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BEHAVIOR OF EXPANSIVE SOILS IN
WESTERN CANADA

by J. J. Hamilton

ANALYZED

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Depuis plus de 25 ans, la Division des recherches sur le bâtiment du Conseil national de recherches du Canada (DRB, CNRC) poursuit des études sur le terrain et en laboratoire, sur les effets du gonflement et du retrait des sols argileux sur les fondations de diverses constructions. Les influences de la végétation naturelle et du climat ainsi que celles des aménagements paysagers, des constructions et des travaux d'entretien sur le comportement de profonds dépôts d'argile à forte dilatation de l'Ouest canadien ont été étudiées. Les mesures des mouvements du sol, de la teneur en humidité et des fluctuations de température, prises parfois depuis vingt ans, indiquent la complexité des réactions du sous-sol en milieux naturels et en milieux remaniés dans le cadre de l'expansion urbaine.

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BEHAVIOR OF EXPANSIVE SOILS
IN WESTERN CANADA

By. J.J. Hamilton, M. EIC-CGS, F. GAC¹

ANALYZED

ABSTRACT

The Division of Building Research, National Research Council of Canada (DBR, NRCC) has been engaged in field and laboratory studies of the effects of swelling and shrinking clay soils on foundations of various structures for more than 25 years. The influences of natural climate and vegetation, and of man's landscaping, building construction and maintenance activities on the behavior of deep deposits of highly expansive clay soils in western Canada have been investigated. Measurements of ground movements, soil moisture content and temperature changes extending over periods as long as 20 years have demonstrated the complexities of subsoil responses in natural and disturbed environments associated with urban development.

INTRODUCTION

In western Canada climate and vegetation are the dominant natural factors affecting the behavior of expansive soils. Initial site conditions (i.e., conditions found at the time of investigation for design and construction purposes) are the product of complex dynamic processes such as seasonal freezing and thawing and seasonal rainfall and drought which have been repeated hundreds of times in the past. Others may be the result of relatively new man made influences such as the introduction of non-native trees in areas that have not previously supported tree growth or the initiation of irrigation in naturally sub-humid or arid environments.

Almost all the populated area of prairie Canada was glaciated and is now covered with thick deposits of glacial drift, outwash, fluvial and lacustrine sediments. Although occasionally the tills and fluvial deposits can be classified as potentially expansive, the most troublesome expansive soils for shallow foundations on the Canadian prairies are those found in many deep lacustrine deposits from the Pleistocene age. The Cretaceous shales from which the expansive clay minerals were largely derived, are usually deeply buried below glacial deposits and outcrop only in the deeper valleys. While they do pose particular problems for stability of natural and man-made slopes involved

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in major engineering works such as dams, canals, highway and pipeline river crossings and river bank stability problems in some urban locations, these expansive clay shales rarely are of concern in the design or construction of shallow foundations in residential and municipal works.

Site location and topography are usually of minor significance in the generally flat, featureless plains that were once the beds of immense glacial lakes. Of these lakes, Agassiz was probably the largest in areal extent and left very deep deposits of highly expansive clay which has subsequently been overlain with thin flood plain deposits in the vicinity of its current rivers. The Assiniboine River rises in southeastern Saskatchewan and flows in oversized valleys that were once glacial spillways deeply cut into the Cretaceous deposits of eastern Saskatchewan and western Manitoba. It then flows out onto the flat Lake Agassiz bed. The Red River rises in Minnesota and North Dakota and flows for more than two hundred miles in a small meandering valley cut into the surface of the Lake Agassiz deposits. The city of Winnipeg, Manitoba, is located where the Assiniboine River joins the Red River which continues its northward flow to empty into Lake Winnipeg. Extensive flooding of the lower Red River valley has been a frequent occurrence during rapid spring thaws in the catchments of rivers that traverse the Agassiz plain. The result of this flooding has been to lay down a few feet of reworked clay and silty materials that have been derived mainly from the original lake bed deposits and hence the overlying fluvial materials are only slightly less plastic and slightly less uniform in stratigraphy than the underlying clays.

Shallow foundations in the city of Winnipeg have had a long history of heaving problems due to subsoil expansion and settlement due to subsoil shrinkage. Some early studies were described in the Proceedings of the First International Research and Engineering Conference on Expansive Clay Soils (Hamilton 1965). Several test plots and many shallow foundations were instrumented and have been monitored since the late 1950's and early 1960's. The effects of natural climate, irrigation, altered vegetation and surface covers, as well as changes in loading and temperatures in the vicinity of man-made structures have been included in these studies (Hamilton 1963, Hamilton 1966, Hamilton 1969).

In virgin terrain, natural climate and vegetation provide the driving forces for changes in soil moisture and volume. Long cold winters with relatively thin ground snow cover cause deep frost penetration and low ground temperatures. Variable spring and summer rainfall often result in drought conditions that can persist for more than a year. The depth of the active layer through which sizable ground movements can be detected is governed by the depth of rooting or the depth of seasonal frost penetration, whichever is greater.

When land is subjected to agricultural use the active layer receives some increased stimulations. Summer cropping with non-native species, summer-fallowing of extensive areas, deep tillage, surface drainage and/or irrigation, snow accumulation or wind sweeping, may all have significant effects on soil moisture and temperature regimes.

Suburban and urban development often impose even larger changes such as cut and fill grading, snow clearing, paving of large areas, establishment of non-native, deep rooted vegetation, extensive irrigation, and increased heat flows through the soil adjacent to heated or cooled structures.

Although climate and vegetation are the major natural energizers in the subsoil environments, man's agricultural activities may alter the natural dynamics significantly. Man's construction and urban development activities bring great changes to the natural environment which magnify seasonal effects and may set off new long-term trends.

