# Deformations and Moisture Movements in Expansive Clays

## Déformations et migration de l'humidité dans des argiles gonflantes

by J. G. ZEITLEN, Prof. of Soil Engineering, and A. KOMORNIK, Lecturer, Israel Institute of Technology, Haifa, Israel

**Summary**

Recent research in Israel has included an investigation of expansive clay soils under seasonal variations of moisture content, particularly with reference to light structures. A typical Israel clay has a liquid limit of 81 and a plastic index of 54, with pronounced volumetric changes occurring with changes in moisture. The clay has a high montmorillonite content. The authors give the results of field investigations in heavy clay in which moisture content and moisture movement vary with the season; they also examine the influence of load intensity on reduction of movement. They have studied changes in foundation levels and crack formation in buildings subjected to foundation movements. Loading arrangements and instrumentation are described. Building movements of several centimetres were found, and cracking was proved to have been caused by differential swelling of only a few millimetres between adjacent columns. The importance of considering lateral forces exerted by clay is stressed. The authors propose methods of designing foundations and structure which will minimise the risk of cracking.

**Sommaire**

De récentes recherches en Israël ont permis la détermination du comportement des argiles gonflantes sous l'influence des changements saisonniers de teneur en eau, particulièrement en ce qui concerne des bâtiments légers.

Une argile typique d'Israël a une limite de liquidité de 81 et un indice de plasticité de 54 avec des changements de volume prononcés pendant les changements de sa teneur en eau. L'argile renferme une proportion importante de montmorillonite. Cette étude contient les résultats des essais sur place d'une argile lourde en tenant compte des variations saisonnières de sa teneur en eau, de ses mouvements ainsi que de l'effet de la charge sur la réduction de ces mouvements.

Les changements du niveau des fondations et la formation des fissures dans des bâtiments sont indiqués, ainsi que la disposition des surcharges et l'appareillage de mesure. On a trouvé des mouvements des bâtiments de quelques centimètres et il a été démontré que la fissuration résulte d'un gonflement différentiel de quelques millimètres seulement entre deux colonnes voisines. L'auteur souligne combien il est important de considérer les forces latérales exercées par l'argile. Des suggestions sont présentées concernant les méthodes de construction des fondations et des bâtiments, afin de réduire au minimum le danger de fissuration.

### 1. Introduction

Throughout the world there has been an increasing interest in the causes of damage to structures founded on swelling clays. Special symposia have recently been held on the subject (SOUTH AFRICA, 1957, COLORADO, 1959). Appreciable research has already been undertaken, and several improved designs have been developed from experience. In Israel, a research programme was initiated in 1955 at the Technion-Israel Institute of Technology to investigate the behaviour of local clay soils subjected to seasonal moisture variations (ALPAN, 1957). The authors give the results of that part of their research which was devoted to field investigations concerning variations of moisture content and moisture movement according to the season, the effect of load intensity on reducing such movements together with changes in foundation levels and cracking of typical light buildings. The study was sponsored by the Israel Ministry of Labour, Housing department, which has undertaken a large programme of residential construction, mostly of single-storey concrete block structures, founded on bored piles or spread footings, with suspended floors.

### 2. Climate

In Israel, seasons are clearly separated into a rainy season in winter, and a hot dry season in summer. Rainfall usually occurs only between November and May, with the heaviest concentration between December and February. At the two locations discussed in this paper, annual rainfall is about 500 mm for Afulah, and 600 mm for Haifa. Daily temperatures at Afulah range from about 7° to 18° C in January to about 21° to 34° C in August. Relative humidity is about 60-85 per cent in winter, falling as low as 40 per cent in the summer. Values of over 90 per cent humidity are found during the summer nights. At Haifa, winter temperatures are about 11°-15° C, and daily summer temperatures average about 25°-30° C. Winter humidities are about 70 per cent, and summer values reach about 50 per cent at noon.

### 3. Afulah research site

In the Yizre'el Valley area, where widespread structural damage has occurred, clay stratum was found to extend to the exceptional depth of 100 metres, without a defined water table. Typical clay has a liquid limit of 81 and a plasticity index of 54. A site in the city of Afulah was chosen for special studies to obtain data under open field conditions for the following measurements :

moisture variations in depth with seasons;

vertical movements of soil at various depths without surcharge;

vertical movements of soil at various depths under various loads.

