Numerical modelling of vertical ground movements in expansive soils

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A numerical model was developed to relate matric suction changes and vertical ground movements. The research considers one-dimensional vertical ground movements under open-vegetated fields subject to changing climatic conditions. A percentage of the Thornthwaite potential evapotranspiration model proved to be adequate to characterize the surface flux boundary condition. The infiltration and exfiltration processes were modelled separately for the field conditions. During infiltration, shrinkage cracks and the macrostructure of the soils dominate behavior. During this process, bulk permeabilities in the order of 10^{-6}–10^{-8} m/s were required to simulate measured ground movements. Exfiltration processes are dominated by flow in the vapour phase as drying occurs in the soil. Bulk permeabilities in the order of 10^{-9}–10^{-11} m/s were required to simulate the measured ground movement. The simulations of ground movements would also indicate that thermally induced suctions (i.e., winter freezing conditions) could account for a significant portion of the seasonal vertical ground movements. The numerical model can also be used to predict seasonal ground movements beneath light engineered structures. Further research, however, is required to better understand how to establish the surface flux boundary condition. As well, there is need for more case histories to enlarge the database of unsaturated soil parameters.

Key words: vertical ground movement, matric suction, modelling, evapotranspiration, field permeabilities.

Un modèle numérique a été développé pour mettre en relation la matrice des changements de succion et les mouvements verticaux du sol. Le projet de recherche traite des mouvements unidimensionnels verticaux du sol sous un terrain à végétation ouverte assujetti à des conditions climatiques changeantes. Un pourcentage du modèle de potentiel d'évapotranspiration de Thornthwaite s'est révélé adéquat pour caractériser la condition à la limite du flux de surface. Les processus d'infiltration et d'exfiltration ont été modélisés séparément pour les conditions du terrain. Au cours de l'infiltration, les fissures de retrait et la macro-structure des sols gouvernent le comportement. Durant le processus, des perméabilités de masse de l'ordre de 10^{-6}–10^{-8} m/s ont été nécessaires pour simuler les mouvements mesurés du sol. Les processus d'exfiltration sont gouvernés par l'écoulement dans la phase vapeur alors que l'assèchement se produit dans le sol. Des perméabilités de masse de l'ordre de 10^{-9}–10^{-11} m/s ont été nécessaires pour simuler le mouvement mesuré du sol. Les simulations des mouvements du sol indiqueraient également que les succions induites thermiquement, comme par les conditions de gel en hiver, peuvent expliquer une portion significative des mouvements verticaux saisonniers du sol. Le modèle numérique peut aussi être utilisé pour prédire les mouvements saisonniers du sol sous les structures légères d'ingéniérie. Cependant, des recherches supplémentaires seront requises pour mieux comprendre comment établir la condition à la limite du flux de surface. Également, des histoires de cas supplémentaires sont nécessaires pour augmenter la base de données de paramètres de sol non saturé.

Mots clés : mouvement vertical du sol, matrice de succion, modélisation, évapotranspiration, perméabilités de terrain.

[Traduit par la rédaction]

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Introduction

The development of a numerical model to quantify the relationship between meteorological information and vertical ground movements (i.e., heave and shrinkage) has only recently become possible as a result of advances in our understanding of unsaturated soil behavior. A simple numerical model has been developed to illustrate how increases in matric suction result in shrinkage and decreases in matric suction result in swelling. The present research focuses on the one-dimensional simulation of vertical ground movements under open-vegetated fields subject to changing climatic conditions. The long-term objective of the study is to be able to predict the vertical movement of light engineered structures such as building foundations and highway pavements (Fig. 1).

Background

Geotechnical engineers throughout the world are familiar with the challenges posed by expansive soils. Vertical ground movements associated with expansive soil deposits cause more damage to light engineered structures than all other natural disasters combined (Jones and Holtz 1973). Documented case histories and a better comprehension of unsaturated soils behavior have contributed significantly to our understanding of expansive soils.

During the late 1950's and 1960's, the Division of Building Research of the National Research Council of Canada in Saskatoon, Saskatchewan, conducted a long-term study involving vertical ground movements in open fields and the performance of building foundations on expansive soils. Vertical ground movement gauges were installed at four open-field locations in Manitoba and Saskatchewan; namely, the Elmwood district of Winnipeg, Manitoba; and Regina, Tisdale, and Eston, Saskatchewan (Hamilton 1963) (Fig. 2). The ground movements were measured using precise survey equipment and deep benchmarks. Measurements of vertical ground movement were taken on approximately a monthly basis for a period of several years at each location.

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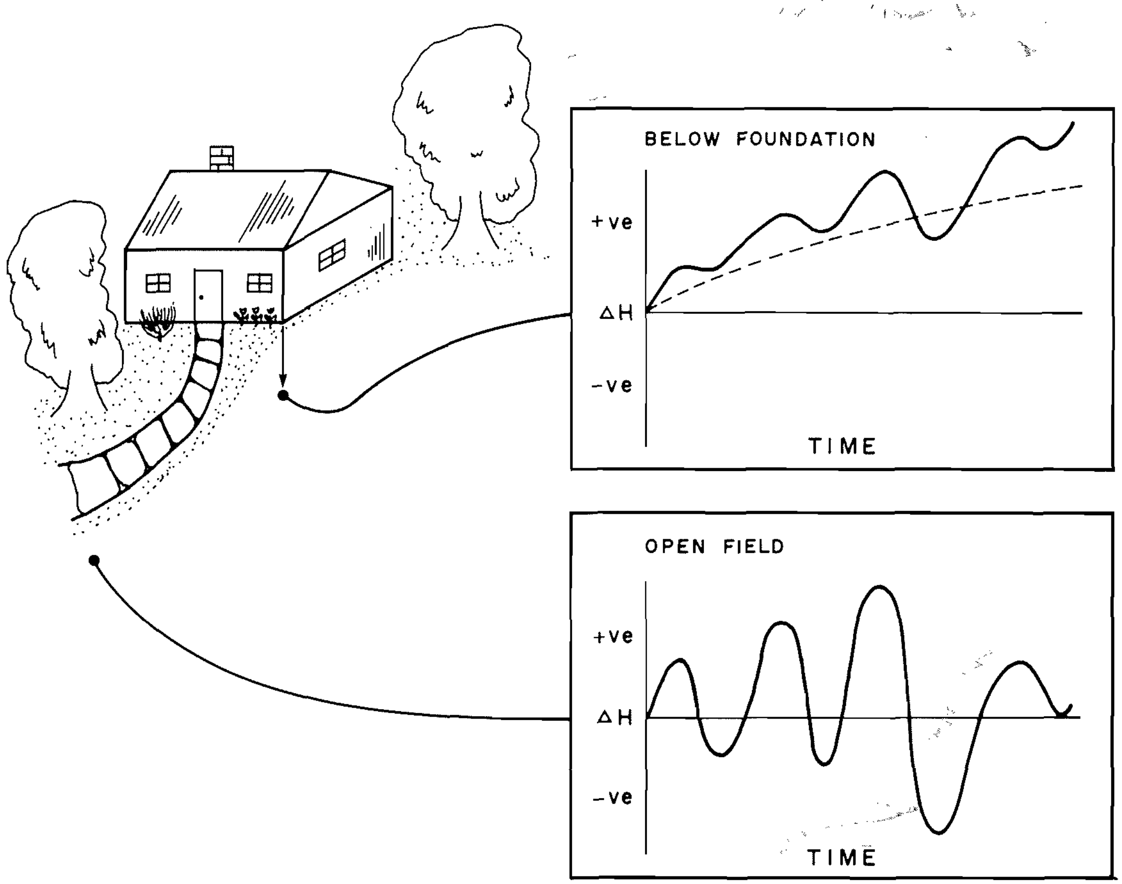

FIG. 1. Objective of the research: to predict vertical ground movements with time.