Much of the research on expansive clays is conducted in regions of the world where deep seasonal freezing is not experienced. Low ground temperatures and steep thermal gradients around heated structures add to the complexity of environmental factors that are important in Canadian problems but which are given little attention in research and engineering developments produced in other countries. It is for this reason that a considerable portion of this paper will be devoted to the influence of deep seasonal freezing on expansive soil profiles.

TEST PLOT STUDIES OF GROUND MOVEMENTS

The Civil Engineering Department of the University of Manitoba (U of M) and the Division of Building Research, National Research Council of Canada began studies of vertical ground movements in the 1950's (Baracos and Bozozuk 1957) patterned after similar studies being conducted in Great Britain at the Building Research Establishment (Ward 1953). Installation of reliable deep bench marks and vertical ground movement gauges under various ground surface and vegetation conditions permitted measurements of vertical ground movements at various depths in the ground (Bozozuk et al 1963, Hamilton 1963). Ground temperatures were measured with thermocouples. Simple standpipe piezometers were occasionally installed to monitor water levels perched in shallow strata and more permanent water levels deep in the clay deposit which are affected by aquifers in the underlying tills and bedrock. Soil moisture content was measured by hand auger, gravimetric water content sampling and after 1960 by the addition of neutron moisture and gamma density depth probes. Early attempts to measure soil moisture stresses in the unsaturated strata above the water table with electrical resistance moisture blocks and mercury manometer tensiometers were of limited success.

EFFECTS OF VEGETATION ON VERTICAL GROUND MOVEMENTS

Figure 1 shows typical ground movements measured at various depths in natural, clay-rich subsoils under the influence of grass, tree, fallow and pavement surfaces from July 1962 to July 1966, with the influences of irrigation and chemical fertilizers added in 1964 to the fallow and grass-covered plots (Hamilton 1969). Following the lead of Bozozuk and Burn 1960, attempts were made to estimate changes in soil moisture content based on a modification of the Thornthwaite 1948 potential evapotranspiration soil moisture budgeting techniques (Hamilton 1966). As illustrated on Figure 1 ground surface movements

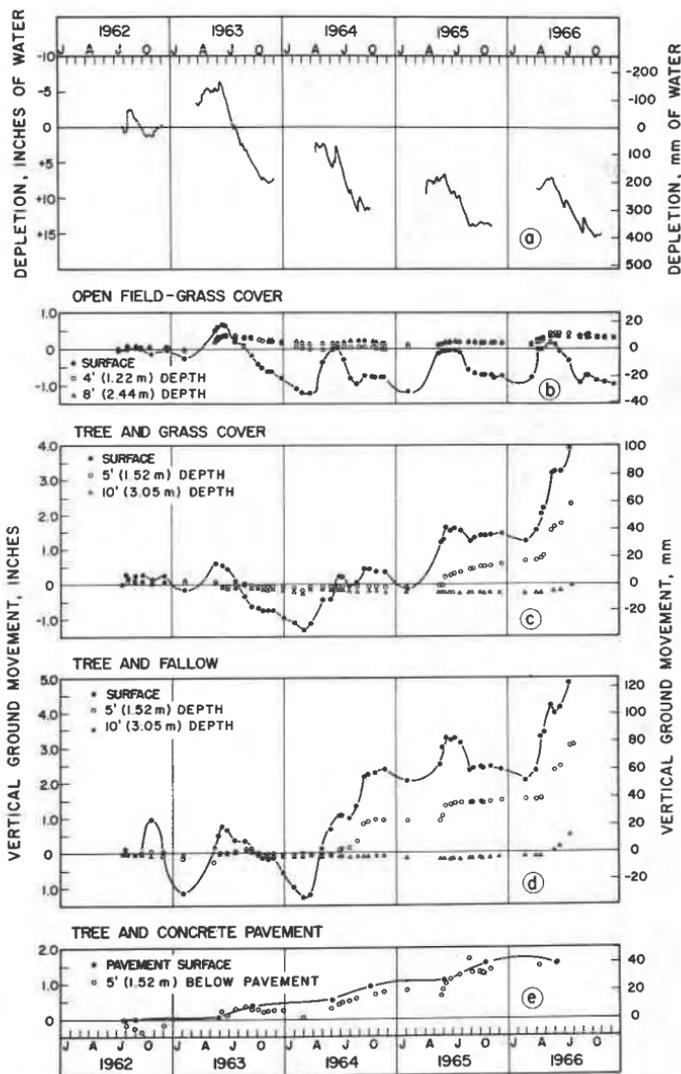


FIG. 1 Calculated Soil Moisture Depletion (a) and Vertical Movements at Various Depths in Undisturbed Soil: (b) in an Open Field with Grass Cover; (c) in a Grass-covered Plot, 22.5 ft. (6.86 m) from a Tree; (d) in a Fallow Plot 22.5 ft (6.86 m) from a Tree; (e) under a Concrete Road Pavement Centerline, 27.5 ft (8.38 m) from a Tree.

showed reasonably good empirical correlations with calculated soil moisture depletion during prolonged drying periods. In open-field grass covered test plots it was indicated that it would be appropriate to apply a root depth constant of approximately eight inches (200 mm) for native species growing on a typical Winnipeg silty clay profile over heavier clay at depth. Where tree roots penetrated several feet into the underlying lacustrine clay, it would be appropriate to select rooting constants as large as 4.5 inches per foot (375 mm/m) of heavy clay penetrated by the rooting system, i.e., where tree roots reached depths of a dozen feet (3.7 m) or more the appropriate rooting constant might be 40 inches (1016 mm) or greater.