(a) *General Soil Characteristics :*

The Afulah clay has a low silt content (15 per cent) and a high percentage (80 per cent) of clay sizes, mostly of montmorillonite. The clay is shattered and has a high proportion

Table 1

| Depth, meters | Gravel (+ No. 4) per cent | Sand (0·074 mm — No. 4) per cent | Silt (0·005-0·074 mm) per cent | Clay Sizes (0·005 mm) per cent | $L_L$ | $P_L$ | $P_I$ | S.L. | F.M.E. | $CaCo_3$ per cent | Free Swell per cent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0·5 | — | 1 | 22 | 77 | 68 | 26 | 42 | 9·6 | 30 | 9·8 | 185 |
| 2·0-2·5 | 7 | 2·5 | 19 | 71·5 | 84·5 | 28 | 56·5 | 12·0 | 31 | 16·7 | 145 |
| 4·0-4·5 | 10 | 4 | 19 | 67 | 91 | 26·5 | 64·5 | 11·4 | 30·5 | 7·4 | 155 |

of slickensides, particularly in the upper two metres. A hard-pan (cemented) layer is found below this depth in the badly cracked zone. Typical results of classification tests are given in Table 1. This clay is classified as *CH* with high to very high expansion properties, according to such criteria as that proposed by Holtz and Gibbs (1956). The upper layer of soil has a maximum density of 1·60 tons per cub. m and optimum moisture content of 23 per cent when compacted by the Modified AASHO procedure.

(b) *Laboratory Swelling Characteristics :*

Typical results for the upper layer are shown in Table 2 for compacted samples 1 in. in height and 2 ½ in. diameter, soaked in consolidometers in which swelling was prevented. Samples allowed to swell under a light confining pressure of 0·04 kg per sq. cm showed the results indicated in Table 3.

Table 2

| Initial Dry density gr/cm³ | Moisture Content | | Degree of saturation | | Swelling pressures kg/cm² |
|---|---|---|---|---|---|
| | Initial per cent | Final per cent | Initial per cent | Final per cent | |
| 1·20 | 4·2 | 47·0 | 29 | 97 | 0·2 |
| 1·30 | 5·8 | 38·2 | 63 | 92 | 1·0 |
| 1·40 | 26·0 | 33·0 | 73 | 91 | 3·2 |

Hence, the results obtained were typical for swelling soils in that the higher the density and the lower the initial moisture content, the higher would be the swelling pressure and the greater the amount of swelling.

