Vertical ground movements near elm trees
Bozozuk, M.; Burn, K. N.

Publisher's version / Version de l'éditeur:

Geotechnique, 10, 1, pp. 19-32, 1960-06-01

NATIONAL RESEARCH COUNCIL
CANADA

DIVISION OF BUILDING RESEARCH

VERTICAL GROUND MOVEMENTS NEAR ELM TREES

BY

M. BOZOZUK AND K. N. BURN

REPRINTED FROM
GEOTECHNIQUE, VOL. X NO. 1, MARCH 1960, P. 19 - 32.

RESEARCH PAPER NO. 99
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

JUNE 1960

PRICE 25 CENTS

NRC 5672

This publication is being distributed by the Division of Building Research of the National Research Council as a contribution towards better building in Canada. It should not be reproduced in whole or in part, without permission of the original publisher. The Division would be glad to be of assistance in obtaining such permission.

Publications of the Division of Building Research may be obtained by mailing the appropriate remittance, (a Bank, Express, or Post Office Money Order or a cheque made payable at par in Ottawa, to the Receiver General of Canada, credit National Research Council) to the National Research Council, Ottawa. Stamps are not acceptable.

A coupon system has been introduced to make payments for publications relatively simple. Coupons are available in denominations of 5, 25, and 50 cents, and may be obtained by making a remittance as indicated above. These coupons may be used for the purchase of all National Research Council publications including specifications of the Canadian Government Specifications Board.

ANALYZED

VERTICAL GROUND MOVEMENTS NEAR ELM TREES

by

M. Bozozuk and K. N. Burn

SYNOPSIS

Vertical ground movements were investigated near a line of high elm trees growing in Leda clay soil, a marine deposit found extensively in the Ottawa St Lawrence Lowlands. The amplitude of these movements was found to be a function of depth, horizontal distance from trees, and seasonal weather conditions. Based on results obtained for the record dry year of 1955, a chart was prepared which could be used as a guide for the design of foundations near high elm trees in these clays. These ground movements were also related to "soil moisture depletion", a quantity computed from weather records. An analysis of the ground movements over a period (1954–57) was made and a method for computing them from weather records is given.

On a fait une enquête relative aux mouvements verticaux du sol sous une rangée de grands ormes située dans les basses terres de l'Outaouais et du St-Laurent. Ces terres marines sont des argiles du type "Leda". On a constaté que l'amplitude des mouvements dépend de la profondeur, de l'éloignement horizontal par rapport aux arbres et des conditions climatiques. A partir des données recueillies lors de l'année de grande sécheresse 1955 on a établi un diagramme qui peut servir au calcul des fondations devant être établies près de grands ormes et dans des sols argileux. On a également établi un rapport entre les mouvements du sol et le "coefficient d'épuisement de l'humidité du sol", ce coefficient étant calculé à partir de certaines observations climatologiques. On a fait une analyse des mouvements du sol observés de 1954 à 1957 et on décrit une méthode permettant de calculer ces mouvements à partir de certaines données climatologiques.

INTRODUCTION

Pavements, sidewalks, and shallow foundations in regions of clay subsoils usually show evidence of vertical surface movements. Much of this movement is of a seasonal nature and appears to be related to natural soil moisture changes caused by variations in weather and vegetal cover. Near large trees, for example, with their deep root systems and huge water demands, non-uniform seasonal moisture changes may be expected to occur to great depths. Large non-uniform surface movements may consequently be expected from the corresponding shrinking or swelling of the soil, resulting in considerable damage to shallow foundations. Fig. 1 illustrates typical movements of this nature.

Problems resulting from seasonal movements in Canadian clays have been reported by Torchinsky (1953)[1] and by Baracos and Bozozuk (1957). Similar problems exist in England where Ward (1947) and Skempton (1954) have suggested that fast-growing trees should not be located closer to shallow foundations than the height of the mature trees. The effects on shallow foundations due to both shrinking and swelling clays in Australia have been discussed by Isaacs (1952) and Tasker (1954). The predominant problem in South Africa is associated with the effects of swelling of the clays after structures are built on them, as reported by Jennings (1953) and Collins (1957).

In order to study what happens in the soil adjacent to large trees; that is, within a radius equal to the tree height, the Soil Mechanics Section of the Division of Building Research, National Research Council of Canada, in 1954 began a programme of measurement of the vertical ground movements near a line of high elm trees, growing in clay soil, and of correlating these movements with seasonal weather conditions. Ground-movement gauges were installed at various depths and distances from the trees and weather records were collected. Graphs have been prepared showing the variation in ground movements with depth and distance from trees, and the relationship between ground movements and soil moisture conditions. Finally,

[1] See references on p. 31

an equation has been developed which relates ground movements to soil moisture conditions at the site.

THE SITE

The location of the studies is in a drained grassy area on the grounds of the Building Research Centre, Montreal Road, Ottawa. Gauges were installed adjacent to a single line of elm trees which range from 45 to 60 ft high. The subsoil is a marine clay, called Leda clay, which is common in the Ottawa and St Lawrence River valleys, the geotechnical properties of which have been discussed by Eden and Crawford (1957). The upper 12–15 ft, where the significant movements occur, is desiccated and highly fissured with the following range of index properties:

	%
Water content	30–80
Liquid limit	60–75
Plastic limit	25–35
Plasticity index	30–50
Shrinkage limit	25–30

INSTRUMENTATION

The instrumentation consisted of thirty-two multi-rod ground-movement gauges, one set of concentric telescoping ground-movement gauges, and three well-points located as shown in Fig. 2. The multi-rod gauges (Ward, 1953) shown in Fig. 3(a) are made up of $\frac{1}{4}$-in.-dia. pipe, capped at the lower end and set in cased holes to predetermined depths varying from 0 to $12\frac{1}{2}$ ft. Groups of these gauges were placed at distances of 5, 10, 20, 30, and 40 ft from the trees. Periodic level surveys of the projecting rods were carried out to measure ground movements at various depths.

