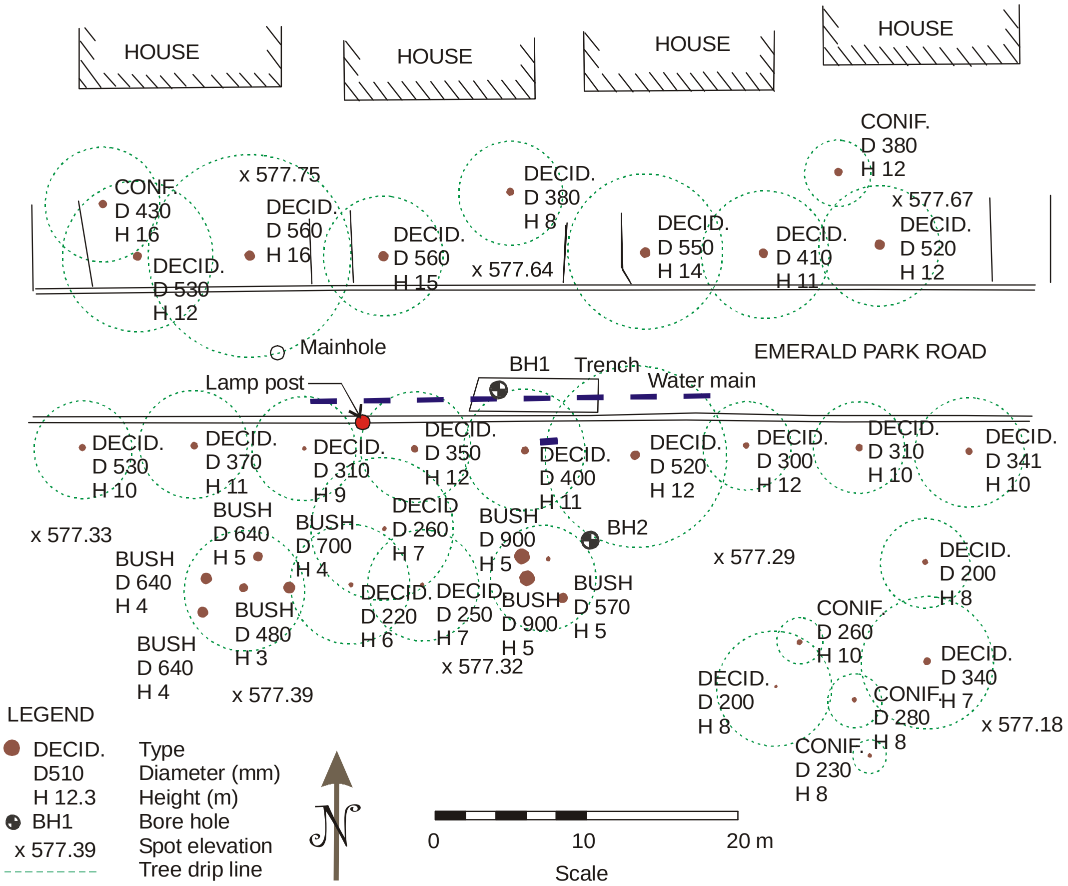

Figure 1. Location of boreholes, water main, trench, trees

3 FIELD INVESTIGATION AND LABORATORY TESTING

Stratigraphy and water content conditions at the site were determined from two boreholes drilled to 15 m depths in October 2005. Borehole BH1 was located north of the water main on the pavement. Borehole BH2 is located in the park approximately 8 m from the south shoulder of the Emerald Park Road. A vibrating wire piezometer was installed at 15 m depth in the till; however, this piezometer has not recorded positive pore-water pressures to-date. Soil laboratory tests include index tests, soil-water characteristic curves, saturated permeability tests, constant volume consolidation tests and measurement of soil suction using the filter paper method.