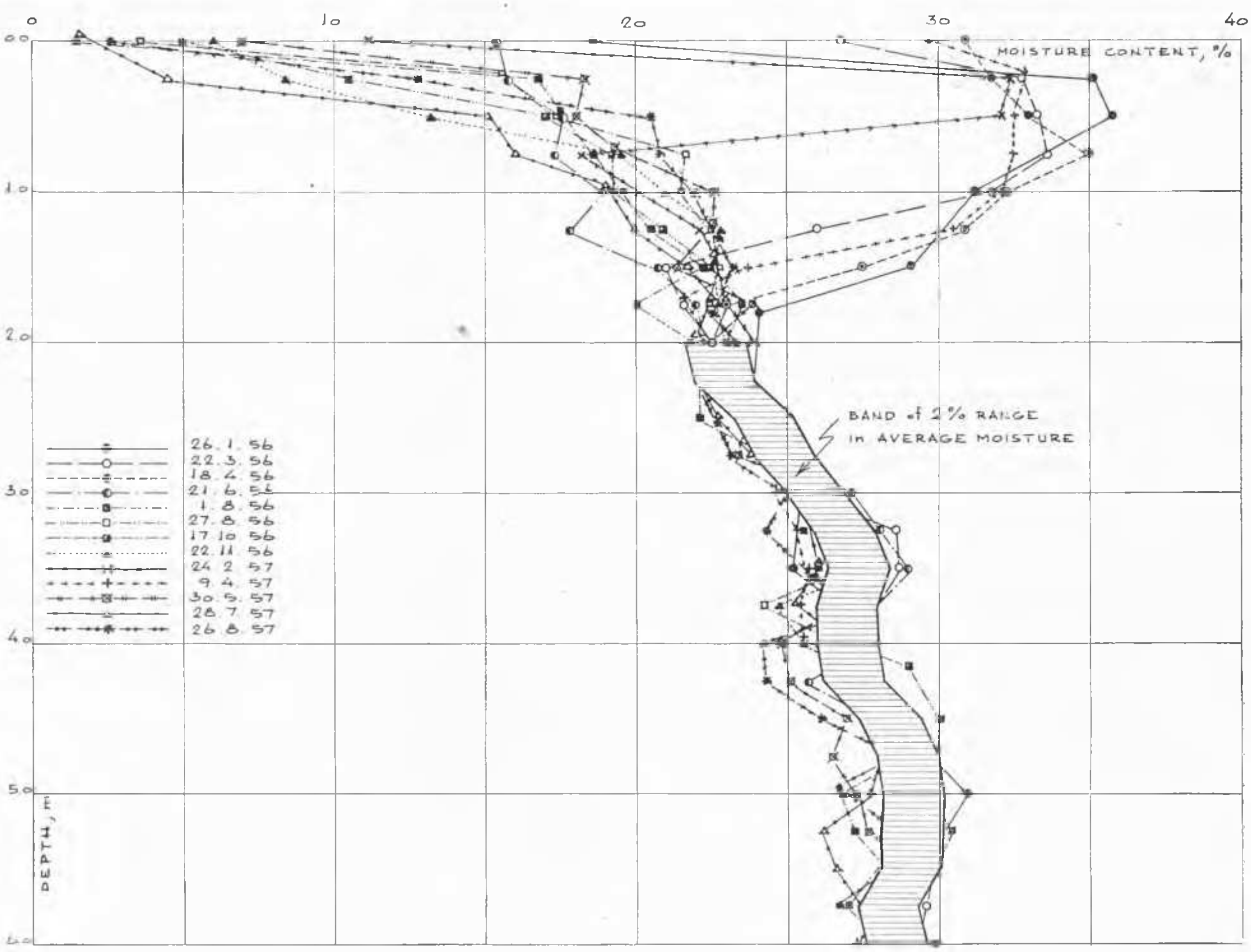


Fig. 1 Moisture variations with depth.
Variation de la teneur en eau avec la profondeur.

Table 3

| Initial Dry density gr/cm³ | Moisture content | | Degree of saturation | | Amount of Swelling per cent |
|---|---|---|---|---|---|
| | *Initial* per cent | *Final* per cent | *Initial* per cent | *Final* per cent | |
| 1·20 | 19·1 | 50·6 | 40 | 90 | 9·8 |
| 1·31 | 14·4 | 51·7 | 36 | 96 | 16·4 |
| 1·39 | 14·4 | 49·3 | 40 | 96 | 20·0 |

(c) *Moisture Variations in the Field :*

Moisture contents were determined by taking disturbed samples every 25 cm from borings performed monthly to a depth of 6 m. Results are shown in Fig. 1. It will be noted that the maximum moisture changes occur at ground level, with values ranging from 6 per cent to 36 per cent. The moisture variations decrease until a depth of about 2 m is reached, where the range is only about 2 per cent. The range remains at 2 to 4 per cent for all depths down to 11 m. The stability of the deeper moisture contents is believed to be caused by a very firm layer of "hardpan" found at a depth of about 2 m composed of apparently the same clay, but cemented with calcium carbonate, about $\frac{3}{4}$ m deep. This stratum, having a higher density, and hence a lower permeability, tends to maintain the moisture content of the soil below this depth at a more nearly constant condition.

(d) *Vertical Movements of Soil without Surcharge :*

Multi-rod gauges based on a principle similar to that used by the British Building Research Station (Ward, 1953) but modified to allow a 6 in. diameter bearing plate at the bottom, were installed at various depths in auger holes every metre from 1·0 m to 6·0 m. A fixed reference point, similar in design to the gauges, was installed to a depth of 11 m. Vertical movements were measured to 0·1 mm by using a micrometer water level apparatus, of the type produced commercially for machine bed levelling. From the movements of the gauges (Fig. 2) the following observations may be made :

1. During the summer, the settlements of the gauges at depths of 1·0 m and 2·0 m were far greater than the settlements of the other gauges. These relatively high settlements were obviously caused by the upper layers of the clay strata being subjected to a greater decrease of moisture content and hence to greater volume changes and vertical movements. Correspondingly, the upper plates show the cumulative effect of all layers below them.