From 1962 to the spring of 1964 the ground movements at the U of M tree test plot were quite similar to those measured in the open-field grass-covered test plot several miles away. Two unexpected and uncontrollable events significantly changed the pattern of ground movements around the tree after June 1964. The first event was the commencement of heavy irrigation of an adjacent field which contributed considerable moisture to the test plot during the remainder of that and subsequent growing seasons. The next was the application of chemical fertilizers by U of M groundskeepers in bore holes spaced in a grid pattern throughout the root spread of the tree in an attempt to revitalize its condition. The result was a change in ground movement patterns with rapid heaving occurring first in the fallow area in the upper five feet (1.52 m) and later in the stratum at depths between five and ten feet (1.52 to 3.05 m). By the summer of 1966 heaving commenced below the ten-foot (3.05 m) depth and exceeded one half inch (12.7 mm) in less than three months. Heaving under the grass-covered area was delayed one year and proceeded more slowly in 1965 until the cumulative effect of irrigation exceeded the moisture demands of the grass. By spring of 1966 the heaving rates at the surface and five-foot depth (1.52 m) were very similar to those for the fallow area and at the ten-foot (3.05 m) depth the beginning of a heaving trend was established. By mid-summer 1964 the subsoil five feet (1.52 m) below the concrete pavement also showed accelerated rates of heaving of similar magnitude to the heaving of the pavement surface. It became apparent that the fissured, silt-stratified, annually frozen upper five to six feet (1.52 to 1.83 m) of the profile acted as a very effective aquifer conducting irrigation and other surface water long distances horizontally from the areas of infiltration to supply moisture to the underlying clay. Perched water tables in these strata often develop quickly after snow melt and early spring rainfall and provide readily available water for uptake by plant roots and underlying clay. Where silt strata exist at or below the depths of seasonal frost penetration they appear to act as capillary breaking layers which limit the suctions induced in underlying strata by frost action above. Often they mark the limit of root penetration for shallower rooted vegetation. Only drought resistant tree varieties seem to extend their root systems beyond into the underlying lacustrine clay.

SOIL SUCTION AND VERTICAL GROUND MOVEMENTS

Figure 2 shows the correlations between soil suctions measured at depths of two feet (0.61 m) and four feet (1.22 m) with vertical

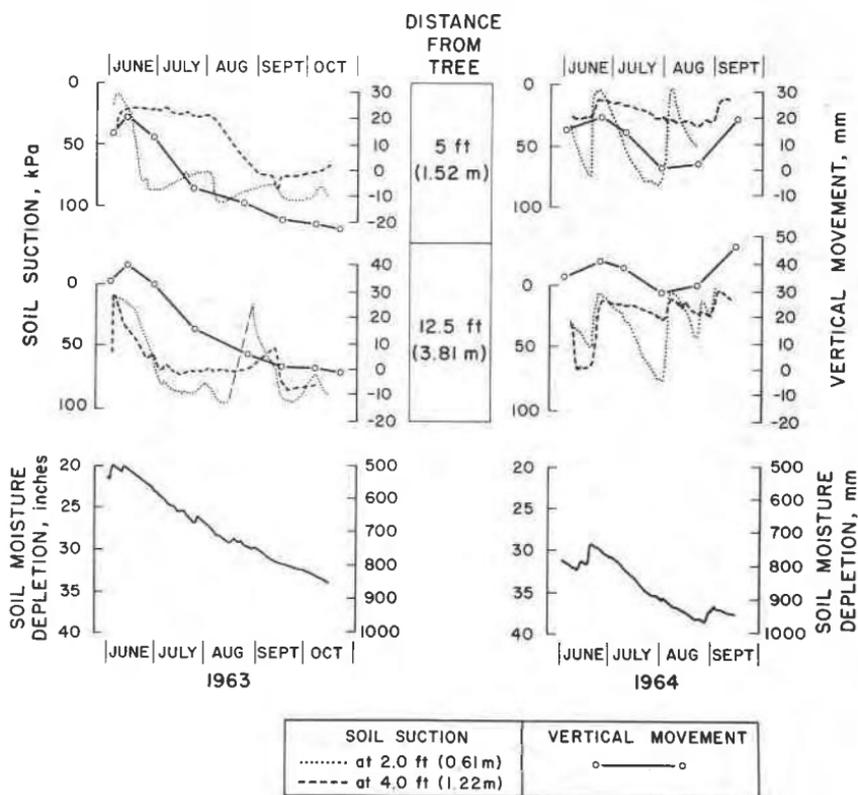


FIG. 2 Soil Suctions Measured by Tensiometers at Depths of 2 ft. (0.61 m) and 4 ft. (1.22 m) at Distances of 5 ft. (1.52 m) and 12.5 ft. (3.81 m) from a Tree; Ground Surface Movements; and Calculated Soil Moisture Depletion (Cumulative from 1951).