Figure 2 shows the soil profile, index properties, measured suction and dry density at the test site. The soil profile consisted of highly plastic clay to a depth of about 9.5 m, and glacial till. For Regina clay, the liquid limit varied from 70 to 94, with a plastic index of 40 to 65. Water contents were slightly below plastic limit for the clay and were at about plastic limit for the till. Water contents varied from 22 to 33 for clay and 12 to 20 for till. Attempt has been made to measure both total and matric suction on undisturbed soil samples using filter paper technique; however, the filter paper method may not be able to measure matric suction greater than 1000 kPa because at this high range of suction, most of moisture movement occurs through vapour transfer rather than capillary transfer. Whatman No. 42 filter paper was used together with a calibration curve suggested by Leong et al. 2002. Measured suctions were about 3000 kPa for the upper 4 m of clay, about 700 kPa for the lower 5.5 m of clay and about 2000 kPa for the underlying till. Dry density ranged from 1400 to 1680 kg/m^3. Three saturated permeability tests on clay samples retrieved at depths 2.7, 3.7 and 4.6 m indicate a saturated permeability of 2.0x10^{-9}, 2.8x10^{-9} and 2.0x10^{-9} m/s, respectively. Constant volume odeometer tests on sampled from 3 m and 4.5 m depth show an initial void ratio of 0.93 and 0.97, swelling index of 0.125 and 0.116, and a corrected swelling pressure of 550 and 500 kPa, respectively.

Figure 3 shows the relationship between water content and suction obtained from both the pressure plate test and filter paper methods. Two boundary soil-water characteristic curves, (e.g., the drying and wetting curves), can cover the range of data points as shown in Figure 3. A middle curve is used for the analysis in this study. Fredlund and Xing (1994) equation was used to describe the SWCC.