2. In these two gauges swelling was recorded during the month of April (one month after they were installed) while on the other gauges only settlement was measured during the same month. About 9 mm of rainfall had fallen, but excess moisture was apparently lost in the upper strata and in evaporation before it could influence the lower strata.

3. No settlements were recorded from the month of June onwards but all the gauges revealed appreciable uplift movements. The tendency for rising during the middle of the summer despite the lack of rain, was more significant for the deeper gauges (3·0 m to 6·0 m) which rose until October to even higher readings than the initial readings taken during March. This change in direction of movement of the plates, in an open field site may be caused by dew, and to internal movement of moisture. The tendency for dew to collect is greater in the late summer and the colder surface temperatures will tend to bring up moisture from below because of differential thermal effects. The authors

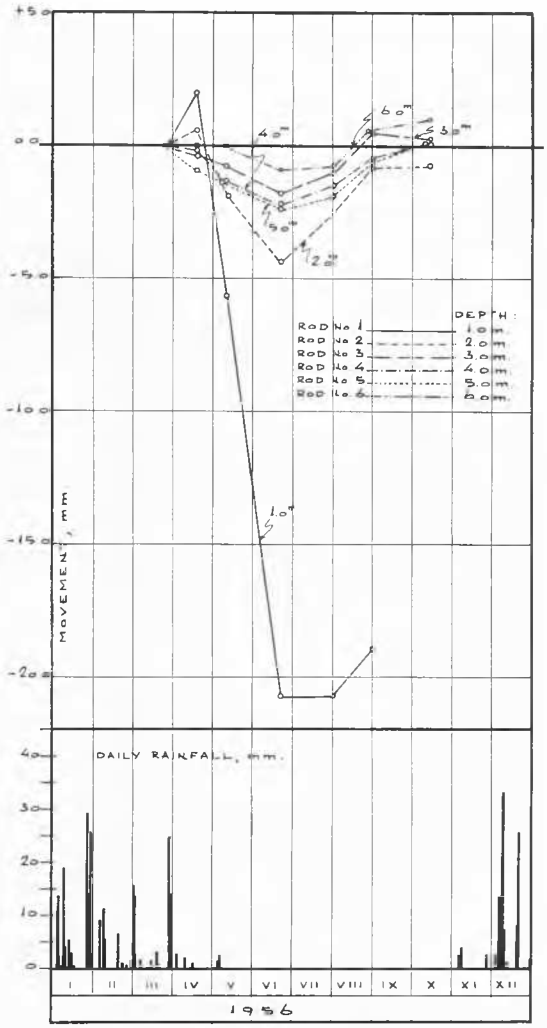


Fig. 2 Vertical movements of soil without surcharge.
Mouvements verticaux du sol sans surcharge.

are now undertaking research in the variation of moisture content and temperature for paved and unpaved areas respectively.

(e) *Vertical Movement of Soil under Various Loads :*

1. *Loading Arrangement*—To determine the effect of different unit soil pressures on the movement of soil strata at different depths, two loading test combinations were constructed. Each group consisted of five loading plates with columns, arranged with four in a rectangle and one in the centre (Fig. 3). Loads were transmitted through two triangular reinforced concrete slabs of 30 cm height each, having their apices on the centre plate (as indicated by the dotted lines in plan) and being loaded with concrete blocks so that the desired unit pressures would be transmitted to the loading plates. The latter were of concrete, 31 cm in diameter and 20 cm in height, poured in place at the bottom of a hole bored to the required depth. Steel pipes filled with concrete, surrounded by protective pipe sleeves, served as loading columns to transmit the loads from the loading slabs. Sponge rubber rings were placed between the protective pipe and the loading plate to prevent the movements of the sleeve from affecting the tests. At depths of 0·5, 1, 2, and 3 m various plates were loaded to 1 and 2 kg per sq. cm, and at depths of 0·5 and 1·0 m plates were loaded to 3 kg per sq. cm.

