A Comparison Between Laboratory Prediction and Field Observation of Heave of Buildings on Desiccated Subsoils

Comparaison entre les pronostics de laboratoire et les observations sur le terrain du soulèvement de bâtiments situés sur des sous-sols desséchés

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Summary

Records of heaving of some buildings on the South African Highveld are summarised. From these data the unit heave for various depths in the soil profile are abstracted and compared with the unit heave predicted from the double œdometer test. The total heave observed in the field is also compared with the total heave predicted by the same test and good agreement is found in all cases where the subsoil is clayey and shattered. Attention is drawn to the possible need for a correction factor if the subsoil is sandy or silty and is also non-shattered.

Sommaire

Les rapports de soulèvement de certains bâtiments situés dans le Highveld (région des plateaux) de l'Afrique du Sud sont résumés comme suit. D'après ces éléments d'information, le soulèvement unitaire à plusieurs profondeurs du profil du sol est analysé et comparé au soulèvement unitaire prévu d'après l'essai de double œdomètre. Le soulèvement total observé sur le terrain est aussi comparé au soulèvement total prévu à la suite du même essai et un bon accord est trouvé dans tous les cas où le sous-sol est argileux et brisant.

Il faut noter la nécessité éventuelle d'un facteur correctif si le sous-sol est sablonneux ou silteux et s'il est aussi non-brisant.

In essence, heave of structures on desiccated subsoils is caused by a swelling of the foundation soil. As in ordinary settlement theory, the problem may be considered in terms of changes in effective stress, the swelling being a consequence of the decrease in effective stress which results from a gain of water in the covered subsoil. However, the practical conditions of the problem are not easily interpreted in terms of normal swelling concepts because the initial effective stress, caused mainly by desiccation, is unknown. Further, the soils are generally unsaturated and frequently fissured, with open air-filled joints (shattered structure). The ordinary effective stress law, which is based fundamentally on the equilibrium of forces across a plane of unit area, no longer applies to these soils and modified effective stress laws for partially saturated soils have been proposed almost simultaneously by JENNINGS (1957 and 1960), CRONEY (1958), BISHOP (1960), AITCHISON (1960) and LAMBE (1960).

All of these modified laws are essentially similar and involve some type of multiplying factor which, when applied to the negative pressure, or tension, in the soil water, converts it into an equivalent porewater pressure acting over the whole unit plane in the soil. Experimental procedure for measuring the factor must still be developed into useful practical laboratory procedures. The modified law proposed by Jennings is as follows :

$$\sigma' = \sigma + \beta p''$$

where p'' is the tension in the soil water and β is a numerical factor equal to or less than unity. The value unity applies to saturated soils or partially saturated soils where the air phase occurs only as occulted bubbles.

Fig. 1. illustrates diagrammatically the heave process in terms of effective stress, using the β factor described above. Heave is caused by an increase in volume resulting from a change in effective stress from a higher initial value $\sigma'_i = AB$, to a lower final value, $\sigma'_f = CD$. With minor assumptions

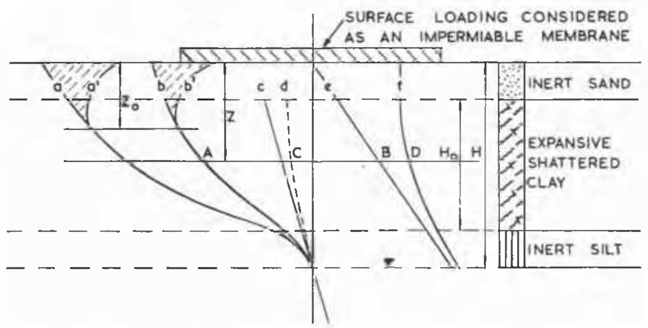

Fig. 1 Pressure involved in Heaving Process :
Cruves (a) the initial p'' curve which changes within zone (a) — (a') depending upon seasonal effects
(b) the initial porewater pressure $\bar{u}_i = \beta_i p''_i$
(c) the equilibrium final $p'' = \gamma_w(H - z)$
(d) the final porewater pressure $\bar{u}_f = \beta_f \gamma_w (H - z)$
(e) the initial total pressure, σ
(f) the final total pressure including effects of surface load, $(\sigma + \Delta p)$.
Heave is due to change in effective pressure from $\sigma'_i = AB$ to $\sigma'_f = CD$.