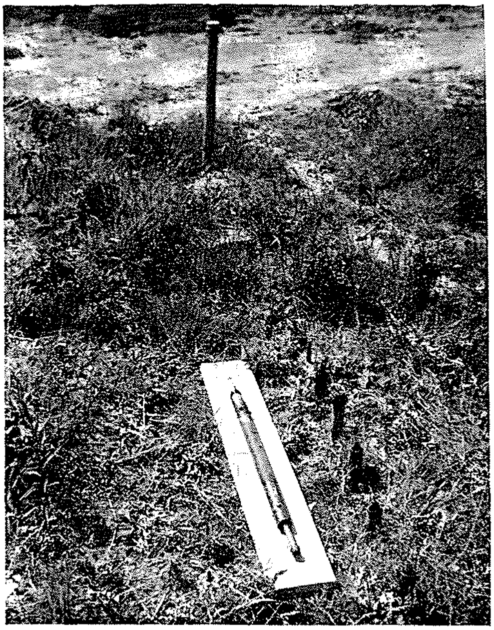
The concentric telescoping ground-movement gauges shown in Fig. 3(b) (Baracos and Marantz, 1953) consist of a series of various length tubes telescoping over each other, with the shorter, larger-diameter tubes on the outside. Each tube is fitted with a 3- × 10-in. horizontal plate which constitutes the foot of the gauge. They are installed in an elliptically shaped hole in sequence from the bottom, around a 15-ft-deep centre rod by turning the plates horizontally into undisturbed soil. The hole is then backfilled with soil as close as possible to its natural density. Relative ground movements are observed by measuring from the centre rod to the tops of the tubes.

Considerable difficulty was experienced in obtaining a good continuous record of ground movements from the time the gauges were installed until the end of 1957. The most serious problems were caused by the gauges freezing-up in the winter. In spite of the care taken to keep the space between the rod and casing filled with grease, some casings filled with water, froze in the winter, and heaved the gauges from their locations by unknown amounts. The foot of the multi-rod gauge has a bearing area of only $\frac{3}{4}$ sq. in. During the wet summer of 1956, the soil appeared to soften allowing the rods to "punch" into the soil under the weight of a survey rod. The concentric gauges were even less satisfactory as they began to jam, due apparently to rusting. It was possible, however, to make reasonable corrections by studying the time-vertical movement curves of groups of gauges.

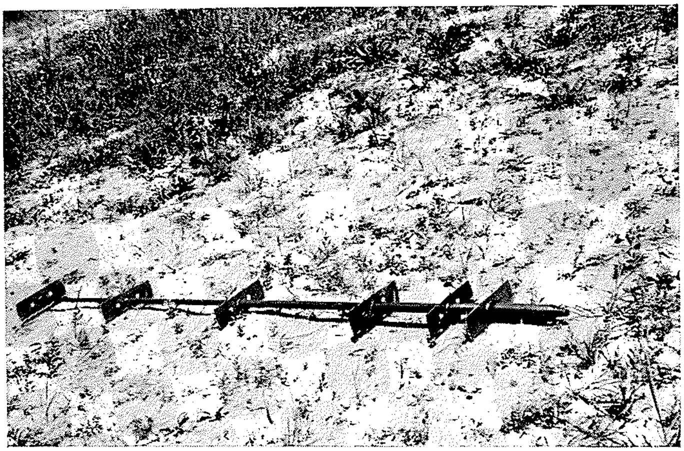
The initial elevations from which the ground movements were measured were taken as the highest elevations measured late in the fall and early in the winter of 1954–55. Because of the above-noted difficulties, however, the results had become unreliable by the end of 1957. Fortunately, an excellent set of readings was obtained for 1955. Since this was a year of extreme movements the more important conclusions of this report are based on these records.

Three well-points, located 5, 20, and 40 ft from the trees, were set in holes drilled to a depth of 12 ft. Water levels were measured by the use of a weighted tape and flashlight. The

Fig. 1. Effect of trees on sidewalk along Argyle Street, Ottawa



(a)



(b)

Fig. 3. Ground-movement gauges used to measure the vertical movements near the elm trees:

(a) multi-rod ground-movement gauge assembly, near installed units;
(b) telescoping ground-movement gauge

well-points, installed late in the summer of 1955, proved to be too shallow to follow the ground-water table to its maximum depth. Because of the comparatively large volume of water required in the stand pipes to record changes in water levels, there is some question as to the validity of such measurements in clays. Therefore no correlation of these readings with other measurements was possible.

CLIMATE, SOIL MOISTURE CONDITIONS, AND GROUND MOVEMENTS

Ottawa is situated in a temperate zone having a mean annual precipitation of 35 in. Most of the significant ground movements occur during the summer months when, as shown by an investigation of rainfall records from May to September, 1926 to 1956, precipitation ranges from a minimum of 9·9 in. to a maximum of 23·3 in. Table 1 compares the 1954–57 summer precipitation and temperatures with the 30-year mean values.

Table 1

Comparison of May–September temperatures and precipitation in Ottawa

Month	30-year mean*		1954		1955		1956		1957	
	Rain (in.)	Temp. (°F)	Rain† (in.)	Tm‡ (°F)	Rain (in.)	Tm (°F)	Rain (in.)	Tm (°F)	Rain (in.)	Tm (°F)
May	2·47	54·5	2·66	53·7	2·21	58·5	2·43	49·7	1·63	53·9
June	3·52	64·3	3·61	64·4	1·65	67·5	2·33	64·0	6·52	66·7
July	3·39	68·9	1·59	66·3	0·76	74·7	3·53	65·1	1·26	68·8
August	2·56	66·8	3·38	64·2	2·87	71·5	5·32	65·0	0·61	64·9
September	3·23	58·0	4·91	55·6	2·38	58·2	0·91	53·9	5·37	60·1
Total rain (in.)	15·17		16·15		9·87		14·52		15·39	
Average mean temp. (°F)	62·5		60·8		66·1		59·5		62·9	

* 30-year mean, from Central Experimental Farm Records, 1926–56.
† Rain = total monthly precipitation, inches.
‡ Tm = mean monthly temperature, °F.