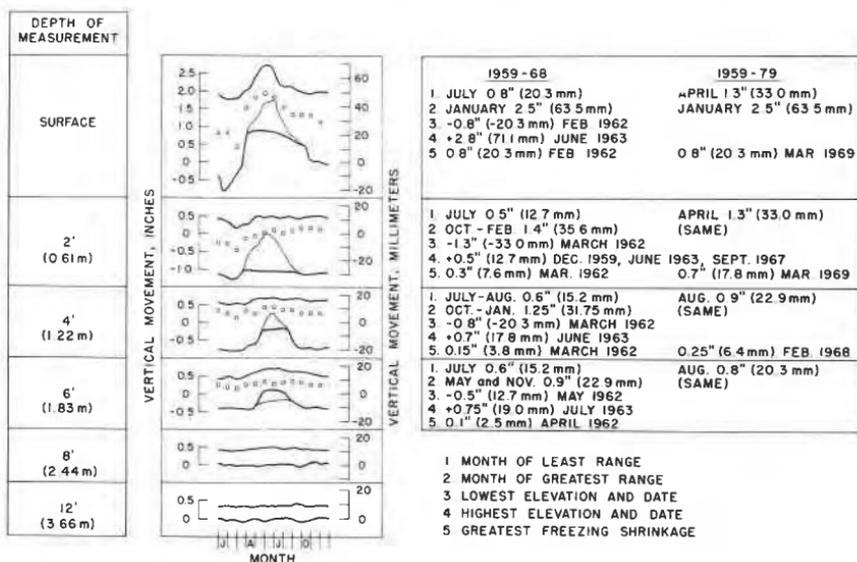


FIG. 3 Mean, Maximum and Minimum Monthly Ground Movements Measured in and Open Field Grass-Covered Test Plot in Winnipeg, Manitoba, 1959 to 1979.

movement of the ground surface at distances of five feet (1.52 m) and twelve and one half feet (3.81 m) from the tree during the summers of 1963 and 1964. During the relatively long dry summer of 1963 the correlations between movement and suction were good and corresponded well to calculated soil moisture depletion as shown on the lower portion of the Figure. In 1964, the new effect of irrigation was experienced and its impact on ground heaving and reductions in soil suctions is contrasted against calculated soil moisture depletions which did not include the water received in the form of irrigation or any adjustment for horizontal migration via the perched water table.

The relatively low levels of soil suctions measured within the upper few feet of the Winnipeg subsoils during the growing season (usually less than pF 3 (approximately 100 kPa)) was considered to be reasonable for the observed secondary structure (locally described as nuggetty or friable) which makes the annually frozen clays act more like silt than clay. Examination of many years of ground movement measurements such as those summarized in Figure 3 for gauges at the ground surface, and various depths ranging from two feet (0.61 m) through twelve feet (3.66 m) below the surface of native grass-covered terrain revealed some interesting patterns and ranges of movements. With reference to Figure 4, a plot of cumulative departure from long-term average annual precipitation for Winnipeg, indicates that the period from 1959 to 1968 was a slightly drier than average decade which followed several years of above average precipitation and also that the period from 1969 to 1979 was another slightly above average

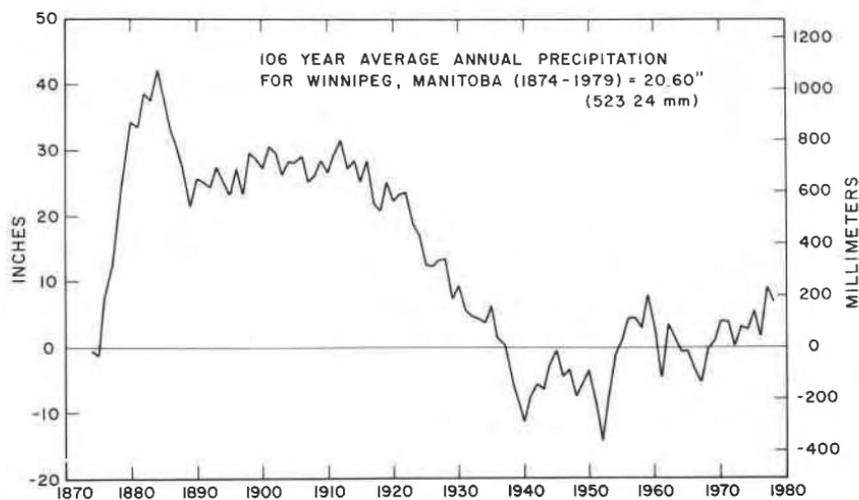


FIG. 4 Cumulative Departure from Long-term Average Annual Precipitation for Winnipeg, Manitoba, 1874-1979.

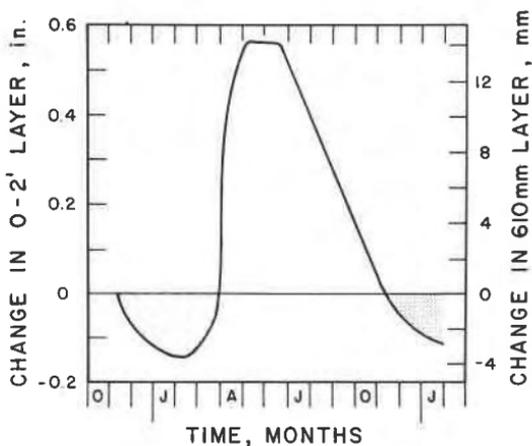


FIG. 5 Typical Seasonal Change in Thickness of the Upper 2 ft. (610 mm) of Soil Below a Grass Covered Ground Surface.

precipitation period. Unfortunately for our purposes neither of these periods included a prolonged drought like that of 1922 to 1940 nor a lengthy wetter than average period such as occurred from 1952 to 1959. Possibly the most significant discovery made from examining the maxima and minima for each month of the twenty-year records as summarized in the plots and table of Figure 3 was the realization that the greatest range in ground surface movements occurred during the month of January and other winter months at various depths through the seasonally frozen layer. Only at depths of six feet (1.83 m) or greater was the range of movements maximum in May and November. A typical pattern of change in dimension of the 0 to 2 foot (610 mm) layer is given in Figure 5. Below freezing temperatures persist in this stratum from early November through late March each winter. Typically the soil begins this frozen period at low moisture contents and saturation below 95 per cent because of usually dry fall conditions. As soil temperatures fall below freezing, the ground settles and vertical cracks open in inverse proportionality to the degree of saturation of the soil. The freezing shrinkage usually is of the order of 0.5 to 1 per cent of layer thickness. Figure 6 shows thermal coefficients of shrinkage for various degrees of saturation on the right hand side that were calculated from field data from an open-field, native grass plot in Winnipeg. On the left hand side, the laboratory determined relationship of freezing shrinkage and degree of saturation of an Edmonton, Alberta compacted clay subgrade soil have been calculated from the data published by A.B. Hamilton in 1966. Figure 7 indicates another very important phenomena of freezing shrinkage consistently taking place in the horizontal dimension (parallel to heat flow) and irrespective of degree of saturation or whether or not freezing