Water content changes were also measured periodically over the span of several years (Hamilton 1963).[1]

The recorded measurements for each location are presented in Figs. 3–6. Figure 3 illustrates that between 1960 and 1968, the maximum change in ground elevation for the open-field test plot at Regina, Saskatchewan, was in the order of 50 mm at a depth of 0.3 m. Measured vertical ground movements for the open-field test plot at Tisdale, Saskatchewan, were characteristically less severe than at Regina (Fig. 4), whereas measured vertical ground movements for Eston, Saskatchewan, were more severe than at Regina (Fig. 5). The maximum vertical rise in ground elevation for Eston was recorded as 63 mm at a depth of 0.3 m in 1962. Measurements recorded for Winnipeg, Manitoba, include 3 years of surface measurements. The maximum recorded vertical ground movement for Winnipeg was about 75 mm at the ground surface in 1963 (Fig. 6).

Hamilton (1965) summarized the results of the research and illustrated a relationship between meteorological observations and vertical ground movements. Data records indicated that building slabs showed a gradual heave over long periods of time, whereas open-field test plots exhibited more of an upward and downward movement (Hamilton 1968). It was observed that increases in the water content of the soil were associated with upward ground movements. During wet periods, both the open field and the building

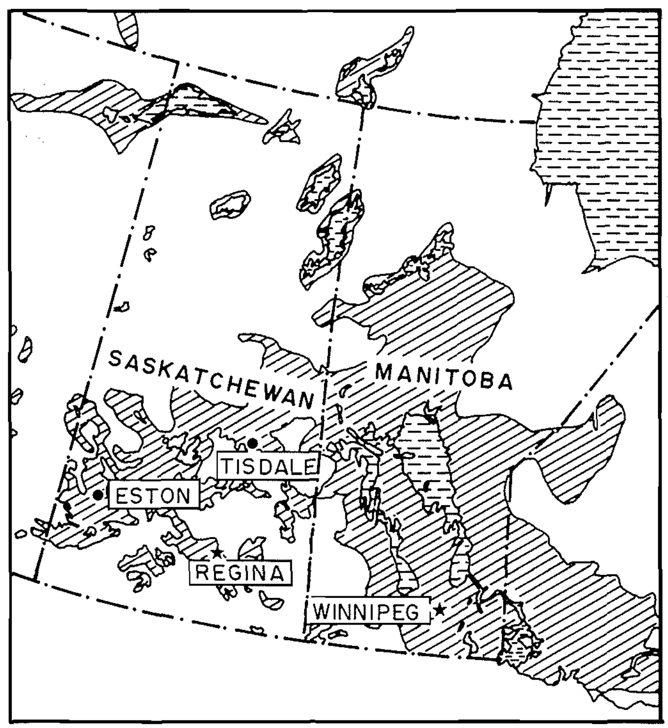

FIG. 2. Glacial lake deposits and associated expansive soil deposits (Hamilton 1965).

[1]During the 1970's, the University of Saskatchewan and the National Research Council of Canada initiated a Technology Transfer Program in which there was an exchange of research information between the two institutions. The University of Saskatchewan gained access to the extensive data that had been accumulated by the Division of Building Research under the direction of J.J. Hamilton.

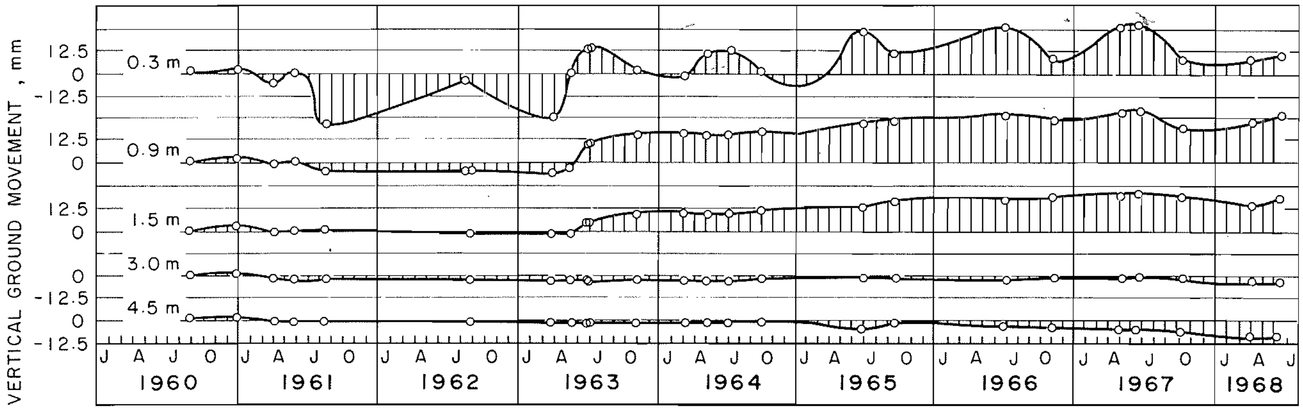

FIG. 3. Measured vertical ground movements for an open-field test plot at Regina, Saskatchewan (Hamilton 1968).

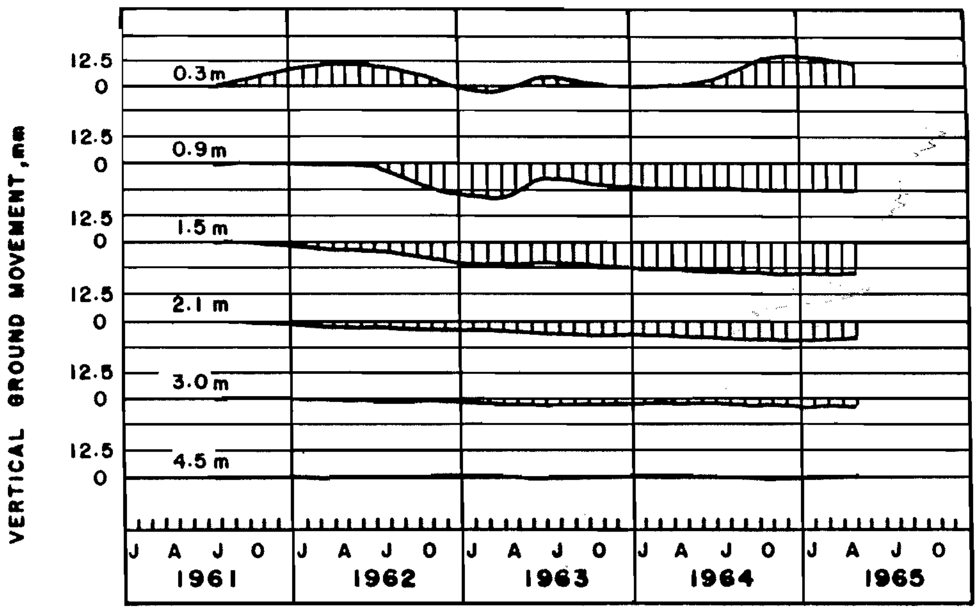

FIG. 4. Measured vertical ground movements for an open-field test plot at Tisdale, Saskatchewan (Hamilton 1968).

slab exhibited upward movement. During dry periods in which the demands of the vegetation become predominant, concrete-slab elevations remained essentially constant, whereas the open-field gauges indicated a downward movement.