To correlate seasonal weather conditions with ground movements, it is necessary to calculate the soil moisture conditions from weather records. Most soil water is thought to be charged by precipitation, and discharged through evaporation from the ground surface and by transpiration from plants. Some of the factors which affect this evapotranspiration are temperature, wind velocity, duration of sunlight, type of vegetation, relative humidity, and availability of soil moisture. The method used to evaluate the evapotranspiration is that proposed by Thornthwaite (1948), which includes most of the above factors.

It is assumed that the soil at the site is fully charged with water after the snow has melted and the frost has left the ground, since the ground-water table is then always at the surface. Subsequent soil moisture conditions can be obtained by comparing the water available from precipitation with the water lost by evapotranspiration. At a certain time, usually in May, the rate of water loss by evapotranspiration begins to exceed the water supplied by precipitation. This excess in inches of water is cumulated as a measure of soil moisture conditions, as shown in Fig. 4(a) and is termed "soil moisture depletion". It differs from Thornthwaite's "soil moisture deficiency" in that no "soil moisture storage" is considered. Calculated in this way, it compares favourably with the measured loss of soil moisture determined from soil borings, as shown in Table 2. However, the computed soil moisture depletion cannot truly represent soil moisture conditions both at a tree and at some distance from it, but it does represent average conditions and provides a common basis for extending test results to other locations.

In Fig. 4 a reasonable correlation between vertical ground movements and soil moisture conditions is shown. The movements at distances of 5 and 40 ft from the elm trees are plotted against soil moisture depletion of the area for the period 1954–57. During the winter months the soil moisture depletion was zero and relatively little ground movements were observed.

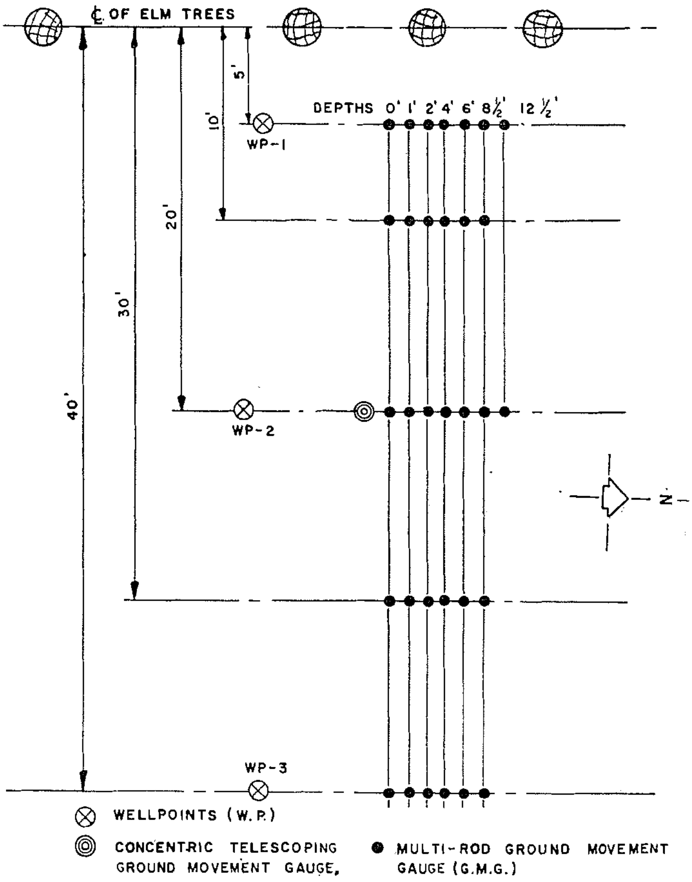


Fig. 2. Instrumentation near the elm trees

Movements began when the soil started losing moisture and reached maximum values at maximum soil moisture losses. In 1956 the maximum soil moisture depletion was 5·1 in., resulting in vertical ground movements of 0·67 and 0·25 in. at the respective distances of 5 and 40 ft from the trees at a depth of 1 ft. In 1954 and 1957 the soil moisture depletion was 8·8 and 7·7 in., respectively, producing correspondingly greater vertical ground movements. However, in 1955 a maximum soil moisture depletion of 15·5 in. was reached. The ground movements were observed to be 2·70 and 0·63 in. at the respective locations, illustrating that the magnitude of the ground movements depended upon seasonal weather conditions. The variations in maximum differential ground movements from 1954 to 1957, at a depth of 1 ft, are shown in Fig. 5.

The ground-water table also reflected the seasonal weather conditions. From 21 July to 27 September, 1955, it was more than 12 ft deep. In 1956 and 1957, the lowest observed water-table was 4 ft 2 in. and 10 ft 3 in. deep, respectively. At the end of the rainy season each autumn or early winter, and at the end of thaw in early spring, it was observed to be at the ground surface.