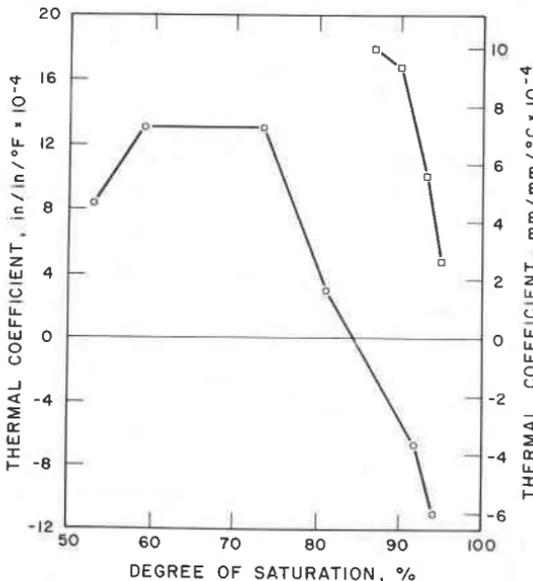


FIG. 6 Coefficients of Freezing Shrinkage Vs Degree of Saturation for \circ — \circ a Compacted Edmonton, Alberta Clay (after Hamilton, A.B.(1966)) and for, \square — \square Field-measured Ground Movements at a Winnipeg Test Plot.

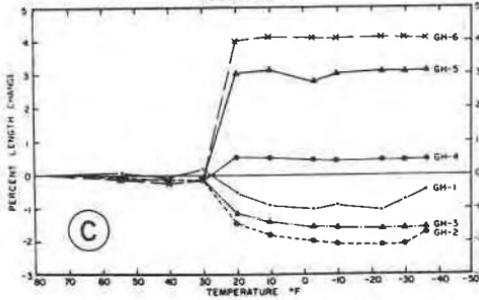
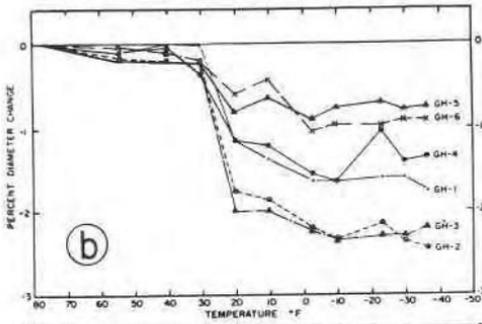
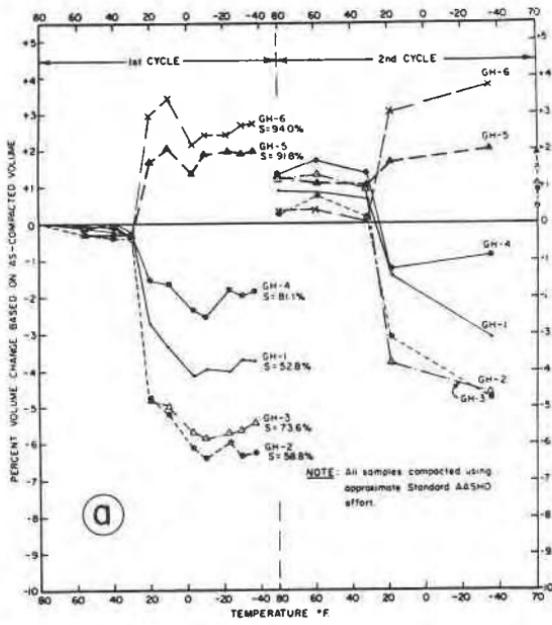


FIG. 7 Volume and Dimension Changes Vs Temperature for a Compacted Edmonton, Alberta Clay (after Hamilton, A.B., 1966).

expansion or shrinkage takes place in the vertical dimension (perpendicular to heat flow). This confirms numerous field observations of vertical cracks opening in clay subsoils as they freeze. At the time of snow melt, these deep cracks assist in rapid infiltration and in large measure are responsible for the very rapid ground heaving rates recorded simultaneously with ground thawing. In stratified profiles vertical cracks provide open channels to underlying silt varves or thicker strata which in turn act as efficient horizontal moisture distributors.

Deep seasonal freezing appears to have another very significant effect on Canadian expansive clay profiles. Croney 1952 and Croney et al 1952 presented the equation for determining suction induced by freezing point depression:

$$pF = 4.1 + \log_{10} t$$

where t is the freezing point depression below zero C. Croney and Coleman 1961, further discussed the very large suctions that are induced by freezing fine-grained soils. "Where ice and water are simultaneously present in soil the extra phase (ice) suppresses one degree of freedom of the system and the suction and temperature instead of being independent variables are uniquely related." "If a road structure (base, sub-base or subgrade) is initially at a low suction and then becomes frozen, the relatively simple measurement of temperature in the frozen zone permits the prediction of the suction of that fraction of the soil water remaining unfrozen at the point of measurement." Further, they postulated that, "in the freezing process nearly all the moisture migration and associated ice segregation may well occur at modest suctions (but at high gradients of suction) very near the freezing zone." In clay soils frozen in a state of unsaturation and at initially high suctions typical of the plastic limit or the optimum water contents for compaction, freezing has been shown to induce both vertical and horizontal shrinkage. If closer to saturation, freezing may induce volume increase as shown in Figure 7a because of expansion parallel to heat flow (see Figure 7c) even though shrinkage continues to take place in dimensions perpendicular to heat flow (see Figure 7b) (Hamilton 1969).