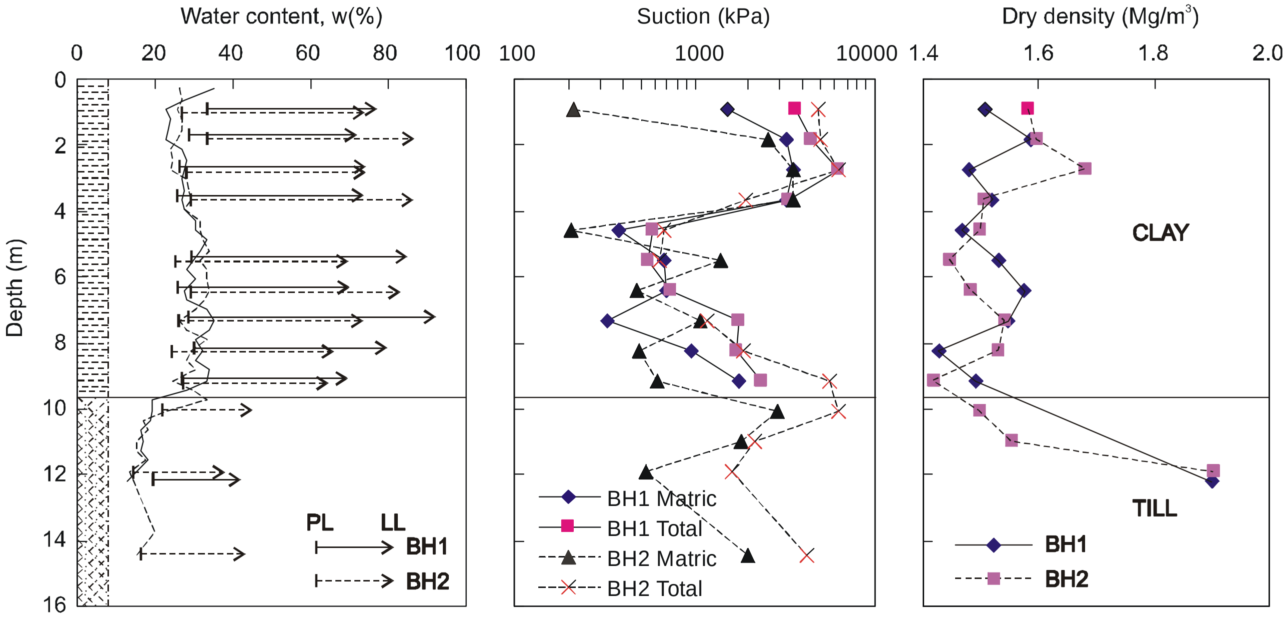

Figure 2. Soil profile and index properties

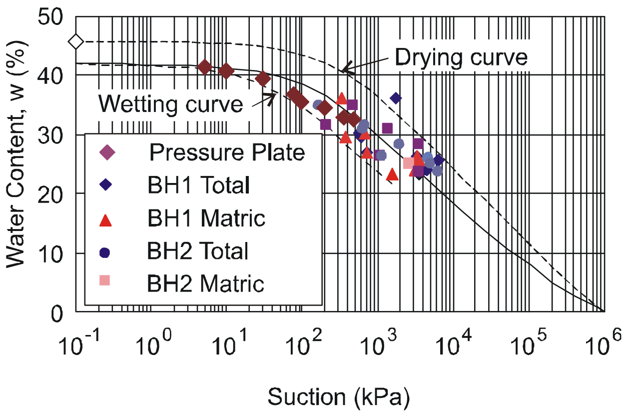

Figure 3. Soil-water characteristic curves

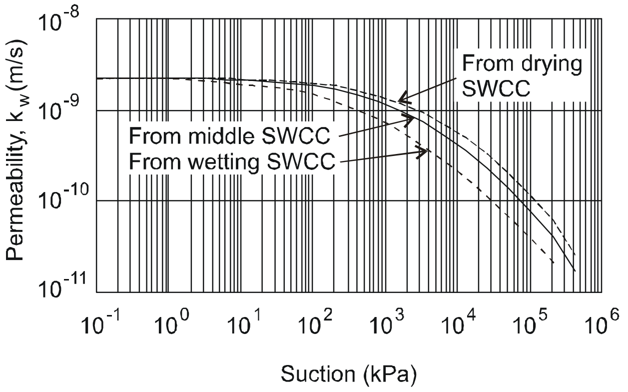

Figure 4. Coefficient of permeability functions

The coefficient of permeability functions were estimated from the SWCC and saturated hydraulic conductivity, using the Leong and Rahardjo (1997) equation. Three permeability functions corresponding to the three SWCC shown in Figure 3 are presented in Figure 4. The middle curve was used for the analysis.

4 GOVERNING PDE FOR MOISTURE (LIQUID/VAPOUR) FLOW

Wilson (1990) presented the governing partial differential equations of heat and mass transfer and their solutions. The governing partial differential equation for a one-dimensional, vertical liquid and vapour flow can be written as follows (Wilson 1990):

$$\frac{\partial}{\partial y}\left[\Bigg(k_y + k^v\left(\frac{\partial h}{\partial y}-1\right)+k_y\right] = m_w^2 \gamma_w \frac{\partial h}{\partial t} \qquad [1]$$

where h is total head, k_y is the hydraulic conductivity in the vertical direction, k^v is the vapour conductivity in the vertical direction (m/s), γ_w is the unit weight of water (kN/m^3), and m_w^2 is the slope of the SWCC (kPa^{-1}).

The vapour conductivity can be expressed as:

$$k^v = \frac{\bar{u}_a + p_v}{\bar{u}_a}\,\frac{g W_v p_v}{R(T+273.15)}\,\frac{D^{v*}}{\rho_w} \qquad [2]$$

where $\bar{u}_a$ is total pressure in the bulk air phase (kPa), u_a + u_{atm}; u_a is pore-air pressure (kPa); u_{atm} is atmospheric pressure, 101.325 kPa; R is universal gas constant, 8.314 J/(mol.K); W_v is molecular weight of water vapour (kg/kmol); T is temperature (^oC); p_v is partial pressure of water vapour (kPa); and D^{v*} is the diffusion coefficient of vapour through the soil.

The diffusion coefficient of water vapour through soil can be estimated as follows:

$$D^{v*} = \alpha\beta D^{v} \frac{W_v}{RT} \tag{3}$$

Where α is tortuosity factor of the soil, $\alpha = \beta^{2/3}$ (Lai et al. 1976); β is cross sectional area of soil available for vapour flow per total area, $\beta = (1-S)n$; S is degree of saturation; n is porosity; D^v is molecular diffusivity of water vapour in air. Kimball et al. 1976 presented the following equation for D^v:

$$D^v = 0.229\text{x}10^{-4}[1+(T+273.15)/273.15]^{1.75}\ (m^2/s)$$

5 EVAPOTRANSPIRATION

Evapotranspiration consists of the combined processes of evaporation and transpiration. This study has been performed using Penman equation (Penman 1948) for potential evaporation and an equation suggested by Wilson et al. 1997 for actual evaporation.