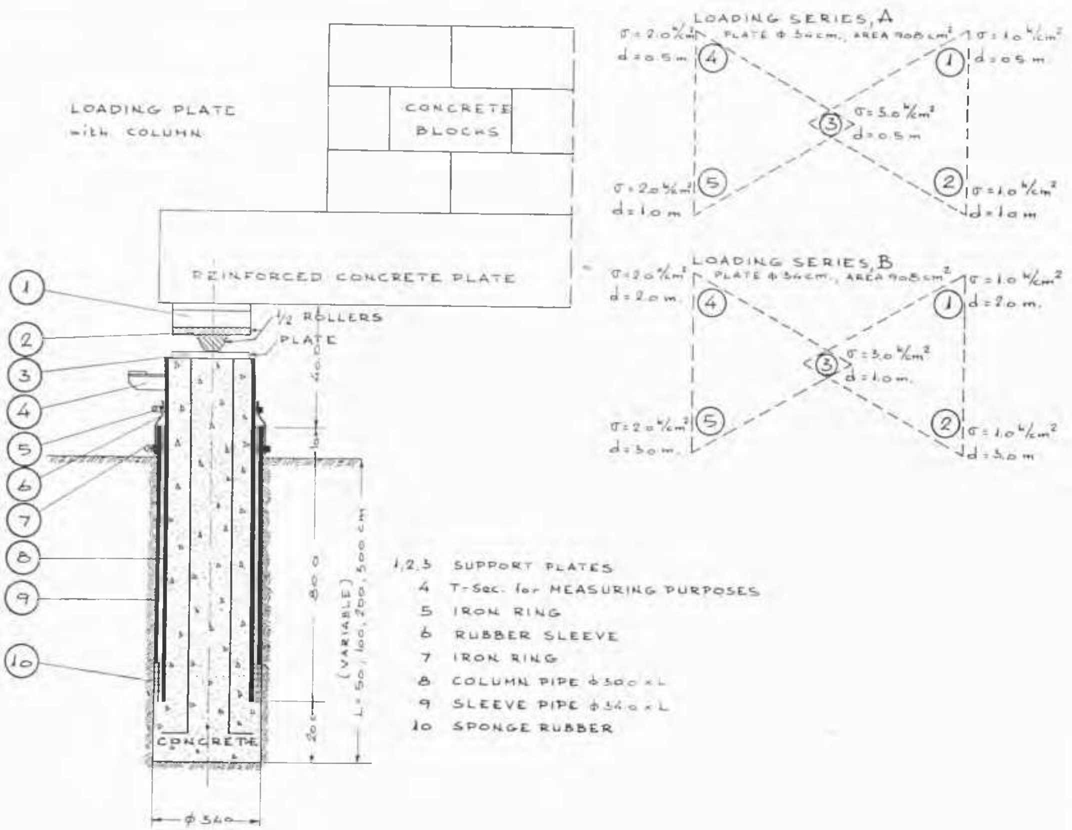


Fig. 3 Loading arrangement for plates at various depths.
Dispositif de chargement des dalles aux différentes profondeurs.

2. *Test Results*—The initial loading to test pressures produced practically no settlement, with a maximum of 1·5 mm resulting from the 3 kg per sq. cm load at 0·5 m depth. Readings were taken each month of the movements of the loaded plates, starting in March 1956. Lateral movements were particularly evident during tests, thereby proving that appreciable lateral pressures could occur. Results are shown graphically in Fig. 4, and may be summed up as follows :

1. At a depth of 0·5 m heavy settlement occurred, reaching more than 28 cm for the plate loaded to 3 kg per sq. cm. The plate loaded to 1·0 kg per sq. cm settled about 6 cm. There was no levelling off and no actual swelling with the arrival of the rainy season.

2. At a depth of 1·0 m, settlements were still appreciable, of about 5 cm for the three loads measured. The rainy season caused two of the plates (loaded to 1·0 and 3·0 kg per sq. cm) to heave slightly.

3. At depths of both 2·0 and 3·0 m, movements were less than 4 mm, with the smaller settlement at the greater depths. With the arrival of the wet season, the more lightly loaded plates (1·0 kg per sq. cm) showed a tendency to heave back towards the original elevation.