Double oedometer tests on samples of Winnipeg silty clay taken from the annually frozen layer typically show much lower void ratios, lower preconsolidation pressures and swelling pressures and much lower free swelling tendencies than clay samples from below the maximum annual freezing depth. Figure 8 illustrates the relatively small free swelling of approximately 3 per cent, the low compressibility in the load range 1 Kg/cm^2 (pF 3.0) to 14 Kg/cm^2 (pF 4.1) compared with that of the deeper clays that do not exhibit the secondary structure. Many questions remain unanswered regarding the stresses imposed and the structural changes caused by freezing but it appears that there are substantial increases in the effective permeability and reductions in the over-all swelling potential of the annually frozen clay-rich strata. Figure 9 presents a typical no-swell and free-swell consolidation test series on a clay from a depth of 9 feet (2.74 m) i.e., beyond annual

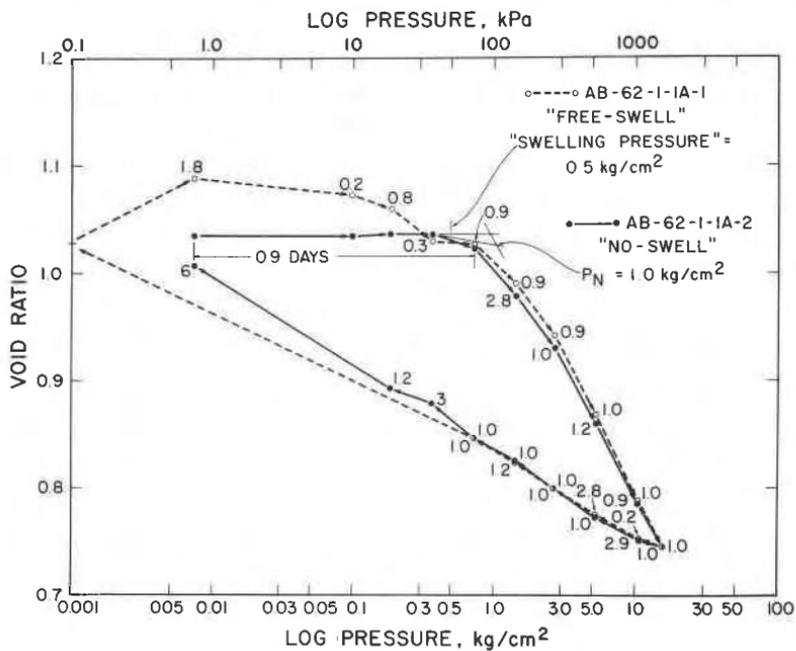


FIG. 8 Pressure - Void Ratio Curves for Undisturbed Samples from 2.5 ft. (762 mm) Depth at the U of M Test Plot in Free-swell and No-swell Loading Cycles.

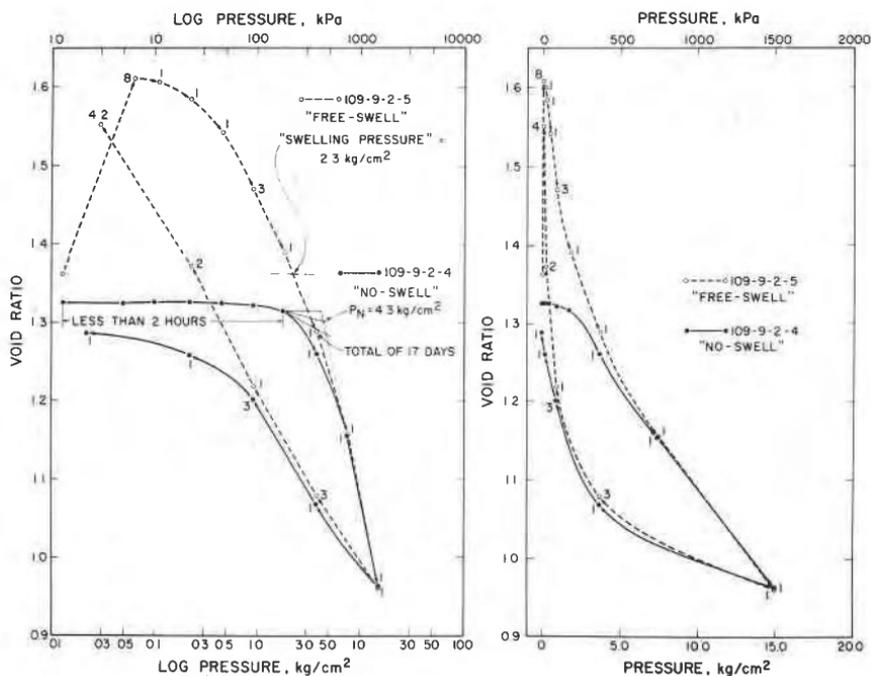


FIG. 9 Log Pressure - Void Ratio Curves for Undisturbed Samples from 9.0 ft. (2.74 m) Below Ground Surface Adjacent to a House Basement in Free-swell and No-swell Loading Cycles.