The potential evaporation at the soil-atmosphere boundary can be calculated as follows (Penman 1948):

$$PE = \frac{\Gamma Q_N + E_a \gamma}{\Gamma + \gamma} \tag{4}$$

where PE is potential evaporation per unit time (m/day); Γ is the slope of the saturation vapour pressure curve with respect to temperature (mmHg/^{o}F); Q_N is heat budget (m/day), g is psychometric constant (0.27 mmHg/^{o}F); and

$$\Gamma = a_1 + 2a_2T_a + 3a_3T_a^2 + 4a_4T_a^3 + 5a_5T_a^4 + 6a_6T_a^5 \tag{5}$$

where a_1 = 0.6283580754, a_2 = 0.0411427320, a_3 = 0.0017217473, a_4 = 0.0000174108, a_5 = 0.0000003985, and a_6 = 0.0000000022.

The Ea parameter (m/day) can be calculated as follows (Gitirana 2005)

$$E_a = f(u)p_{vsat}^{air}(1 - RH_a)$$

where p_{vsat}^{air} is vapour pressure of the air above the surface (mmHg); f(u) = 0.35[1+0.146(3.6W_w)]; W_w is wind speed (m/day); and RH_a is the relative humidity of air.

The heat budget can be calculated as follows (Gray 1973):

$$Q_N = \frac{R_e}{L} \tag{6}$$

where R_e is net radiation; and L is latent heat of evaporation, L = 591-0.51T_a.

Actual evaporation (AE) at the ground surface can be calculated as follows (Wilson 1997):

$$AE = PE\left(\frac{p_v - p_v^{air}}{p_{vsat} - p_v^{air}}\right) \tag{7}$$

Vegetation plays a significant and dynamic role in the evapotranspiration process (Saxton 1982). The potential transpiration is a function of the leaf area index (LAI), which is the ratio of the surface area of the leaves and the surface area of the soil covered. The LAI is used to reduce the amount of net radiation intercepting the soil surface which in turn reduces the computed potential evaporation (Unsaturated Soils Group 1996). The potential transpiration is calculated as follows (Ritchie 1972):

$$PT = 0 \ \ \textit{if} \ \ LAI < 0.1$$
$$PT = PE(-0.21 + 0.70LAI^{0.5}) \ \textit{if} \ \ 0.1 \le LAI < 2.7$$
$$PT = PE \ \ \textit{if} \ \ 2.7 \le LAI$$

Where PT is potential transpiration rate (m/day); LAI is leaf area index; and PE is potential evaporation rate (m/day).

The predefined LAI curves for excellent, good, and poor vegetation condition are suggested in SoilCover (Unsaturated Soils Group 1996). Growth season for vegetation was assumed for the period from April to October for this study.

It was assumed that mass flux due to transpiration can be distributed in a triangular shape in the soil (Tratch 1995). The potential root uptake (PRU) at a given point in the soil is calculated as follows:

$$PRU = \frac{2PT}{R_T}\left(1 - \frac{R_n}{R_T}\right) \tag{8}$$

where RT is total thickness of the root zone (m); and R_n is depth (m).

The actual transpiration sink is calculated from the potential transpiration by a reducing term that is based on the moisture availability:

$$S_{root} = PRU\text{x}PLF$$

where S_{root} is actual transpiration sink term (m^3/day); and PLF is plant limiting factor.

The PLF is a reduction term that describes a decrease in transpiration with an increase in matric suction. A limiting point of 500 kPa and a wilting point of 2500 kPa were assumed for this study. The PLF is one for suction less than 500 kPa. Between 500 kPa and 2500 kPa the plant limiting factor is reduced linearly as a function of the log of matric suction. The actual transpiration reaches zero at suction equal to 2500 kPa.

6 COMPUTER PROGRAM

Several commercial software packages are available to model the moisture flow in soils, including SoilCover (Unsaturated Soils Group 1996), HYDRUS-2D (Simunek et al. 1999), Vadose/W (GeoSlope International Ltd. 2005), SVFlux (SoilVision Systems Ltd. 2007) and FlexPDE (PDE Solutions Inc.). SVFlux and FlexPDE were used for the analyses in this study.