The amplitudes of measured vertical ground movements were in the order of 75 mm near the ground surface. Under severe drought, movements were recorded to depths exceeding 2.5 m. Both vertical and horizontal shrinkage were observed in winter. Hamilton (1963) concluded that the magnitude of vertical movement "increases during periods of extremes in weather conditions and wanes during periods of more or less average weather conditions."

The ground-movement measurements have proven to be a valuable record of the magnitude of shrinking and swelling which can be anticipated on the prairies. Some of the data has been used to illustrate correlations with climatic conditions. Hamilton (1966) performed soil moisture depletion calculations for the Winnipeg study site based on Thornthwaite's evapotranspiration model (1948) and precipitation data for Winnipeg. A definite correlation was shown between climatic conditions and vertical ground movements.

Physical relationships required for a ground-movement model

The derivation of an equation to describe vertical ground movements in expansive soils is based on unsaturated soil mechanics theories (Fredlund 1979). Two independent stress-state variables are used to describe the engineering behavior of the soil mass; namely, (*i*) net normal stress $(\sigma - u_a)$ and (*ii*) matric suction $(u_a - u_w)$ (Fredlund and Morgenstern 1977). Matric suction is the negative pore-water pressure referenced to the air pressure. Changes in the negative pore-water pressure occur as a result of changes in the climate and can be related to changes in soil volume through the use of constitutive relations.

The form of the constitutive equation linking the stress-state variables to soil volume change is illustrated in Fig. 7. Swelling in the field occurs along the rebound curve, i.e., with slope a_{ms} at an overburden pressure (i.e., $(\sigma - u_a)_o$)

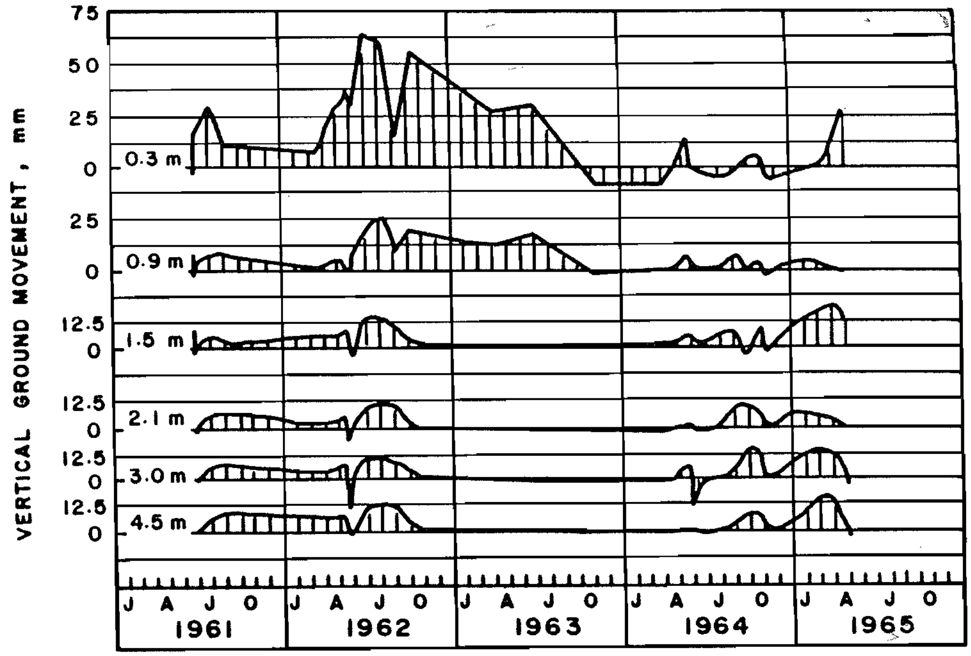

FIG. 5. Measured vertical ground movements for an open-field test plot at Eston, Saskatchewan (Hamilton 1968).

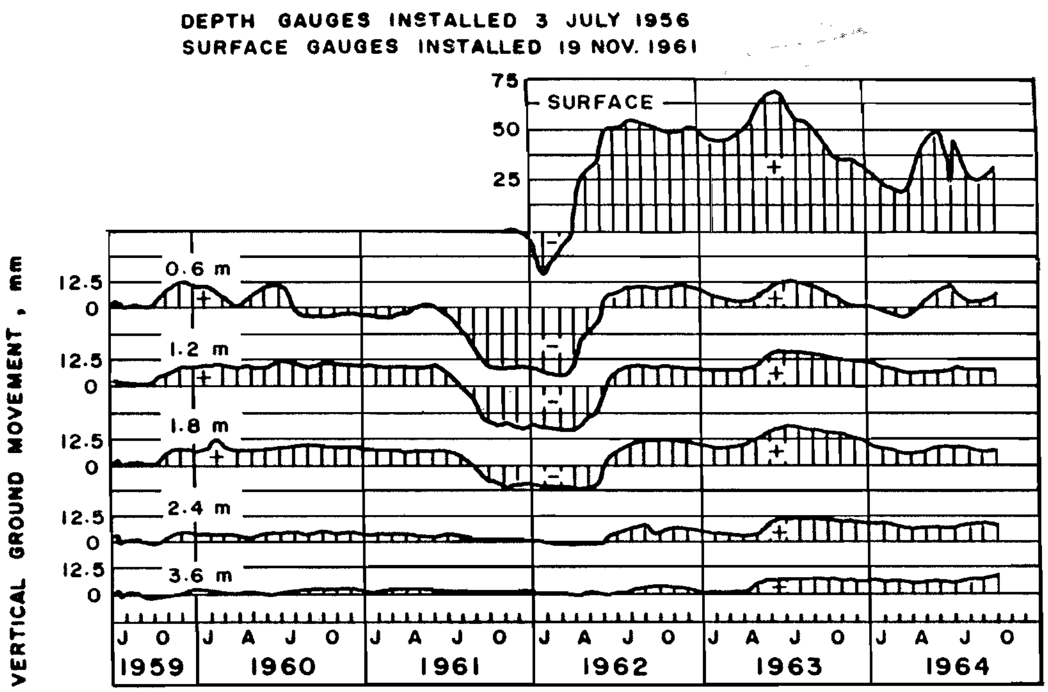

FIG. 6. Measured vertical ground movements for an open-field test plot at Winnipeg, Manitoba (Hamilton 1968).

and an *in situ* matric suction (i.e., $(u_a - u_w)_o$). Shrinkage occurs along either a recompression branch or the virgin compression branch. The arithmetic form of the constitutive equation for the virgin branch can be written as follows:

$$[1] \quad de = a_t\, d(\sigma - u_a) + a_m\, d(u_a - u_w)$$

where de is the change in void ratio, a_t is the coefficient of compressibility with respect to a change in $(\sigma - u_a)$, and a_m is the coefficient of compressibility with respect to a change in $(u_a - u_w)$.