GROUND MOVEMENT VARIATIONS WITH DEPTH AND DISTANCE

During 1955, the computed soil moisture depletion was 15·5 in. of water. This was the driest year since 1931, when the depletion was 13·4 in. The maximum ground movements at

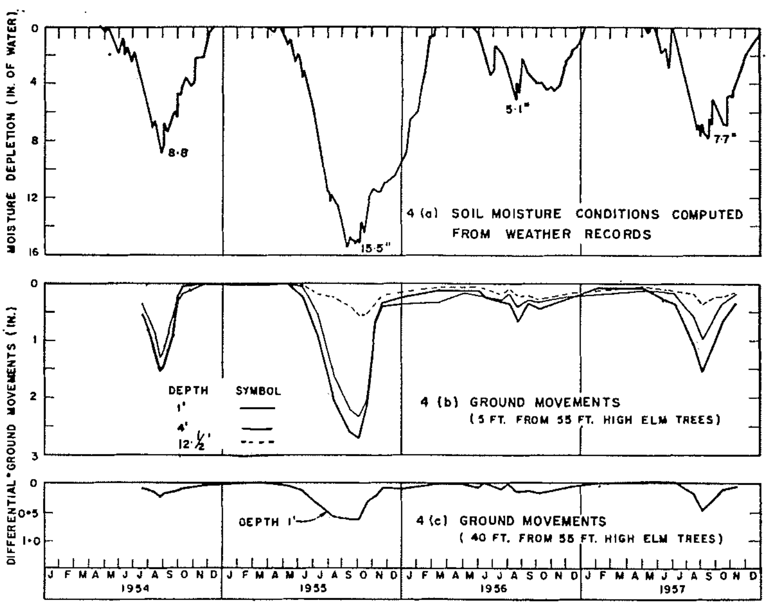


Fig. 4. Seasonal variations in moisture conditions and vertical ground movements in Leda clay soil at the Division of Building Research, National Research Council, Ottawa

(a) Soil moisture conditions computed from weather records;
(b) Ground movements (5 ft from 55-ft-high elm trees);
(c) Ground movements (40 ft from 55-ft-high elm trees)

various depths during 1955 are shown in relation to distance from the trees in Fig. 6. Within a horizontal distance of 20 ft from the trees, the movements at or near the ground surface were quite large. The movements diminished rapidly with distance until at 40 ft they were representative of the values in a grass plot nearby. They also diminished with depth but even at a depth of 12½ ft, movements greater than ½ in. were observed 20 ft from the trees.

From the curves of Fig. 6, a chart was prepared showing the variation in ground movements with depth in relation to the ratio of distance from the trees to height of trees. Shown in Fig. 7, it could be used as an aid in designing lightly loaded, shallow foundations in Leda clay soils near large elm trees. Knowing any two of the three variables: (*a*) depth of foundation; (*b*) allowable ground movements; (*c*) distance between tree and structure, it is easy to solve for the third.

It should be noted that these curves apply to one particular situation only and will therefore suffer from the usual discrepancy associated with the extrapolation of empirical data. They do, however, portray extreme conditions and may therefore be a useful guide in design. Field observations have illustrated good correlation for actual cases in Ottawa.

RELATIONSHIP BETWEEN GROUND MOVEMENTS AND SOIL MOISTURE CONDITIONS

To understand more fully the causes of ground movements and to permit of the application of observations in one area to problems in another, an attempt has been made to obtain a relationship between ground movements and soil moisture conditions. The observed ground movements at various depths were plotted against the empirical soil moisture depletion in inches of water as shown in Fig. 8(a) for a location 5 ft from the trees. As it was impossible to show all the points, they are also given in Table 3. The ground movements appeared to follow a shallow curve at first changing abruptly to a series of steep curves. The location of these intercepts appeared to depend on depth, that is at the greater depths it occurred at greater losses of soil moisture. Although the exact nature of the ground movements are not understood, it is deduced that the shallow curve representing "minor" ground movements is the result of elastic compression due to the increase in effective stresses in the soil as the ground-water table lowers. The steep curves showing much greater movements, with equal increments of soil moisture depletion, are thought to be caused by soil shrinkage and are

Table 2

Comparing loss of soil moisture by field measurement with soil moisture depletion

Dates	Distance from trees: ft	Depth: ft	Dry density of soil: lb/cu. ft	Change in % moisture content	Loss of soil water: in.	SM_D* in.
April–19 September, 1955 . .	5	0–1	64	29·6	3·6	
		1–2	84	20·7	3·3	
		2–4	85	9·6	3·1	
		4–6	83	7·0	2·2	
		6–9	76	6·0	2·6	
				sum	14·8	15·0
April–20 July, 1955	48	0–1	64	20·7	2·6	
		1–2	84	12·9	2·1	
		2–4	85	5·7	1·9	
		4–6	83	4·7	1·5	
		6–9	76	4·4	1·9	
				sum	10·0	9·6
April–29 October, 1956 . . .	20	0–1	64	12·6	1·5	
		1–2	84	8·0	1·3	
		2–4	85	3·6	1·2	
		4–6	83	2·5	0·8	
		6–9	76	negligible	—	
				sum	4·8	4·0
April—27 August, 1957 . . .	20	0–1	64	24·0	3·0	
		1–2	84	12·0	1·9	
		2–4	85	4·5	1·5	
		4–6	83	2·8	0·9	
		6–9	76	negligible	—	
				sum	7·3	7·3

* SM_D = Soil moisture depletion calculated from weather records.

Note: The soil borings did not extend to the maximum depths at which ground movements were observed. However, neglecting the loss of soil moisture from these greater depths where the moisture content changes appear to be small would result in only a slight increase in the totals shown.