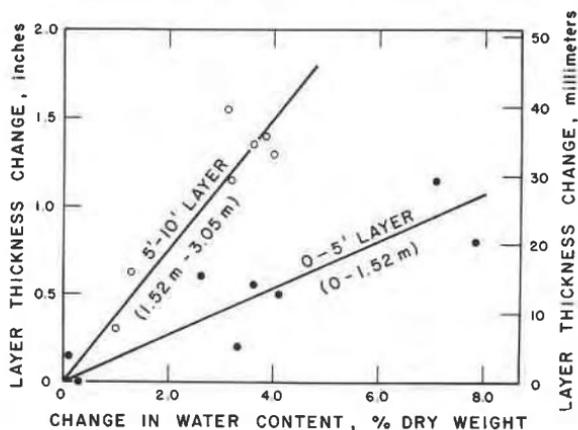


FIG. 10 Field Measured Relationships Between Vertical Dimension Change and Average Change in Water Content for Two Upper 5 ft. (1.52 m) Strata

frost penetration but within the depth of tree rooting. No-load, free swelling of 10.5 per cent increase in vertical dimension took place as the sample assumed its final water content of 57.6 per cent at a vertical stress of 3 kPa after starting with an initial water content of 47.3 per cent. The preconsolidation pressure of 4.3 Kg/cm² (pF 3.6) is within the range of expected suctions induced by tree roots. Beyond this loading the compressibility of the clay is very high as is the rebound-swelling index (shrink-swell is reversible with only slight hysteresis over a broad range of water contents from 35 to 55 per cent). The matrix suction equivalent (Fredlund et al 1980) for this sample appears to be approximately 180 kPa. Figure 10 is illustrative of the difference in layer thickness changes as water content increases with no change in total stresses i.e., ground movements occurring in unfrozen profiles during spring and summer moisture changes. In the upper 5-foot (1.52 m) stratum an average change in water content of 4 per cent produces a layer thickness change of 0.5 in. (0.8 per cent). In the 5 to 10 foot (1.52 - 3.05 m) deep stratum a 4 per cent change in water content has produced a change in layer thickness of approximately 1.5 in. (2.5 per cent). Figure 11 illustrates the differential heaving of the concrete road surface adjacent to the U of M tree test plot from the beginning of observations in July 1962 to the end of the measurements in July 1966. The subsoil at this location exhibits the swelling tendencies shown in Figure 10. As discussed earlier and shown on Figure 1 most of the swelling took place below the 5-foot (1.52 m) depth during summer months as moisture increases took place most rapidly at the greatest distances from the tree.

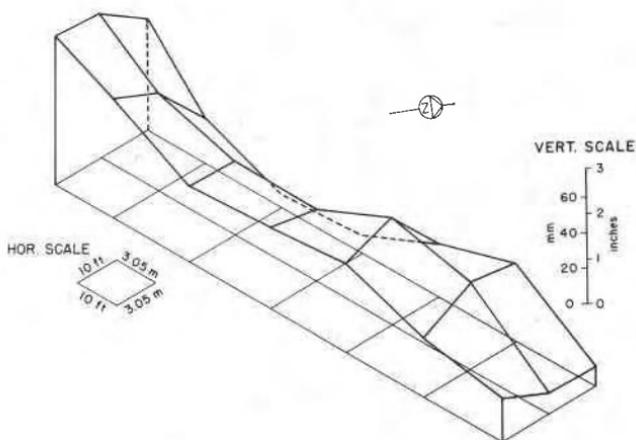


FIG. 11 Differential Heaving of a Concrete Road Surface Adjacent to the U of M Tree Test Plot

EFFECTS OF REDUCED LOADING AND SUCTION CHANGES

Laboratory and field measurements of swelling under reduced loading and solute suctions have demonstrated the large rebound-swelling potential of Winnipeg clays from below the seasonally frozen stratum. A typical excavation for a house basement six feet (1.83 m) deep and construction of cast-in-place concrete footings, foundation walls and basement floor slab plus a wood frame one-storey house superstructure can cause a large total stress reduction in the subsoil. Added to this is the reduction in total suction brought about when deep rooted vegetation is removed and intensive landscape irrigation is instituted. Reference to a typical stress reduction distribution published earlier (Hamilton 1969) and the rebound-swelling in excess of 10 per cent shown on Figure 9 graphically illustrates how footings and floor slabs can be expected to undergo total heaving and differential heaving of the order of one foot (305 mm) and one-half foot (152 mm) respectively due to reductions in effective stresses. Trees located close to shallow foundations can further amplify differential movements as they control subsoil suctions within the spread of their root systems. Figure 12 illustrates the total and differential heaving of perimeter footings of two adjacent houses over a period of 17 years. Footings for the house shown on the bottom were placed on a uniform deep deposit of the clay with swelling properties as shown in Figure 9. An empirical relationship that has been found useful in predicting the maximum swollen water content for Winnipeg clays in one-dimensional swelling under very light loading takes the form:

$$w_{\max} = 0.64 \text{ PI} + 16.67$$

when w_{\max} = maximum swollen water content (% dry weight basis), and PI = plasticity index (%). Footings in the northeast corner of the foundation for the house shown on top were also founded on the same clay. The large differentials in heaving of the foundation on the left is explained by an increasingly thick layer of silt underlying the footings in the southwest quadrant to a maximum depth of 4 feet (1.22 m) below the footing at the southwest corner. Non-uniformity of subsoil stratification can cause large differentials in rates and total amounts of movements of shallow foundations.

DISCUSSION

Complex interrelationships link soil moisture stress and strain conditions to climate, vegetation, man's landscaping and building activities. Many of the factors are quite specific to relatively small regions as typified by the Lake Agassiz plain in the vicinity of Winnipeg, Manitoba. Some semi-empirical climate-soil response relationships have been found useful in understanding and extrapolating the behavior of near-surface expansive soils.