The form of the constitutive equation for the rebound curve is similar to [1] except that the moduli are from the rebound branch (i.e., a_{ms} and a_{ts}). One-dimensional volume change (i.e., vertical ground movement) for a soil mass of "n" layers is equal to the sum of the volume changes in individual layers of thickness, H_{io}, for each of the "n" layers. The change in layer thickness for each layer is computed from the following expression:

$$[2] \quad \Delta H_i = H_{i_0} \frac{(\Delta e_i)}{1 + e_{i_0}}$$

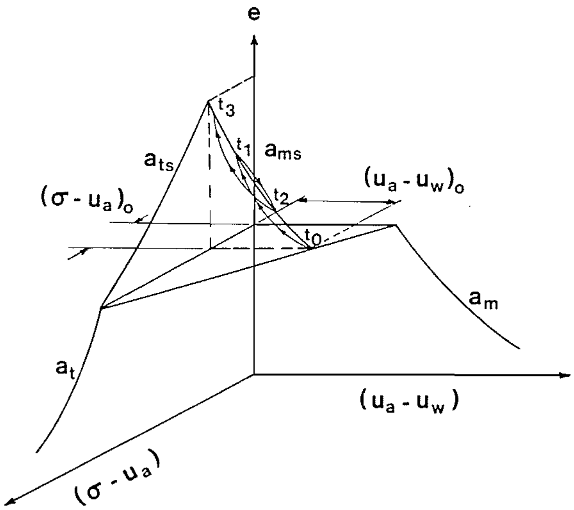

FIG. 7. Schematic diagram of the constitutive relationship for void ratio in terms of matric suction and net normal stress.

where i is the number of the soil layer, where the soil layers range from 1 to the total number of layers, n; ΔH_i is the change in thickness of an individual layer; H_{i_0} is the initial layer thickness; Δe_i is the change in void ratio for the layer; and e_{i_0} is the initial void ratio for the layer.

The change in void ratio for each layer is computed from [1].

The sum of the changes in layer thickness (i.e., vertical ground movement) is written as

[3] $$\Delta H = \Sigma\, \Delta H_i$$

Changes in matric suction occur throughout the soil mass as water flows from a greater to a lower hydraulic head. The classic seepage equation for a saturated soil can be extended to describe the flow of water in an unsaturated soil. As a first approximation, the transient-flow equation can be written as

[4] $$\frac{\partial h}{\partial t} = \frac{k_y}{\rho_w\, g\, m_2^w} \frac{\partial^2 h}{\partial y^2}$$

where h is the total hydraulic head; $\frac{\partial h}{\partial t}$ is the derivative of total hydraulic head with respect to time; k_y is the permeability of the soil in the vertical direction; ρ_w is the density of water; g is the acceleration due to gravity; m_2^w is the coefficient of water volume change, which is equal to $a_{ms}/(1 + e_{i_0})$ on the rebound branch; and $\frac{\partial^2 h}{\partial y^2}$ is the second derivative of total hydraulic head with respect to depth above the datum.

The coefficient of permeability, k_y, for an unsaturated soil is a function of matric suction, which in turn is a function of hydraulic head. A more rigorous formulation of the unsaturated-seepage equation was presented by Lam and Fredlund (1984). However, for the purposes of developing a first-approximation model, the linear form of the seepage equation (i.e., eq. [4] above) is proposed.

The total hydraulic head in an unsaturated soil is written the same as for a saturated soil:

[5] $$h = \frac{u_w}{\rho_w g} + y$$

where y is the elevation head above the chosen datum.

Conventionally, the air pressure, u_a, is assumed to be equal to zero. Therefore, the matric suction stress-state variable (i.e., $u_a - u_w$) is equal in magnitude and opposite in sign to the pore-water pressure (i.e., u_w).

The volume-change moduli, a_{ms} and m_2^w can be estimated from experimental data. To a large extent, estimates of the volume-change moduli were used for the four field-site locations. The volume-change modulus, a_{ms}, was estimated from a knowledge of the swelling index data (i.e., C_s) and the shrinkage limit of the soil. Modulus values were in the order of 1×10^{-2} to 1×10^{-5} per kilopascal. Further details regarding the estimation of the soil parameters and initial conditions are described in Sattler (1989).

Initial boundary conditions

Initial conditions required for the model include the negative pore-water pressure, the void ratio, the water content, and the degree of saturation. Profiles of initial negative pore-water pressure were estimated from typical swelling pressure profiles (Yoshida *et al.* 1983) and field soil suction data for prairie locations (van der Raadt 1988). Profiles of the initial void ratio, water content, and degree of saturation with depth were established from summaries of statistical properties (Fredlund and Hasan 1979) and measured water contents for the study locations (Hamilton 1968).

For the numerical modelling, the lower boundary below which volume changes are negligible was set at 7.5 m, in accordance with observations by Hamilton (1965). The surface boundary was subjected to a transient flux computed from precipitation and evapotranspiration data.

Surface flux boundary condition

The flow of water across the surface boundary was assumed to conform to Darcy's law:

[6] $$q = k_y \frac{\Delta h}{\Delta y}$$

where q is the rate of water flow or surface boundary flux in units of distance per time, k_y is the coefficient of permeability in the vertical direction at ground surface, Δh is the change in total hydraulic gradient across the surface layer, and Δy is the distance across the surface layer.

The surface boundary flux is computed from the difference between the infiltration and exfiltration processes at the surface. For the flat prairie locations under study, runoff was assumed to be negligible. Therefore, infiltration was equal to precipitation. Exfiltration was computed from estimates for actual evapotranspiration (i.e., the sum of evaporation from the soil and transpiration by plants).

The Thornthwaite model was used to estimate the potential evapotranspiration based upon simple calculations using temperature and day length (Thornthwaite 1948):

[7] $$\text{PET} = 1.6\, F \left[\frac{10t}{I}\right]^a$$

where PET is the monthly potential evapotranspiration (cm), F is the sunlight duration correction factor based upon Thornthwaite and Mather (1957), t is the mean monthly temperature (°C), and I is the sum of the 12 monthly heat