7 CLIMATIC DATA

The study period for this modelling task is from 1 November 2005 to 31 October 2006. Climate data obtained at the weather station located at the Regina Airport, approximately 5 km from the site was used. Climatic data obtained for this period include daily precipitation, air temperature, net radiation, wind speed, and relative humidity.

The recorded daily precipitation is presented in Figure 5. Annual precipitation of 366 mm for the study period was recorded. A maximum daily precipitation of 39 mm was measured on 17 April 2006.

The park area is approximately 7860 m^2. The park is watered twice a week for 60 to 75 minute each time with 50 USGPM for 16 weeks from 23 June to 12 October.

The park watering was distributed to two days a week and considered as an additional precipitation amount.

The net infiltration (or moisture flux) at the ground surface was determined from the amount of precipitation, park watering and estimated actual evaporation. Actual evaporation was estimated based on the potential evaporation and a limiting function (Wilson et al. 1997).

Daily net radiation was estimated from solar radiation, using an albedo value of 0.1 for the period from 1 November to 31 March and 0.3 for the period from 1 April to 31 October. The estimated daily net radiation is presented in Figure 6.

Figure 7 shows the recorded daily air temperature. The temperature was essentially below zero for the months from November to March, with an average temperature of about -10 ^{o}C. Average temperature for the months from April to October is about 10^{o}C. Recorded air temperature varied from -28 ^{o}C in March 2006 to 26 ^{o}C in July 2006. Recorded daily wind speed and relative humidity are presented in Figures 8 and 9, respectively.

Because the site is located in a residential/park area with mature trees (Figure 1), the daily wind speed and net radiation recorded at the weather station may not be applied directly to the site condition. A scale factor of 0.5 was applied to these data to represent the wind speed and net radiation for the analysis in this study. Air temperature in the park may be somewhat lower than the recorded temperature in a hot day; however, this was not considered in this study.

Vegetation conditions at the site were considered: LAI. Root zone from ground surface to 0.15 m depth was assumed to represent a grass portion of vegetation in the park. Water uptake by mature trees was not included in the current model.