Pressions concernant le processus de soulèvement :
Courbes (a) courbe initiale p'' changeant à l'intérieur des zones (a) — (a') dépendant des effets saisonniers
(b) pression interstitelle initial $\bar{u}_i = \beta_i p''_i$
(c) équilibre final $p'' = \gamma_w(H - z)$
(d) pression interstitielle finale $\bar{u}_f = \beta_f \gamma_w (H - z)$
(e) pression totale initiale σ
(f) la pression totale finale comprenant les effets des charges en surface $(\sigma + \Delta p)$
Le soulèvement est dû à la variation de la pression effective à partir de $\sigma'_i = AB$ à $\sigma'_f = CD$.

it is possible to estimate the final condition, σ'_f, but it is not yet possible to estimate σ'_i for the conditions applying in the field. The double œdometer test proposed by JENNINGS and KNIGHT (1957) attempts to overcome this difficulty and provides an indirect method of estimating the void ratio changes which take place in the heaving process. Fig. 2.

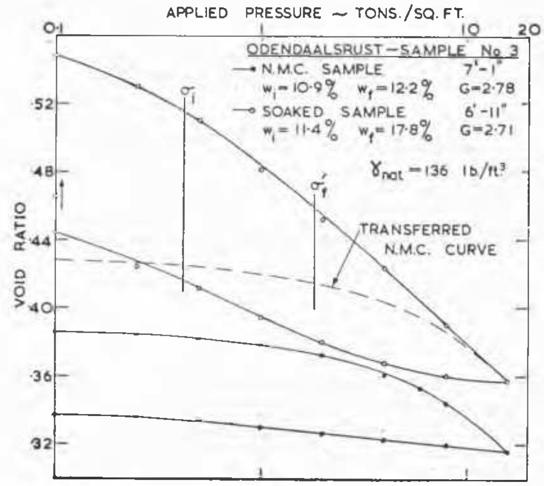

Fig. 2 Typical results from the double oedemeter test

$$\frac{e}{1 + e_0} = \frac{0.034}{1.424} = 2.38 \times 10^{-2}$$

Résultats typiques d'un essai de double oedomètre:

$$\frac{e}{1 + e_0} = \frac{0.034}{1.424} = 2.38 \times 10^{-2}$$

shows the result of a typical double œdometer test taken from one of the practical cases described later in this paper. Interpretation has been made on the assumption $\beta_f = 1$. The prediction also involves all the assumptions made in ordinary settlement theory; further it must be accepted that the desiccated soils involved are generally over-consolidated and consequently overpredictions of the type described by TERZAGHI and PECK (1948) and SKEMPTON and BJERRUM (1957) may be anticipated.

From Fig. 1. it can be seen that the following factors will be of importance in the prediction of heave :

(a) the thickness of the expansive layer, H_o
(b) the depth to water table H
(c) the initial overburden pressure, σ.
(d) the degree of desiccation, which determines σ'_i
(e) the applied pressures, Δp, due to load of the structure, which tends to restrain the swelling.

The soil properties, as reflected in some coefficient of swell, such as C_s, m_{vs} or a_{vs} are also important. Where the depth of seasonal movement, z_o, is of the same order as the depth of the bottom of the expansive layer, important cyclic effects may be introduced, particularly at the edges of the structure.

Field records of heave on the Highveld of South Africa show the characteristic curve Fig. 3. Work on the prediction of rate of heave from laboratory tests is still in progress and until a suitable method has been found, data of the type shown in Table I, which summarises the results of nine fully observed field cases, provide a basis for an approximate empirical estimation of the field heave : time curve in the locality concerned.