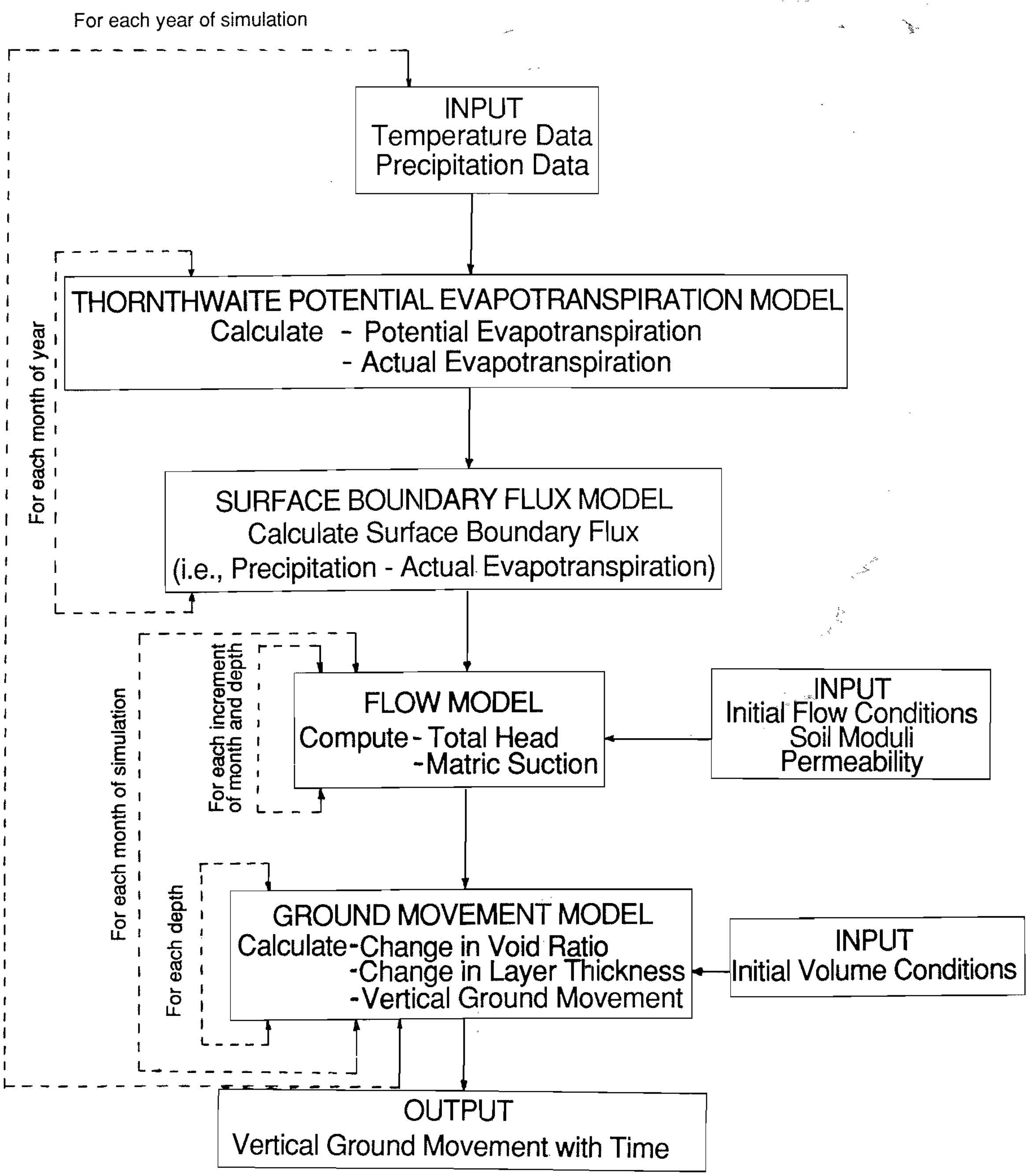

FIG. 8. Flow chart for the computer model used to predict vertical ground movements with depth and time.

indices, i, and where $i = (t/5)^{1.515}$ and a is a constant dependent on the heat indices, which varies from 0 to 4.25; $a = 6.75E\text{-}07\ I^3 - 7.71E\text{-}05\ I^2 + 1.792E\text{-}02\ I + 0.49239$

Potential evapotranspiration is defined as the moisture loss from a surface completely covered with vegetation when there is an unlimited supply of water available for plant use (Thornthwaite and Mather 1955). Potential evapotranspiration can be considered as an upper limit on actual evapotranspiration, since actual evapotranspiration is dependent upon the available soil moisture. Actual evapotranspiration can be estimated from computations of potential evapotranspiration and empirical correlations between actual and potential values for evapotranspiration (Granger and Gray 1989).

The actual evapotranspiration was estimated as a percentage of potential evapotranspiration based upon concurring results from several analyses, including (*i*) the use of net groundwater recharge observations for Saskatchewan, (*ii*) the use of historic temperature and precipitation data, and (*iii*) the use of long-term mean values for precipitation and temperature (Sattler 1989). Results of the analyses indicated that a ratio of 0.70 between actual and potential evapotranspiration was reasonable for the four prairie locations that were studied. In hydrology, a value of 0.70 is also used to represent the ratio of the classic "pan evaporation" as a percentage of actual "lake evaporation" (Gray and Male 1980). Just as actual evapotranspiration is less than potential evapotranspiration because of limited available

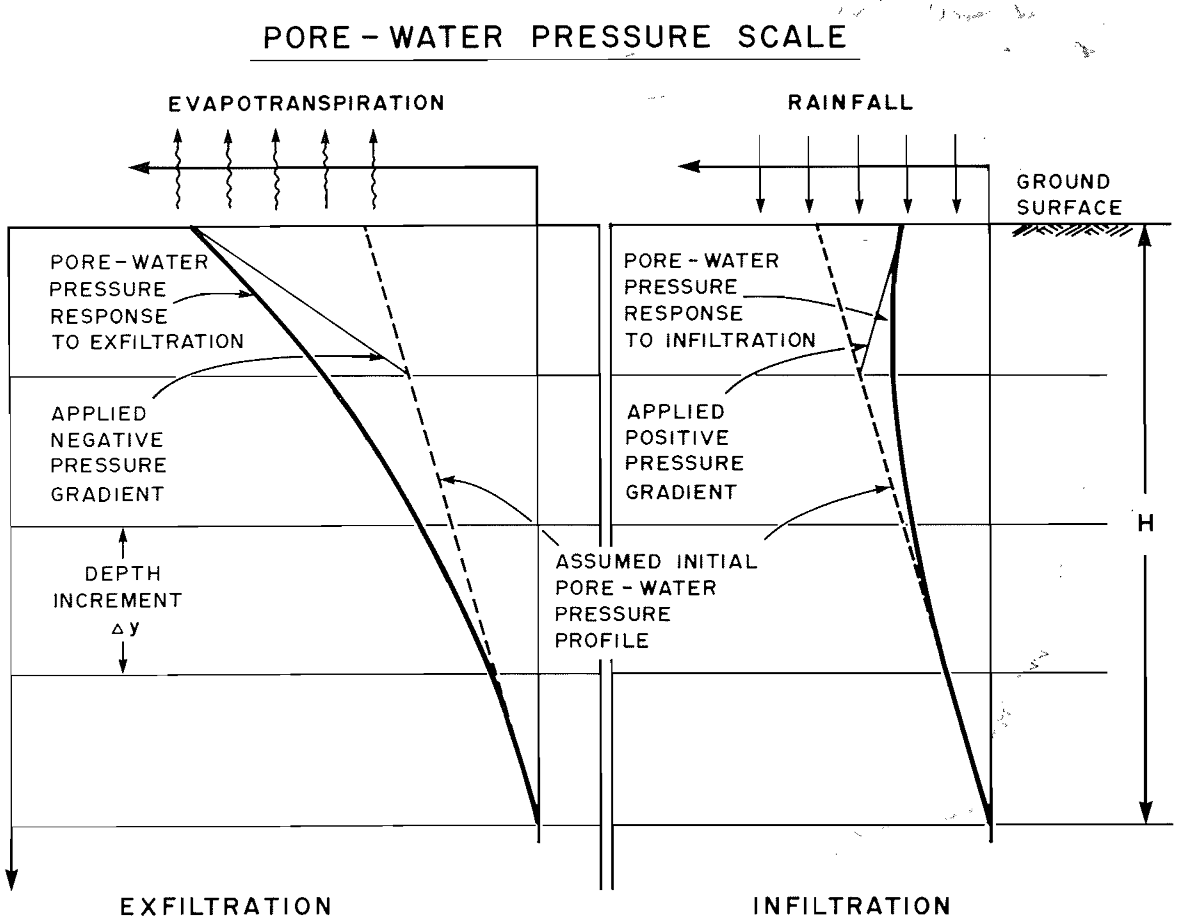

FIG. 9. Schematic representation of pore-water pressure response to a changing surface boundary flux (after Fredlund and Dakshanamurthy 1982).

water in the soil, likewise, pan evaporation is less than lake evaporation because of natural limitations on the pan measuring ability.