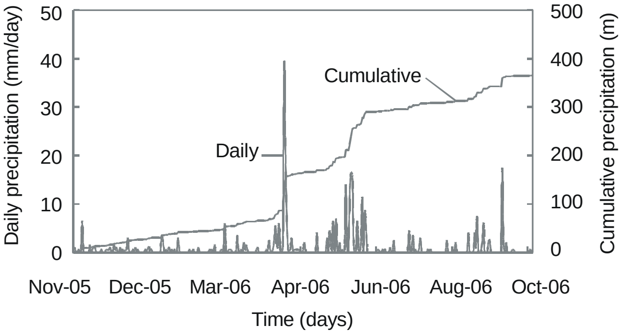

Figure 5. Daily and cumulative precipitation

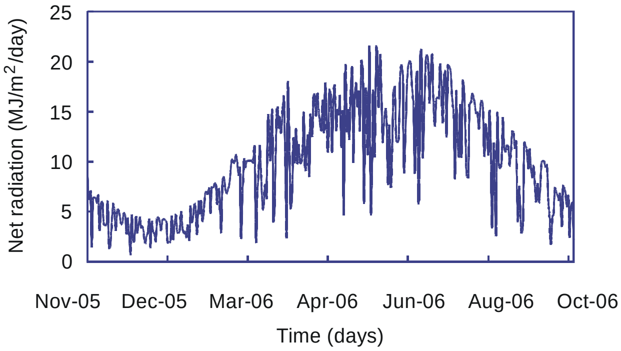

Figure 6. Daily net radiation

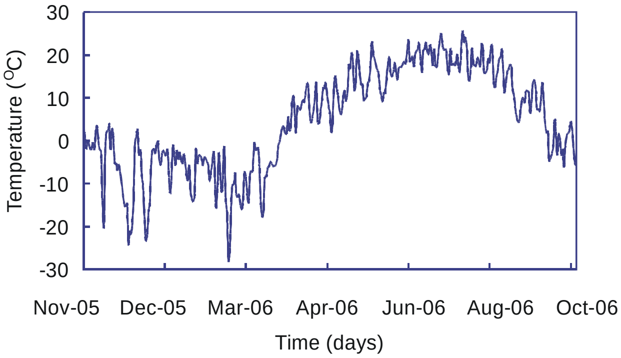

Figure 7. Daily temperature

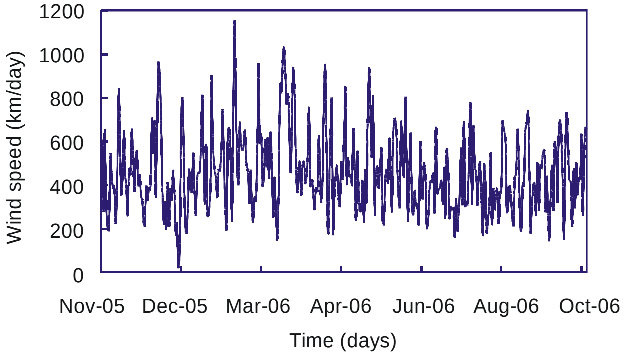

Figure 8. Daily wind speed

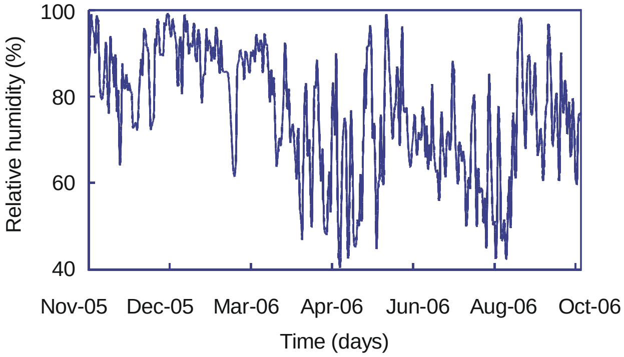

Figure 9. Daily relative humidity

8 NUMERICAL MODELLING RESULTS AND DISCUSSIONS

A one-dimensional moisture flow model was used. Location of a soil profile for the model was selected in the park relatively away from mature trees to exclude the water uptake by the mature trees. The model considered 9.5 m of clay overlying 5.5 m of till. It was assumed that the upper 4 m of clay was fissured; a higher value of saturated permeability of the clay was used for the fissured portion of clay.

Climatic conditions were applied on the top boundary, no flux conditions were applied at lower boundary. Water uptake by mature trees is a subject of future work and is not considered in this study. It was assumed that no infiltration was taken place during the winter time from November to March, when temperatures were below zero. Precipitation for this period were cumulated and applied on 1 April 2006.

Soil properties used for the analysis are shown in Figure 3 for the SWCC and Figure 4 for the coefficient of permeability function.

Initial suction conditions were estimated from suction profile shown in Figure 2. A constant suction of 1600 kPa was used for the upper 4 m of clay, 600 kPa for the lower 5.5 m of clay and 2000 kPa for the till.

A parametric study was performed to determine the significance of each of the input parameters to the predicted results. Parameters under considerations include the climatic data, vegetation conditions, soil properties, initial soil conditions, thickness of the fissured clay layer and the amount of park watering. The climatic data include daily precipitation, net radiation and wind speed. Soil property data include the SWCC and hydraulic conductivity functions for the fissured clay, intact clay and the till. A reasonable range of the values for each parameter was selected and shown in Table 1. During the sensitivity analyses, the parameter under consideration was varied while all other parameters were kept unchanged and equal to the “base case” value.

Figure 10 shows the predicted results of the cumulative boundary fluxes for the “base case” analysis. Positive flux indicates moisture enters into the soil while negative flux indicates moisture leaving from the soil. For a total precipitation of 424 mm, including 366 mm of precipitation and 58 mm of park watering, the predicted total net cumulative flux is -139 mm. The total cumulative potential evaporation, actual evaporation and potential transpiration are -594 mm, -566 mm, and 400 mm, respectively.