(f) *Soil Movements :*

The general tendency for settlement of all unloaded and loaded plates may be attributed to the drying of the clay and consequent shrinkage. In Fig. 1 it is noticeable that moisture content decreases in the upper strata during early summer. The difference in behaviour between the unloaded and loaded plates is not attributed to consolidation under load, but may be explained by the multi-rod plates not exerting pressure on the soil which would close up cracks, whereas the loaded plates always tend to close them. Continuation of settlement for the more heavily loaded plates during the latter part of the summer may be due to a slight loss in soil strength in the crack zone with formation of dew in the cracks. Hence, the effect of load on the plates at the shallow depths of 0·5 and 1·0 m was to produce considerably greater settlements than that shown by the multi-rod gauges. Horizontal cracks observed in this upper zone are considered to be largely responsible for the increase of settlement with load, since higher pressure tends to close these cracks. Vertical cracks also allowed greater settlement through release of confining pressure. With greater depths, the effect of pressure was not critical, since, while additional load on the plate founded at a depth of 2.0 m increased settlement appreciably, the higher load at a depth of 3 m did not appear to influence movement. The occurrence of slight swelling under the loaded plates at greater depth is attributed to the effect of confining pressures, and to the relatively small moisture increases at that depth.

(g) *Crack Observations :*

The information obtained has been influenced by the presence of surface cracks during the dry season. It was therefore considered important to determine for a typical condition the depth of cracks in the field at the end of summer, and to compare the moisture content-depth relation at the point of cracking and between the cracks. In order to find the depth of cracking, a cement grout was poured into two typical adjacent cracks. The hardened cement was then uncovered by digging pits. The depth of cement grout was found to be between 1·50-1·75 m. The cement grout revealed both horizontal and vertical cracks. A boring was

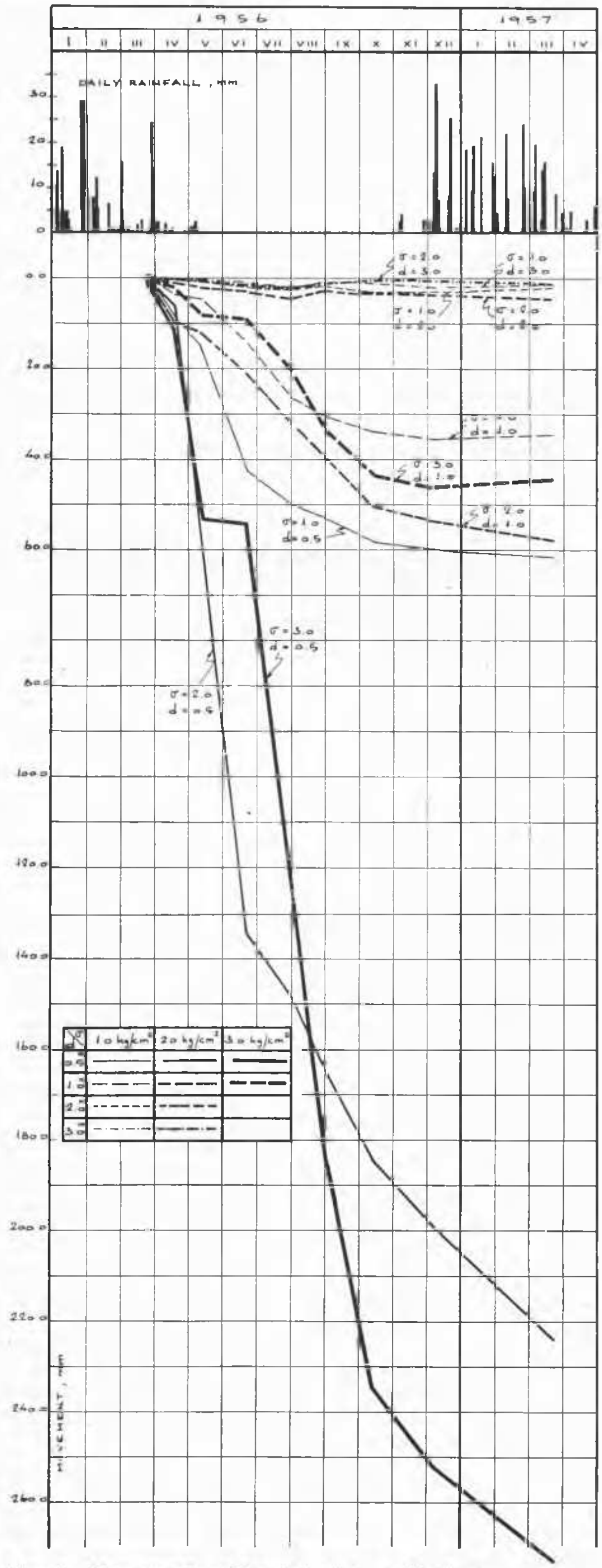


Fig. 4 Movements of loaded plates with time.
Mouvement avec le temps des dalles chargées.