Table 3

Settlements in inches near elm trees, 1955

Date		16–3	28–4	11–5	9–6	24–6	7–7	19–7	12–8	16–9	3–10
Depth: ft	SM_D / Dis.	0·01	0·45	1·18	3·38	4·72	7·27	9·39	11·89	14·74	15·19
0	5	0·00	0·12	0·13	0·50	0·82	1·24	1·62	2·21	2·76	2·86
	10	0·00	0·00	0·08	0·25	0·62	1·04	1·42	2·02	2·65	2·77
	20	0·00	0·00	0·02	0·32	0·37	0·92	1·16	1·72	2·24	2·29
	30	0·00	0·00	0·11	0·24	0·42	0·65	0·84	1·10	1·37	1·37
	40	0·00	0·04	0·05	0·26	0·36	0·55	0·66	0·67	0·76	0·76
1	5	0·00	0·01	0·10	0·25	0·58	0·95	1·32	2·03	2·60	2·70
	10	0·00	0·00	0·00	0·17	0·53	0·90	1·26	1·91	2·52	2·64
	20	0·00	0·02	0·12	0·14	0·37	0·71	1·02	1·57	2·09	2·16
	30	0·00	0·00	0·00	0·11	0·29	0·52	0·70	0·90	1·20	1·22
	40	0·00	0·04	0·05	0·13	0·22	0·38	0·48	0·59	0·64	0·64
2	5	0·01	0·00	0·00	0·18	0·48	0·88	1·24	1·95	2·52	2·63
	10	0·01	0·03	0·00	0·19	0·53	0·86	1·21	1·86	2·47	2·59
	20	0·00	0·05	0·01	0·12	0·31	0·61	0·90	1·40	1·94	1·99
	30	0·00	0·03	0·00	0·07	0·19	0·37	0·50	0·72	1·01	1·07
	40	0·00	0·05	0·01	0·07	0·13	0·23	0·29	0·41	0·44	0·47
4	5	0·02	0·03	0·00	0·06	0·29	0·46	0·92	1·62	2·22	2·34
	10	0·01	0·03	0·00	0·07	0·26	0·53	0·82	1·45	2·03	2·15
	20	0·00	0·02	0·00	0·08	0·18	0·37	0·60	1·07	1·57	1·67
	30	0·00	0·03	0·00	0·12	0·24	0·34	0·38	0·59	0·83	0·89
	40	Gauge inoperative				—	—	—	—	—	—
6	5	0·01	0·02	0·00	0·06	0·18	0·38	0·68	1·36	1·92	2·06
	10	0·00	0·03	0·00	0·06	0·17	0·32	0·59	1·19	1·74	1·87
	20	0·00	0·02	0·00	0·08	0·18	0·29	0·43	0·83	1·30	1·39
	30	0·00	0·03	0·00	0·06	0·10	0·16	0·17	0·35	0·52	0·58
	40	0·00	0·05	0·00	0·06	0·12	0·17	0·12	0·17	0·19	0·24
8½	5	0·01	0·03	0·00	0·05	0·17	0·25	0·36	0·92	1·46	1·62
	10	0·03	0·02	0·00	0·05	0·17	0·24	0·34	0·82	1·32	1·48
	20	0·00	0·02	0·00	0·07	0·16	0·16	0·23	0·48	0·85	0·95
	30	0·00	0·04	0·00	0·05	0·10	0·14	0·12	0·29	0·36	0·41
	40	0·00	0·00	0·00	0·08	0·13	0·17	0·12	0·18	0·18	0·24
12½	5	0·01	0·03	0·01	0·02	0·12	0·18	0·16	0·24	0·40	0·56
	20	0·00	0·01	0·00	0·07	0·10	0·16	0·16	0·23	0·43	0·55

SM_D = Soil moisture depletion in inches of water.
Dis. = Horizontal distance from trees in feet.

called "major" ground-movement curves. For any given distance from the trees, when the ground movements had passed from "minor" to the "major" stage, the curves attained similar slopes, becoming parallel to each other. This indicates that the relationship between settlement and soil moisture depletion had then become constant. The settlement was naturally observed to decrease with increasing distances from the trees.

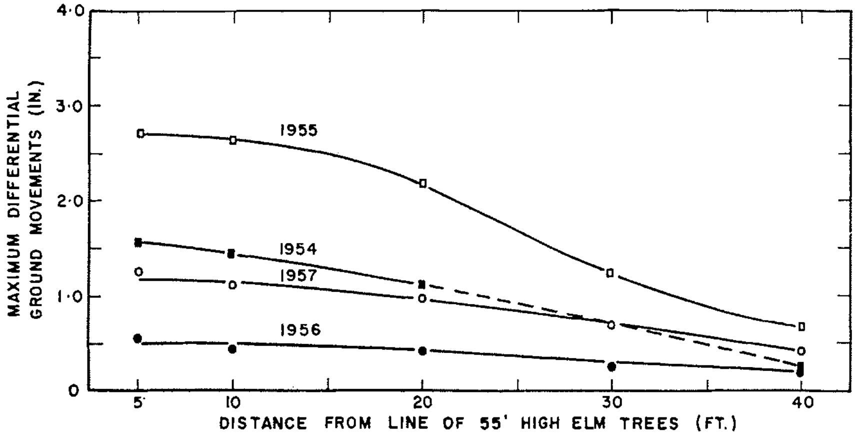


Fig. 5. Maximum vertical ground movements at 1-ft depth near 55-ft-high elm trees in Leda clay soil, 1954–57

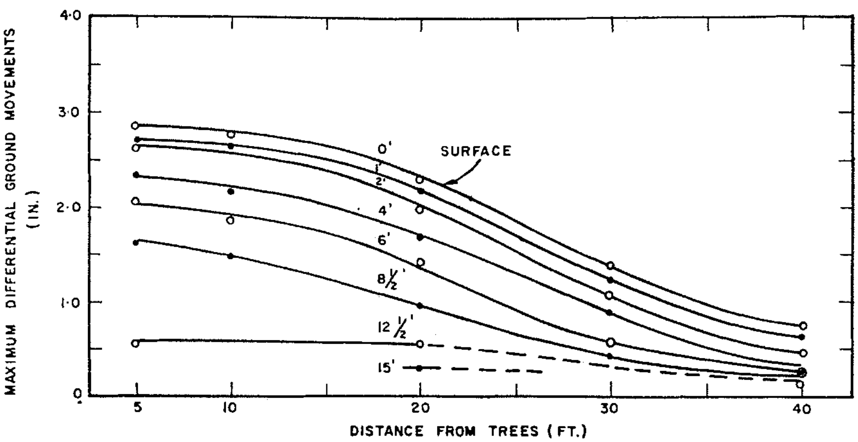


Fig. 6. Variation with depth of the maximum differential ground movements near the 55-ft-high elms in 1955

If, for a given depth, the variations in ground movements with distance from the trees are plotted against soil moisture depletion, curves as shown for the 2-ft depth in Fig. 8(b) are obtained. When the depletion is small, the amount of settlement is small, falling into the "minor" category. In the "shrinkage" range, the curves have different slopes depending on distance from the trees, but converge towards a common intercept at the "shallow" curve. The location of the intercept depends on depth, and is a constant for all distances from the trees for this site. This supports the contention that the water that is lost from the soil above a particular depth causes a lowering of the ground-water table resulting in an "elastic" compression of the soil below. Additional moisture losses are drawn from the soil below the particular depth resulting in "shrinkage" of the soil and an increased rate of settlement.