Numerical solution

The marching forward finite-difference numerical technique was used to solve the transient-flow equation (i.e., [4]) in terms of hydraulic head, subject to the boundary conditions:

$$[8] \quad \frac{h_1 - h_0}{\Delta t} = \frac{k_y}{\rho_w g m_2^w} \frac{h_2 - 2h_0 + h_3}{(\Delta y)^2}$$

where h_0 is the total hydraulic head at time j and depth k, h_1 is the total hydraulic head at time $j + 1$ and depth k, h_2 is the total hydraulic head at time j at depth $k - 1$, h_3 is the hydraulic head at time j and depth k + 1, Δy is the increment of vertical depth, and Δt is the increment of time.

Equation [6] was rewritten to solve for the hydraulic head at ground surface corresponding to the computed surface boundary flux. The corresponding pore-water pressure profiles were computed using [5].

Figure 8 shows a flow chart of the steps undertaken by the computer model. The surface boundary flux is computed on a monthly basis and applied proportionally to each time increment within a month. The marching forward procedure is used for each time increment within a month to compute the next set of values for hydraulic head. At the end of the month, values are computed for pore-water pressure, degree of saturation, water content, void ratio, and vertical ground movement. The ground movements are accumulated for the duration of months simulated.

The accuracy of the solution is dependent upon the value of the β parameter, which is defined as follows:

$$[9] \quad \beta = \frac{k_y \Delta t}{\rho_w g m_2^w (\Delta y)^2}$$

Von Neumann (Smith 1975) concluded that the value of β must be less than one-third to one-half to avoid computational instability. Twenty-six nodes were considered the optimal discretization in the vertical direction. The time discretization was changed during the solution to ensure that the value of β would fall within the limits imposed by the surface boundary flux.

To accommodate a layered soil profile in which the permeability and modulus varied with depth, the geometric mean was used to average the values of the parameters (Haverkamp and Vauclin 1979). The geometric mean for the coefficient of permeability was defined as

$$[10] \quad k^* = (k_1 \times k_2)^{1/2}$$

where k^* is the geometric mean of the coefficient of permeability between the layers, k_1 is the coefficient of permeability of layer 1, and k_2 is the coefficient of permeability of layer 2.

FIG. 10. An example of fissured Regina clay.

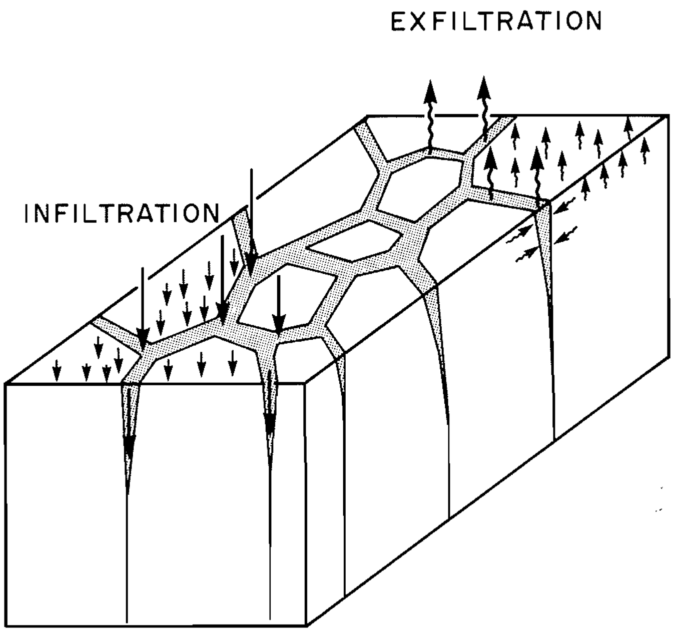

FIG. 11. Schematic diagram illustrating infiltration and exfiltration in a cracked clay soil.

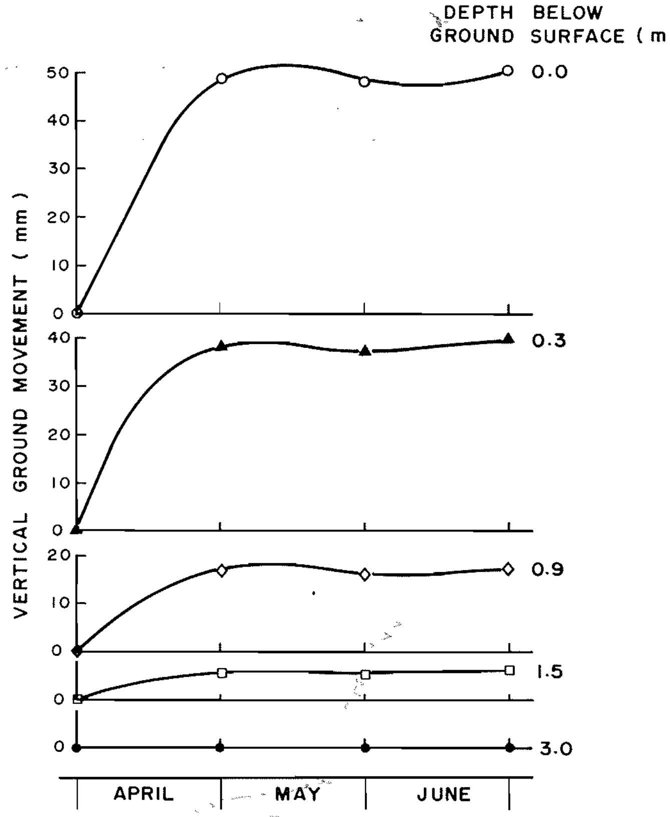

FIG. 12. Predicted vertical ground movements for an infiltration event.

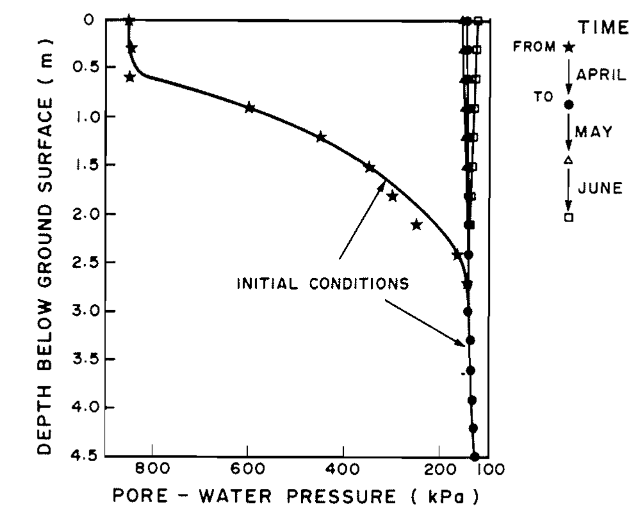

FIG. 13. Corresponding negative pore-water pressures for an infiltration event.

The geometric mean for the water volume change modulus was defined similarly. The use of the geometric mean compensates for sharp changes in permeability or modulus between nodes in the finite-difference grid.