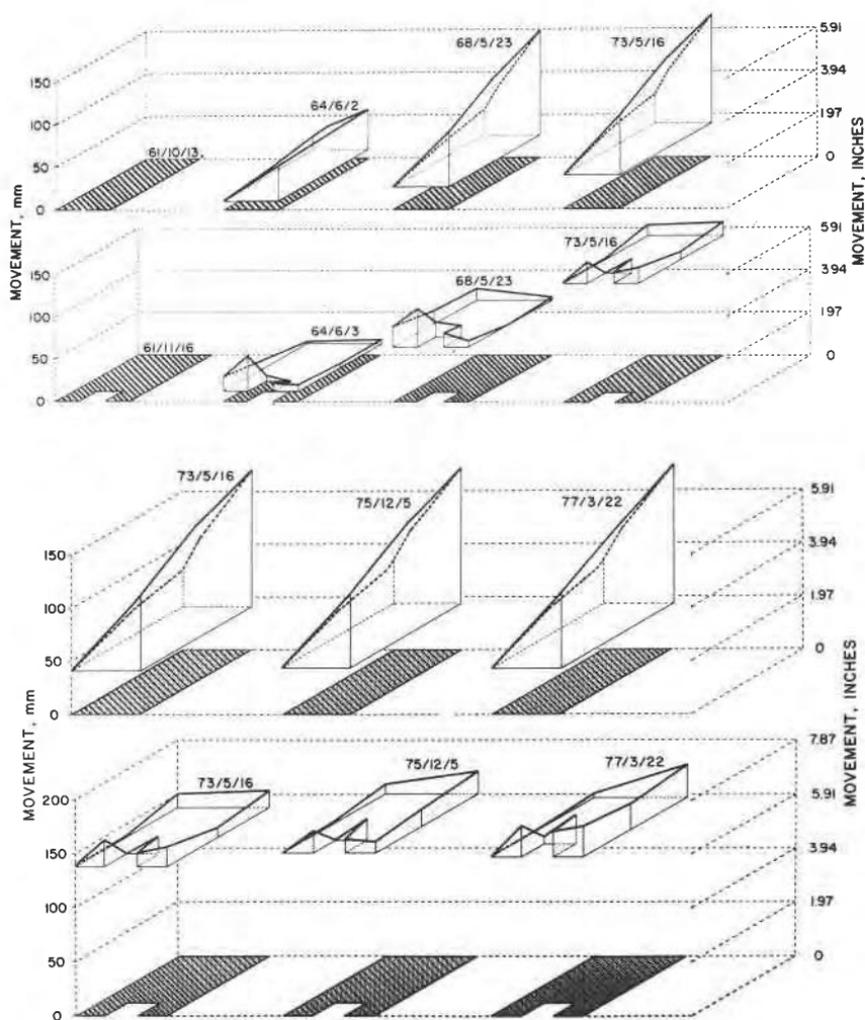


FIG. 12 Heaving of House Basement Footings at Two Adjacent Houses:
 Upper - on 4 ft of Silt in SW Corner Decreasing to No Silt in NE Corner.
 Lower - on Uniform Expansive Clay Subsoil Represented by FIG. 9

Annual freezing may exert higher suctions than those caused by plant evapotranspiration. Surface settlements due to freezing shrinkage of the order of one per cent of the depth of frozen soil are not unusual.

The magnitude of freezing shrinkage seems to be related to degree of saturation at the time of freezing and probably is different for compacted compared with "undisturbed" natural deposits. Secondary structure induced by freezing shrinkage in relatively dry profiles appears to increase vertical permeability and assists moisture infiltration during early spring and summer. Depositional stratification such as varves or silt layers may provide porosity for perched water tables and aids horizontal transmission for considerable distances under paved surfaces from the area of entry of surface water.

The annual amplitude of ground surface movements in open-field, native grassland conditions is usually about two inches (51 mm) with the range of movements over twenty years of near average precipitation being approximately four inches (102 mm). The amplitudes are considerably increased and long-term trends of shrinkage are established when deeper rooted vegetation is added to the competition for subsoil moisture.

Trees exert a powerful influence on soil moisture stress and water content at depths below seasonal frost penetration. During the growing season, grass roots may use much, if not all, of the available surface moisture forcing the trees to seek moisture from deeper strata.

Intensive irrigation and the use of fertilizers in landscaping cultural practices can set off rapid, large changes in ground movement patterns.

Great care must be exercised in order to measure the relatively small changes in moisture content or bulk density in the field which are associated with large total heaving in thick active layers. Tensiometers and psychrometers have not yet been used successfully in the field either on a year-round basis or at depths below annual freezing.

Careful laboratory consolidation-swell tests can indicate the order of magnitude of volume change to be expected under combined changes in total stresses and suctions.

Performance of shallow foundations can be predicted only if the combined effects of physical loading and moisture stress changes can be accurately anticipated. For simple boundary conditions, predictive methods such as the hyperbolic extrapolation (Dakshnamurthy 1978) may be applicable in predicting rates of heaving. Detailed investigations of individual sites carried out in the context of an understanding of the factors at play in the larger environment of the area, would be necessary to enable predictions of future movements where there is complex stratigraphy or vegetation conditions.

CONCLUSIONS

A greater understanding of the more significant environmental factors affecting reactions of expansive soils is slowly emerging. The climatic, geologic and vegetative factors are specific to relatively small geographic areas and extrapolations beyond these regions are risky unless these can be based on more fundamental relationships and measurements than are now in use in western Canada. Engineering designs will continue to be based on limited past experience and semi-empirical methods until the state of the science is advanced to include all environmental factors such as deep seasonal freezing in a coherent theory and until establishment of "an appropriate technology to render engineering practice financially viable" (Fredlund 1979).

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