Combining curves of the type shown above and using statistical analysis the best average "minor" and "major" ground-movement curves are obtained showing the relationship between ground movement and soil moisture depletion near the trees as illustrated for two depths in Fig. 8(c). With a complete set of curves it is possible to determine graphically the ground movements at all depths and distances from the trees for any soil moisture condition.

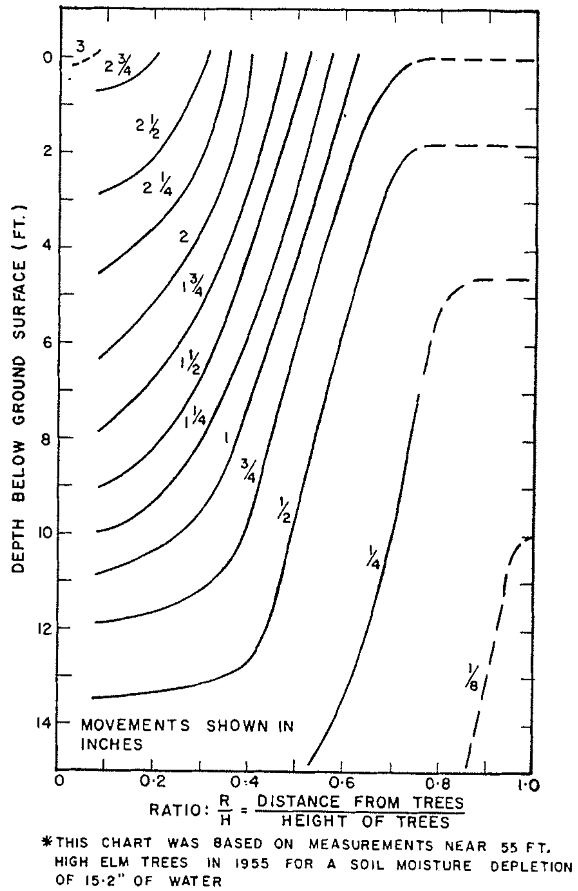


Fig. 7. Variation in vertical ground movements near trees in Leda clay soils at the National Research Council, Ottawa

Plotting the intercepts of the "minor" and "major" ground-movement curves against depth of gauge in Fig. 9 gives a curve which shows the soil moisture depletion limits for "minor" ground movements. If soil moisture losses at a given depth exceed the limiting values indicated by the curve, the ground movements would come into the "shrinkage" range due to the removal of soil moisture from below that depth. The curve is therefore a representation of the amount of free water stored to the various depths at the site. Attempts are being made to correlate this curve with ground-water table changes.

If the slopes of the "major" ground-movement curves, that is, vertical-ground-movement/soil-moisture-depletion are plotted against distance from trees or against the ratio of distance

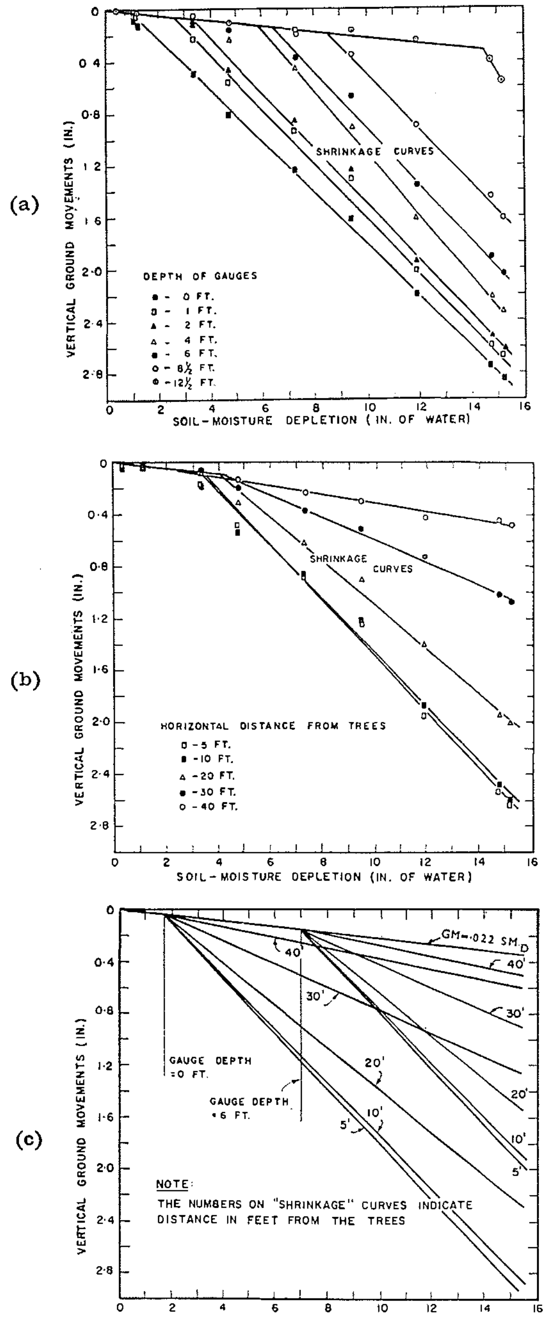


Fig. 8 (a) Effect of soil moisture depletion on ground movements at the indicated depths, 5 ft from the elm trees, 1955;
(b) Effect of soil moisture depletion on ground movements at indicated distances from the trees, at a depth of 2 ft, 1955;
(c) Computed relationship between ground movements and soil moisture depletion for depths 0 and 6 ft, 1955.