Figure 9 shows a schematic representation of the pore-water pressure response to a changing surface boundary flux, assuming that the initial conditions do not establish a gradient that controls the response. During exfiltration, the matric suction or negative pore-water pressure becomes greater at the surface, and the remainder of the profile adjusts accordingly. During infiltration, the matric suction decreases at the surface (i.e., the pore-water pressure increases), and the negative pore-water pressures continue to decrease as water infiltrates to greater depths.

Presentation and discussion of results

The numerical model can be used to illustrate the relationship between matric suction and vertical ground movements. The model shows how increases in matric suction result in shrinkage and decreases in matric suction result in swelling. Simulated vertical ground movements can be fit to measured vertical ground movements using estimated soil properties and reasonable initial boundary conditions.

A preliminary investigation was conducted to determine the range of reasonable matric suction values at the surface

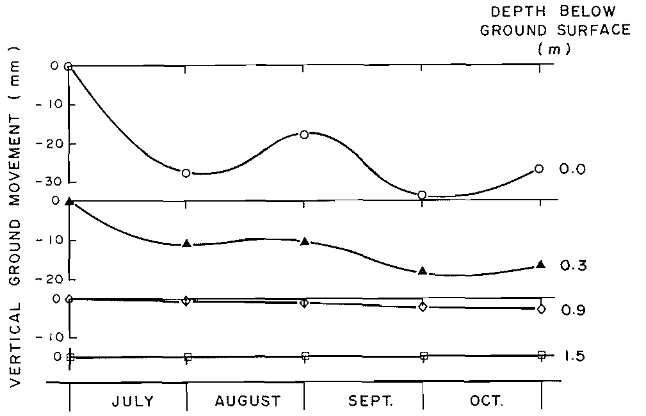

FIG. 14. Predicted vertical ground movements for an exfiltration event.

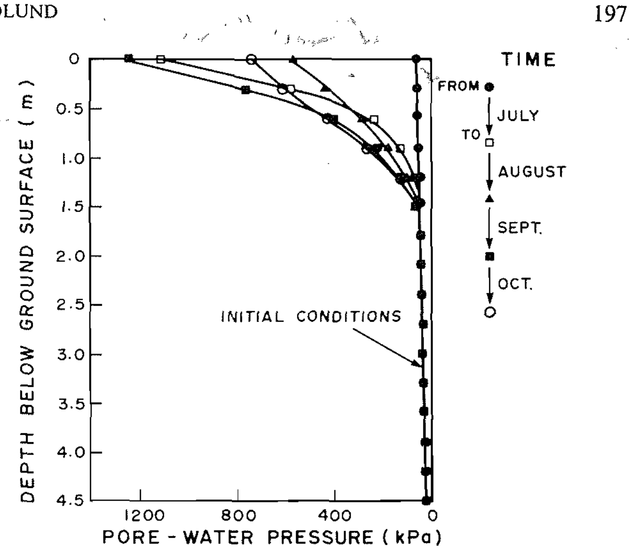

FIG. 15. Corresponding negative pore-water pressures for an exfiltration event.

for reasonable permeabilities and surface boundary fluxes. The preliminary results suggested that two independent ranges for the coefficient of permeability were required: one permeability for infiltration and one permeability for exfiltration. Permeability values in the order of 10^{-6}–10^{-8} m/s were required for modelling infiltration events for the four prairie locations. These permeability values suggest that the soil profile behaves as though it were sand during the infiltration process. This can be attributed to the presence of shrinkage cracks as evident in the field into which the water can readily flow (Fig. 10). The associated volume-change behavior is mostly related to the macrostructure of the soil mass during the infiltration event.

For the exfiltration process, considerably smaller coefficients of permeability (i.e., in the order of 10^{-9}–10^{-11} m/s) were required during the simulation. This low coefficient of permeability can be attributed to the form of water flow that occurs during exfiltration. Exfiltration occurs primarily as a vapor transport process from the intact clay clods into the fractures in the soil (Fig. 11). The volume change behavior during exfiltration is more closely linked to the microstructure of the soil.

To model an infiltration event, the permeability was chosen to equal the infiltration rate. In other words, the permeability of the cracked soil profile was assumed to be large enough to accommodate all water flow into the cracks during the infiltration process. The initial matric suction profile was assumed to remain constant with depth, corresponding to a hydraulic head gradient of 1.0.

Exfiltration occurs as a result of evaporation from the ground surface and transpiration through plants drawing water out of the soil. To match vertical ground movements with measured ground movements, large matric suction values were generated at the surface during the exfiltration process, corresponding to the low coefficients of permeability.

The coefficient of permeability is usually expressed as a function of the matric suction, which in turn is a function of the hydraulic head. However, the characterization of the coefficient of permeability solely in terms of matric suction is not sufficient for the cracked nature of the soil and the difference between the infiltration and the exfiltration processes. The extreme ranges in simulated permeability values suggest the inadequacy of expressing the coefficient of permeability in terms of matric suction for simulation of field conditions. The use of a constant permeability value in [4] and two modelling processes is therefore felt to be justified, particularly for first-order approximation in highly fissured and fractured clays.

Figure 12 shows the simulated vertical ground movement for the Regina site for a simple infiltration event (i.e., one in which the surface boundary flux is positive for each of the 3 months of simulation). Figure 13 presents the corresponding matric suction values required to model the infiltration event. The majority of movement occurs during April as the accumulated winter snowfall melts and penetrates the soil profile. The simulated vertical ground movement is in the order of 50 mm at surface. At depths of 0.3, 0.9, and 1.5 m, respectively, the predicted vertical ground movement is in the order of 40, 18, and 7 mm. The measured movements for these depths over the same period were in the order of 41, 18, and 7 mm, respectively.

Figure 14 illustrates the predicted vertical ground movement for a simple exfiltration event for the Regina site. The corresponding matric suction profiles are presented in Fig. 15. Extreme changes in matric suction occur at the surface as the soil profile dries. In reality, there is significant lateral volume change (i.e., cracking) in addition to vertical volume change. However, simulation of the ground movements still appears to be possible.

Figure 16 shows the predicted and measured vertical ground movements for each of the 10 events modelled for the Regina site. In general, the correspondence between measured and predicted vertical ground movements was readily accomplished using reasonable soils parameters and initial boundary conditions. However, the matching of volume-change behavior becomes more difficult for winter conditions and for complex events (i.e., events in which the surface boundary flux fluctuated from positive to negative during the simulation period). This suggests that the winter temperature phenomenon is significant to the estimation of seasonal vertical ground movements. The difficulty in matching complex events is most likely the result of oversimplifications and accumulated errors related to the event being modelled.