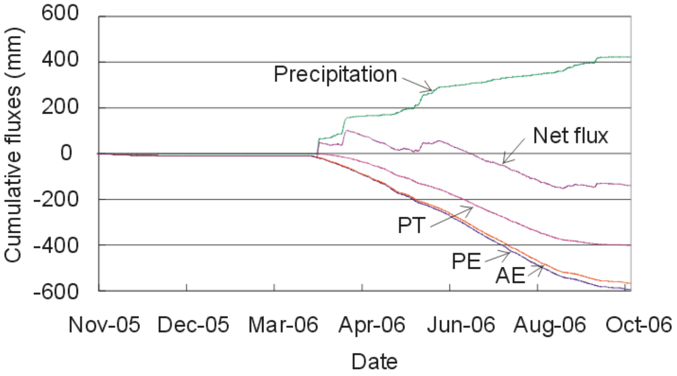

Figure 10. Calculated cumulative boundary fluxes. PE, potential evaporation; AE, actual evaporation; PT, potential transpiration.

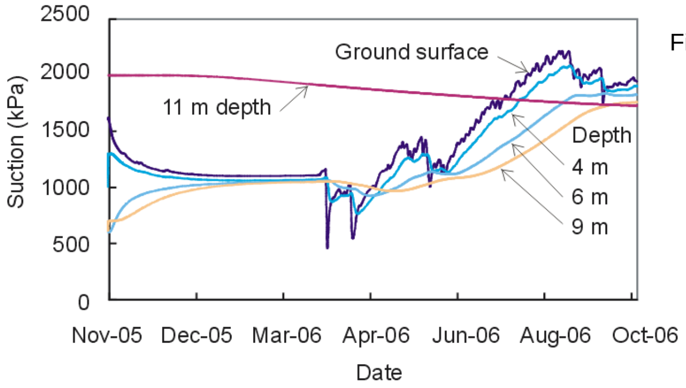

Figure 11. Suction change versus time at various depths

Table 1. Results of the parametric study

Parameter	Base case value	Value range	Cumulative infiltration range (mm)	Variation (%)
Wind speed scale factor	0.5	0.3 to 1.0	-89 to 265	-36 to 91
Net radiation scale factor	0.5	0.3 to 1.0	-9 to -452	-94 to 225
Precipitation scale factor	1	0.75 to 1.5	-230 to 43	65 to -131
Leaf area index	Good	No to excellent	-143 to -138	3 to -1
Park watering factor	1	0 to 5	-195 to 84	40 to -160
Thickness of fissured layer	4	0 to 5	-135 to -139	-4 to 0
Permeability of fissured clay (m/s)	2.27E-08	1.14E-8 to 2.27E-7	-136 to -142	-2 to 2
Permeability of clay (m/s)	2.27E-09	2.27E-9 to 2.27E-8	-138 to -137	< 1
Permeability of till (m/s)	1.00E-10	1.00E-11 to 1.00E-9	-137 to -136	<2
SWCC for clay	Middle curve	Drying to wetting	-138 to -140	<1
Initial suction of upper 4 m of clay (kPa)	1600	1000 to 2000	-141 to -135	1 to -3
Initial suction of lower 5 m of clay (kPa)	600	400 to 800	-139 to -138	0 to -1
Initial suction of till (kPa)	2000	1000 to 2500	-141 to -138	1 to -1

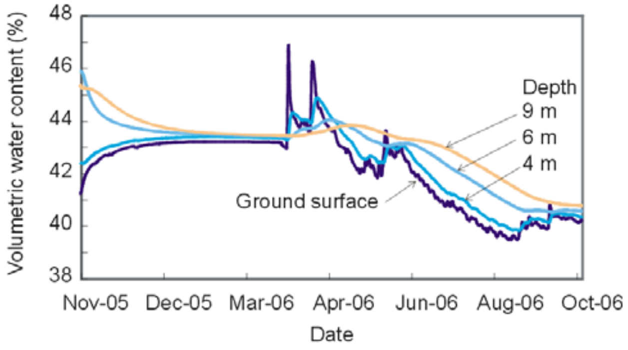

Figure 12. Volumetric water content change versus time at various depths

Figures 11 and 12 present the suction change and water content change versus time at various depths, respectively. Figure 13 shows suction profiles at various times for the “base case” analysis. Soil suction reached equilibrium condition in December 2005 and remained relatively unchanged until April 2006. Variation in suction was more pronounced near ground surface. A zone of suction change was predicted to the depth of 13 m in the till layer; however, only minor suction change was predicted in the till. Under the applied climatic condition, predicted suction in clay varied from 600 to 2150 kPa. September appeared to be the month with highest soil suction in the soil. Figure 14 shows volumetric water content profiles at various times. Predicted volumetric water content in clay varies from 40 to 46 percent.