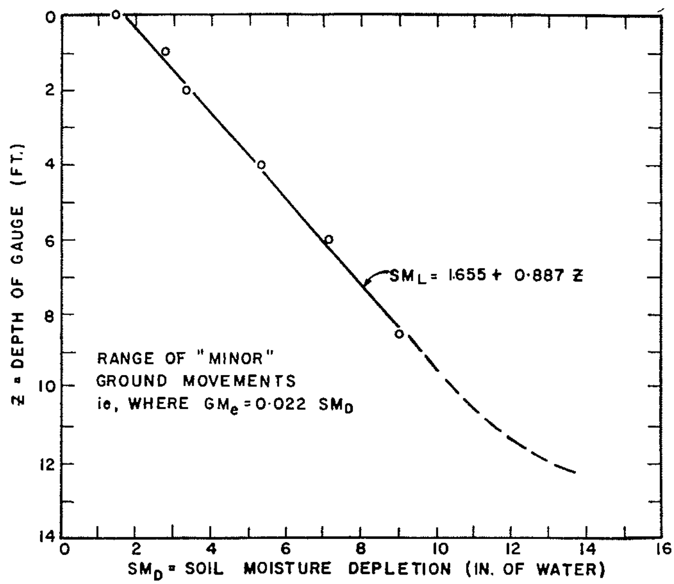


Fig. 9. Soil moisture depletion limits (SM_L) for "minor" ground movements

to tree height, the slopes decrease with distance as shown in Fig. 10. They would also vary for different soils, type of vegetation and location. Ward (1953), in measuring vertical ground movements in grass plots, obtained different values for the ratio of change in soil moisture storage to corresponding vertical ground movements at three different locations in England.

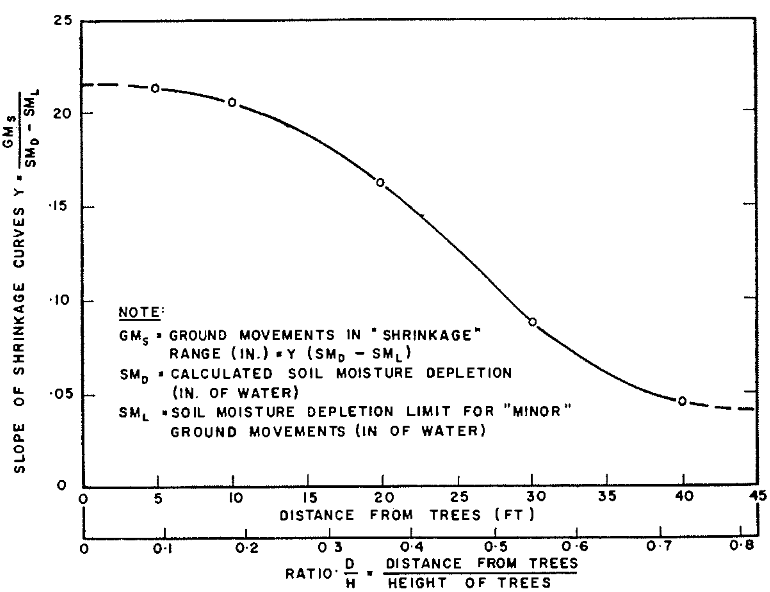


Fig. 10. Variation in slope of "shrinkage" curves with horizontal distance from 55-ft-high elm trees

With the curves of Figs 9 and 10, it is possible to calculate the ground movements at any depth, distance from trees, and soil moisture conditions at this site. Substituting equations for these curves and combining them algebraically, it is possible to develop a statistical solution for ground movements from the soil moisture conditions (see the Appendix).

Table 4 was prepared in order to compare the ground movements computed from the chart in Fig. 7 and from the curves of Figs 9 and 10, or their statistical equivalents, with observed ground movements for various soil moisture conditions. The values computed from the curves agreed closely with the observed ground movements for various values of soil moisture depletion in 1954 and 1955. The greatest errors occurred in 1956, the wet year. The values obtained from Fig. 7 agreed quite well with those observed at the high values of soil moisture depletion. At the low values the calculated ground movements were generally larger than the observed. This results from the incorrect assumption that ground movements were directly proportional to soil moisture depletion.

Table 4

Comparison of computed ground movements, and those obtained from the chart in Fig. 7, with observed values

SM_D*	Z†	Dis.‡	Ground movements: in.		
			Observed values	From Fig. 7‖	Computed
3·38 (1955)	1	5	0·25	0·6	0·24
3·38 ,,	1	30	0·11	0·3	0·13
7·27 ,,	2	10	0·86	1·2	0·86
7·27 ,,	4	30	0·34	0·4	0·30
7·27 ,,	8½	40	0·17	0·1	0·16
11·89 ,,	0	40	0·67	0·6	0·45
11·89 ,,	6	20	0·83	1·1	0·96
11·89 ,,	12½	5	0·24	0·5	0·27
15·19 ,,	0	5	2·86	2·9	2·91
15·19 ,,	4	10	2·15	2·2	2·17
15·19 ,,	12½	20	0·55	0·6	0·68
8·63 (1954)	1	40	0·25	0·4	0·30
8·63 ,,	4	20	0·48	1·0	0·68
4·03 (1956)	1	5	0·68	0·7	0·38
4·03 ,,	2	40	0·16	0·1	0·10

* SM_D = soil moisture depletion in inches of water.
† Z = depth below ground surface in feet.
‡ Dis. = horizontal distance from trees in feet.
‖ Assuming the ground movements are in proportion to the soil moisture conditions based on the 1955 moisture depletion of 15·2 in. of water on which the chart was prepared.

CONCLUSIONS

1. The multi-rod gauges used to measure the vertical ground movements near the trees gave fairly good results in the first 2 years, but became unreliable after 4 years. This was due mainly to frost action and to the punching of the rods into the soil. The concentric-type gauges were less satisfactory.