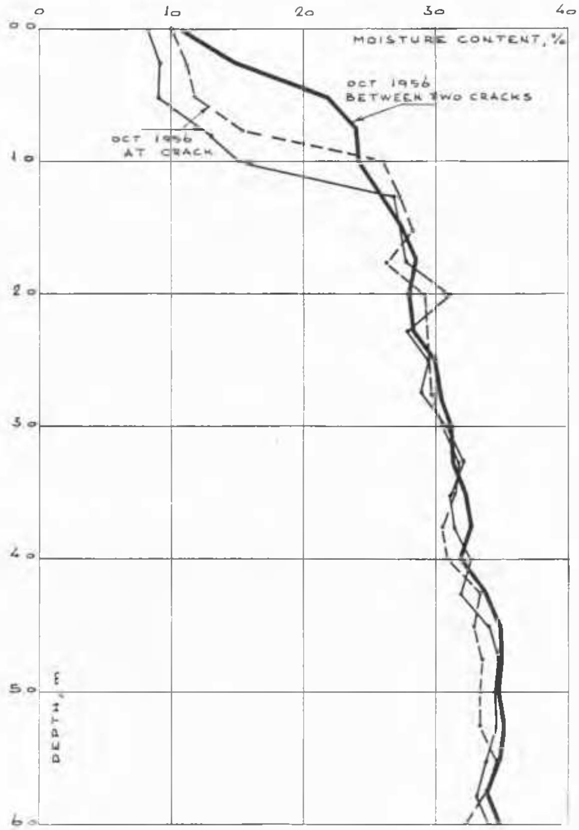


Fig. 5 Effect of cracks on moisture.
Effet des fissures sur la teneur en eau.

made at each crack, and between adjacent cracks. Samples for moisture determination were taken for each 25 cm of depth. The results are plotted in Fig. 5.

The moisture content at the cracks was found to be 10 per cent lower than the moisture content between the cracks at a depth of 0·5 m. There a were no appreciable differences at the surface nor below a depth of 1·25 m. These data indicated that, although the cracking might be deeper, the effect of drying through the cracks appeared to be limited only to the first metre of depth. However, the cracking makes it possible for the first rains to influence the moisture changes at greater depths.

### 4. Tirah site

During the erection of a large housing project at Tirah, near Haifa, six houses were made available for comparing different designs of foundations. The soil here was a mixture mainly of gravel and clay. Percentage of clay varied greatly from point to point, often ranging from 15 per cent to 30 per cent. Although the clay content was relatively small, previous experience had shown that many structures founded in this area had been damaged. Typical results of classification tests are given, in Table 4. The large quantity of stones in the ground would have precluded bored piles, and the buildings

Table 4

| *Depth* m | *Gravel* (+4) per cent | *Sand* (0·074 mm–4) per cent | *Silt Sizes* (0·005-0·074) per cent | *Clay Sizes* (*less than* 0·005 mm) per cent | $L_L$ | $P_L$ | $P_I$ | *S.L.* |
|---|---|---|---|---|---|---|---|---|
| 2·0 | 57 | 7 | 14 | 22 | 47 | 22 | 25 | 12·5 |

were therefore founded on concrete slabs cast in open excavation. Floors were suspended to avoid contact with the ground. The structures were one storey in height, 54 m long and 5·5 m wide, divided by two construction joints into three connected structures. Columns and supporting footings were at approximately 3 m spacings. For this project, the original design called for a foundation depth of 2·0 m and an allowable bearing pressure of 1·0 kg per sq. cm. The variations tried in these foundation experiments included varying the depth of foundations (to 1·0 and 1·5 m) and the bearing pressures of the foundation slabs (to 2·0 kg per sq. cm and 2·5 kg per sq. cm). Level readings were taken on the columns over a period of about two years and the structures were observed for formation of cracks. Results for a typical column row is presented in Fig. 6. Conclusions of this study can be summed up as follows :

(a) The higher the bearing pressure the smaller will be the amount of swelling and the lower will be the corresponding upward movement of columns.

(b) The deeper the foundation the lower will be the amount of swelling.

(c) The maximum swelling measured was 17 mm for columns founded with 1·0 per kg per sq. cm pressure at depths of 1·0 m and 1·5 m. The columns of the structures founded with 2·50 kg per sq. cm design pressures, and at 1·0 and 1·5 m depth, showed swelling of 6 mm, but differential movements of the plates were relatively small in comparison with those of the other structures.