There was insufficient meteorological data for the 1960's for the sites located at Tisdale and Eston. An attempt was

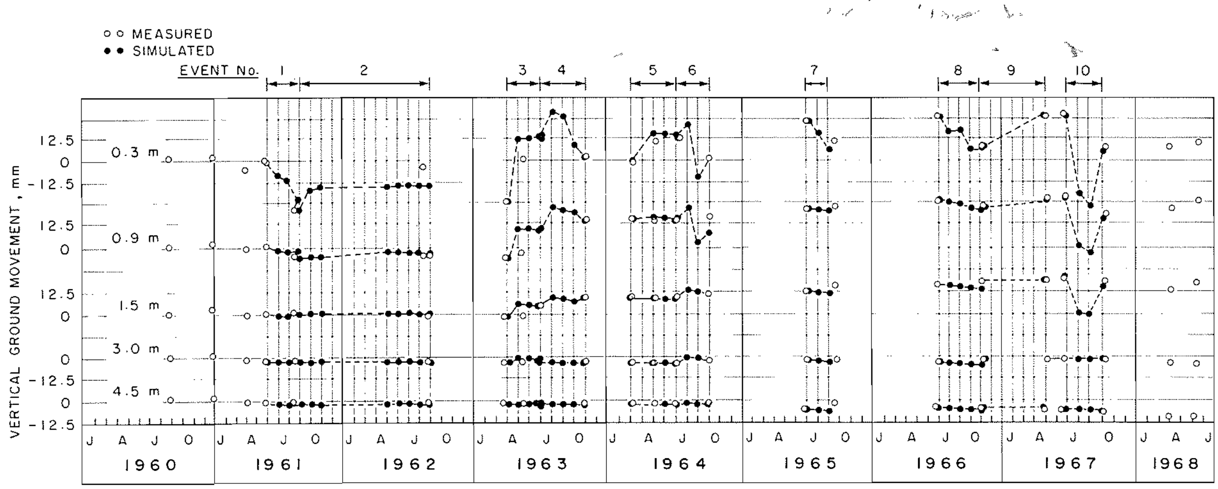

FIG. 16. Comparison of predicted and measured vertical ground movements for each of the 10 events modelled for Regina, Saskatchewan.

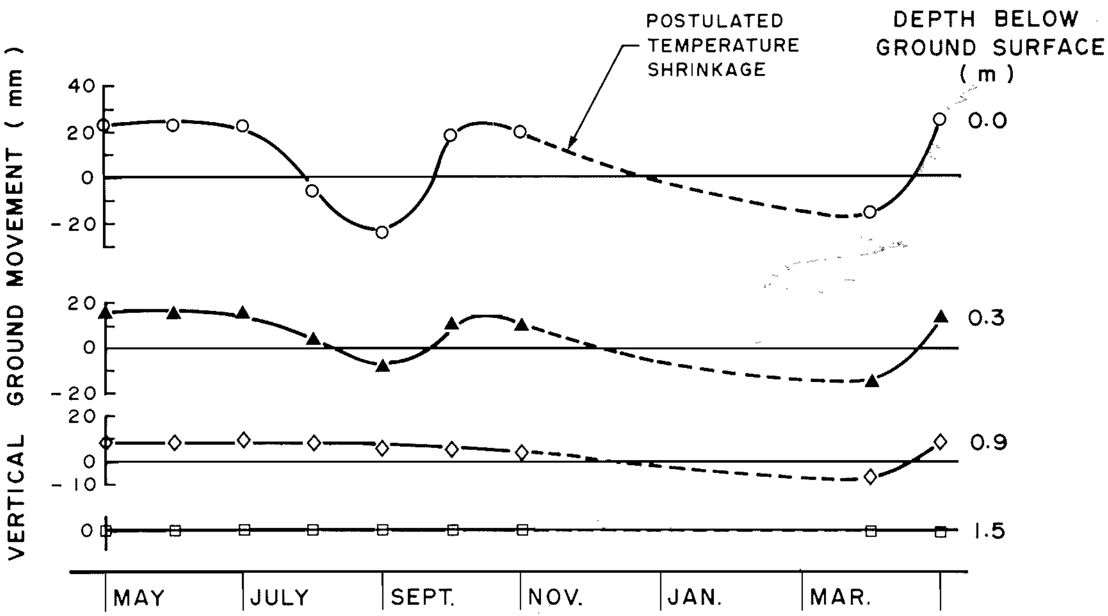

FIG. 17. Simulated average vertical ground movements for Regina, Saskatchewan.

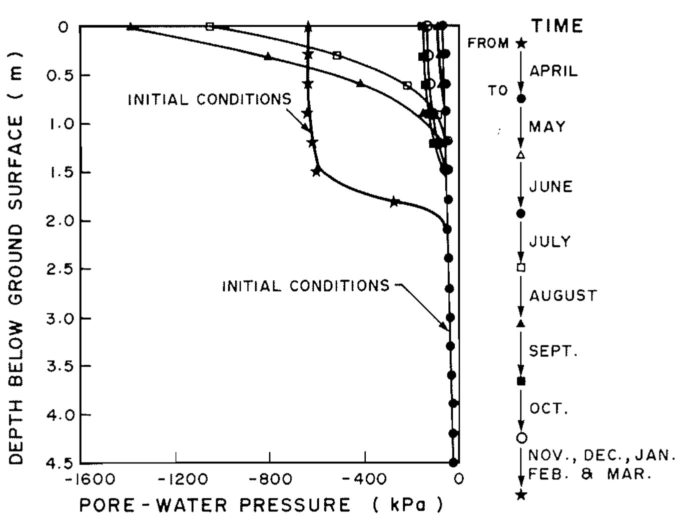

FIG. 18. Corresponding negative pore-water pressures for average vertical ground movements for Regina, Saskatchewan.

made to use meteorological data from nearby sites, but the results showed that it was important to have a meteorological station located reasonably close to the site for which vertical ground movement estimates were required.

The results for the Winnipeg site were satisfactory but have been excluded from the discussion because of their similarity to those at Regina.

Average seasonal ground movements were postulated for the Regina site based upon the information gathered during the simulation of the individual events. The average seasonal vertical ground movements for Regina are presented in Fig. 17. The assumption was made that there should be neither a net positive nor a net negative shrinkage during an average year. To satisfy this assumption, approximately 40 mm of temperature shrinkage was required during the winter months.

The corresponding suction profiles are presented in Fig. 18. Typical seasonal matric suction values are suggested to vary between 50 and 1400 kPa at the soil surface. During the summer months, the negative pore-water pressure at the surface becomes large, resulting in the formation of shrinkage cracks. During the winter months, the matric suction also becomes large because of temperature gradients induced during freezing. In the spring, the accumulated snowmelt penetrates the dry soil, resulting in large positive vertical ground movements.

Conclusions and recommendations

The numerical model illustrates the relationship between vertical ground movement and matric suction changes. The model shows how increases in matric suction result in shrinkage and decreases in matric suction result in swelling.

Reasonable agreement between measured and predicted vertical ground movements was achieved using soil parameters that vary with depth. The modelling studies indicated that the infiltration and exfiltration processes were characteristically different. Bulk coefficients of permeability were required to simulate measured ground movements during infiltration. These were relatively high, in the order of 10^{-8} - 10^{-9} m/s. The high values are probably due to the formation of shrinkage cracks and the associated macrostructure of the soil.

Bulk coefficients of permeabilities required for the exfiltration processes were in the order of 10^{-9} - 10^{-11} m/s. These lower values possibly reflect the change from water flow in the liquid phase during infiltration to water flow primarily in the vapour phase during exfiltration.

The Thornthwaite potential evapotranspiration model provided a reasonable characterization of the surface boundary flux, with the "actual" evapotranspiration estimated to be 70% of "potential" evapotranspiration based upon several methods.

The model could be extended to predict seasonal ground movements beneath light-engineered structures using available meteorological data (e.g., precipitation and temperature) and appropriate boundary conditions.

Further research is required to better establish the surface boundary conditions and to enlarge on the database of typical soil properties.

Thermally induced matric suctions should be studied and included in the modelling of vertical ground movements. The cracking phenomena exhibited in the field and the associated flow processes for the cracked profile should be examined in further detail.

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