2. The chart showing the maximum variations in vertical ground movements near large elm trees in Leda clay soil for 1955 can be used as an aid in the design of shallow foundations and for estimating tree-planting distances for similar site and climatic conditions. As 1955 was an extremely dry year, the fourth hottest on record and driest since 1926, the values represent severe conditions.

3. Vertical ground movements, the magnitude of which depends on depth and proximity to trees, can be related to "soil moisture depletion", a quantity based on weather records.

These movements appear to occur in two stages. It is thought that "minor" movements result when, owing to moisture loss above a particular level in the ground, there is a change in the effective weight of the soil resulting in an elastic compression of the soil below that level. Shrinkage movements on the other hand result from volume changes due to loss of water from the soil below the level of observation.

4. A method of computing ground movements using weather records is given and supported by ground-movement observations at a particular site.

5. The report is based on measurements taken at one location only. These measurements will be checked by a new installation using an improved type of ground-movement gauge. Soil moisture contents will be measured and special piezometers will be used to measure ground-water table variations. It is hoped that, following these checks, new installations can be made in other parts of Canada in order to extend this study of ground movements to other conditions of climate, soils, and type of vegetation.

ACKNOWLEDGEMENT

The Authors are indebted to C. B. Crawford, head of the Soil Mechanics Section of the Division of Building Research, for his assistance and direction in this study. The Paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

REFERENCES

BARACOS, A., *and* M. BOZOZUK, 1957. "Seasonal movement in some Canadian clays." *Proc. Fourth Int. Conf.*, Soil Mech., 1 : 264–268.

BARACOS, A., *and* O. MARANTZ, 1953. "Vertical ground movements." *Proc. Sixth Canadian Soil Mech. Conf., Winnipeg. Nat. Res. Counc. Assoc. Cttee on Soil and Snow Mechanics, Tech. Mem.* No. 27, pp. 29–36.

COLLINS, L. E., 1957. "Some observations on the movement of buildings on expansive soils in Vereeniging and Odendaalsrus." *Symposium on expansive Clays,* Pt I, *South African Instn civ. Engrs,* 7 : 273–285.

EDEN, W. J., *and* C. B. CRAWFORD, 1957. "Geotechnical properties of Leda clay in the Ottawa area." *Proc. Fourth Int. Conf. Soil Mech.*, 1 : 22–27.

ISAACS, D. V., 1952. "Footings for houses, flats and schools." *Commonwealth Exp. Bldg Stat., Special Report* No. 8, Sydney, Australia.

JENNINGS, J. E., 1953. "The heaving of buildings on desiccated clay." *Proc. Third Int. Conf. Soil Mech.*, 1 : 390–396.

SKEMPTON, A. W., 1954. "A foundation failure due to clay shrinkage caused by poplar trees." *Proc. Instn civ. Engrs*, 1 : 3 : 66–83.

TASKER, H. E., 1954. "Design of footings for use in Adelaide." *Commonwealth Exp. Bldg Stat., Special Report* No. 16, Sydney, Australia.

THORNTHWAITE, C. W., 1948. "An approach toward a rational classification of climate." *Geogr. Rev.*, 38 : 55–94.

TORCHINSKY, B. B., 1953. "Foundation movements on highly plastic clays." *Proc. Sixth Canadian Soil Mech. Conf., Winnipeg. Nat. Res. Counc. Assoc. Cttee on Soil and Snow Mechanics, Tech. Mem.* No. 27, pp. 37–45.

WARD, W. H., 1947. "The effects of fast-growing trees and shrubs on shallow foundations." *J. Inst. Landscape Architects*, 11 : 7–16.

WARD, W. H., 1953. "Soil movement and weather." *Proc. Third Int. Conf. Soil Mech.*, 1 : 277–288.

Appendix A

MATHEMATICAL EXPRESSIONS FOR COMPUTING GROUND MOVEMENTS FROM SOIL MOISTURE DEPLETIONS

Ground movements near trees occur in two stages. When moisture is lost from above a particular level in the ground, there is a change in the effective weight of the soil resulting in an elastic compression of the soil below, causing the "minor" ground movements. "Major" movements result from soil shrinkage caused by loss of water from the soil below the level of observation.

The curve in Fig. 9 gives the soil moisture depletion limits (SM_L) for the minor ground movements and is represented by:

$$SM_L = 1{\cdot}655 + 0{\cdot}887\,Z \qquad (1)$$

where Z = depth of gauge or observation.

Minor ground movements (GM_e) occur when the computed soil moisture depletion (SM_D) is less than SM_L, and is given by:

$$GM_e = 0{\cdot}022\ SM_D \quad \text{(2)}$$

The major ground movements (GM_s) are given by:

$$GM_s = y(SM_D - SM_L) \quad \text{(3)}$$

when SM_D is greater than SM_L determined by equation (1). y is the slope of the ground-movement curves in the shrinkage range which vary with horizontal distance from the trees as illustrated in Fig. 10. An approximate equation of this curve, valid only within the limits of field instrumentation, is given by:

$$y = 0{\cdot}004\,H + 0{\cdot}026\left(\frac{D}{H}\right) - 0{\cdot}78\left(\frac{D}{H}\right)^2 + 0{\cdot}57\left(\frac{D}{H}\right)^3 \quad \text{(4)}$$

where D = distance from trees (feet)
H = height of trees (feet).

The total ground movement (GM_t) at a given depth for a soil moisture depletion greater than SM_L from (1) is given by the sum of equations (2) and (3). That is:

$$GM_t = GM_e + GM_s$$

or

$$GM_t = 0{\cdot}022\ SM_D + y(SM_D - SM_L) \quad \text{(5)}$$

where y may be obtained from equation (4) or read directly from the curve in Fig. 10, p. 29.

A list of all publications of the Division of Building Research is available and may be obtained from the Publications Section, Division of Building Research, National Research Council, Ottawa, Canada.