Table 1 and Figure 15 present the results of the parametric study. The results of the parametric study suggest that soil properties, including the SWCC and coefficient of permeability, have only minor effects on the predicted results. Initial suction condition also appeared to have insignificant effect to the predicted infiltration rate. The parameters that have the most significant effect on the predicted cumulative infiltration are the net radiation, precipitation and park watering.

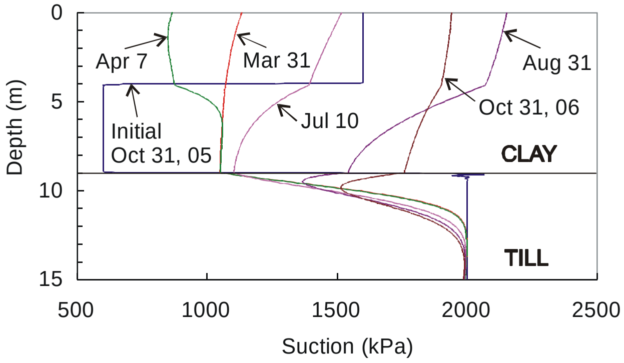

Figure 13. Suction profiles at various times

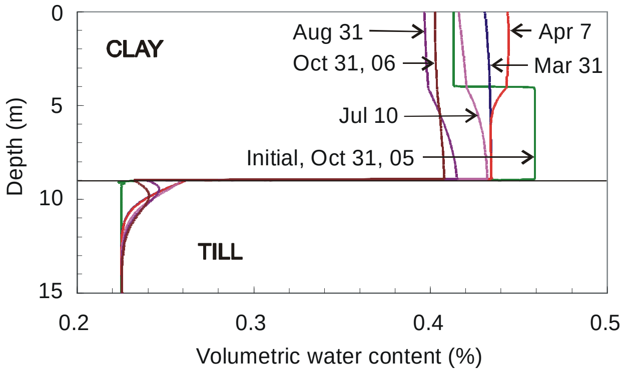

Figure 14. Volumetric water content profiles at various times

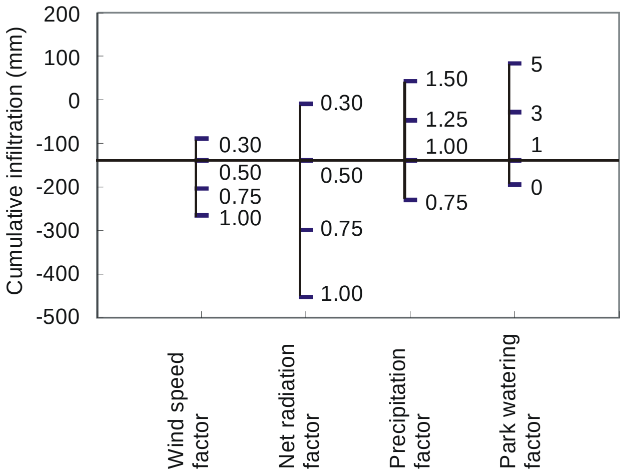

Figure 15. Effect of variable parameters on calculated cumulative infiltration for period from 1 November 2005 to 31 October 2006

9 SUMMARY

The computed infiltration at ground surface and soil suction in the expansive soils in Regina area was found to depend strongly on weather variables such as solar radiation, precipitation and wind speed. The amount of park watering was also found to be of significant important to the modelling results. Soil properties such as the SWCC and permeability function appeared to have only minor influence to the modelling results under the considered specific site condition. With an annual precipitation of about 400 mm, the annual net infiltration varied from -452 to 84 mm for the site under study. Suction changes can takes place throughout the clay soil profile in to till at a maximum depth of approximately 13 m. The month of September was found to have the highest soil suctions in the soil near the ground surface.

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