(d) Cracks occurred in the walls when differential settlements of the order of 2 mm were measured between adjoining columns.

(e) Construction joints made between parts of the building structures still resulted in appreciable cracking when a single slab was used for two adjacent columns. However, the amount of damage was much reduced when separate slabs were used to carry each column load, and the joint divided the building completely into two separate parts.

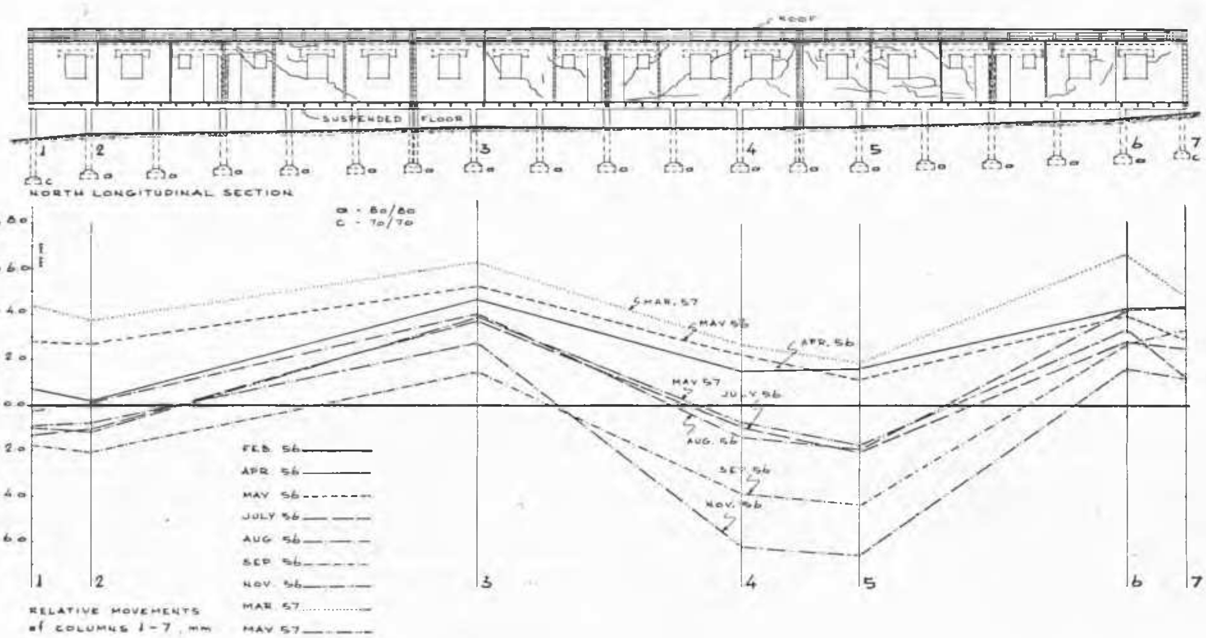


Fig. 6 Structural cracking and deformations, Tirah Site.
Fissuration et déformation des constructions à Tirah.

## Conclusions

The authors have reached the following conclusions based mainly on their own researches and on the experience gained of structural conditions in Israel :

(a) Foundations should have a minimum depth of 2·0 m.

(b) Moisture content should be maintained at a value as high as possible, and excavations should not be allowed to dry out.

(c) Foundations columns or piles should be isolated from contact with the upper two metres of soil, usually by two layers of building felt with a core of asphalt between them.

(d) Maximum allowable bearing pressures should be used, taking into account the maximum moisture content expected in the clay.

(e) Number of column rows to be reduced to a minimum (usually two).

(f) Complete separation of foundations at expansion joints.

(g) The rigidity of a building must be high to resist the tendency for differential movements. Continuous reinforced concrete beams must be placed above and below wall openings, tied in with concrete columns.

(h) Paved areas or membranes should be provided around structures in order to inhibit drying out in summer, to carry off surface water, and to minimize differential moisture conditions inside and outside a building.

(i) Design of utilities for flexibility when such lines are buried in unloaded soil, and allowing for movements in their connection to the structure.

(j) Piles to be designed for tension, as well as for compression.

(k) Lateral pressures acting on piles and columns to be considered in designing the structural elements.

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