Depth points have been established in the subsoil below buildings on two sites. The differences in movements at different levels in the subsoil allow calculation to be made of the unit heave (cms heave/cm of depth) at various

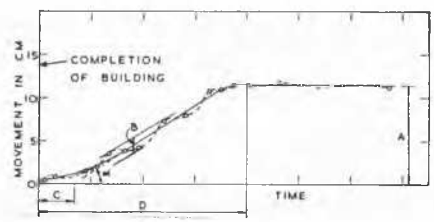

Fig. 3 Typical field time : heave curve (Case No. 8, Table 1).
Courbe typique observée sur le terrain : soulèvement en fonction du temps (cas n° 8, table 1).

depths in the profile. These data are shown on Figs. 4 (a) and 4 (b). The unit heave will be zero at the lower limit of heaving or bottom of the expansive soil layer which often coincides with the water table. The unit heave may also be expressed as $\Delta e/1 + e_o$ which may be estimated from the double œdometer test. Figs. 4 (a) and 4 (b) also include such predictions for the same sites and reasonable agreement is obtained with the observed values.

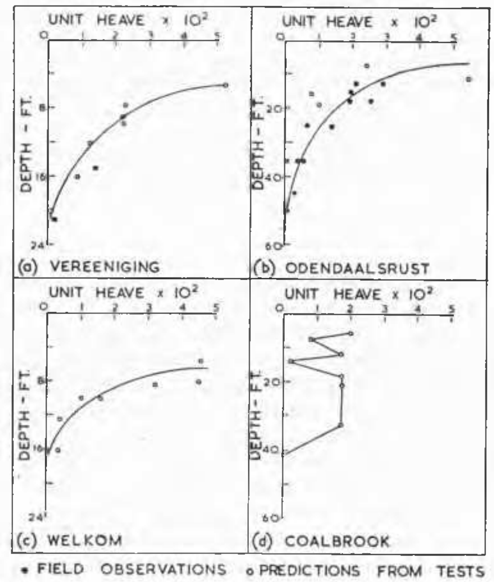

Fig. 4 Unit heave : depth curves for four sites.
Soulèvement unitaire en fonction de la profondeur pour quatre sites.

Figs 4 (c) and 4 (d) show similar predicted unit heave data from two sites where level observations of heave on buildings have not been fully recorded. The general form of the curve in Fig. 4 (c) agrees with Figs. 4 (a) and 4 (b) and all these curves indicate that the subsoil is fairly uniform. The curve in Fig. 4 (d) is somewhat different and represents the condition where the strata have non-uniform swelling characteristics.

An important feature of the curves, and in particular Figs. 4 (a) to 4 (c) is that they also define the lower unit of heaving. This is most important on sites where water-table position is difficult to define.

For each of the sites represented by Figs. 4 (a) to 4 (d), estimates of the total heave of single storey brick dwellings have been made and compared with observed average movements of the external walls. Table II shows this comparison for cases (a), (b) and (d). In case (a) the measurements of movements have been very carefully made at fortnightly intervals on one structure (case 9, Table I). In case (b),

Table I

Summary of observations of heaving on single storey brick dwellings

Case No.	Locality	Site Information			Total Recorded Heave Factors					Recorded Time Data		
		Depth and Nature of Inactive Soil Cover-ft.	Total Thickness of Expansive Soil H_0 ft.	Water Table Depth ft.	Total Heave " A " cms.	Cyclic Heave " B " cms.	Average Unit Heave $\frac{A}{H_0} = \frac{\Delta H}{H} \times 10^2$	Maximum Differential Heave $\delta \Delta$ cms.	Differential Heave Ratio $\frac{\delta \Delta}{A}$ %	Time to enter steep Tangent C years	Time to enter asymptote D years	Maximum Average Rate of Heave α cms./day × 10
1	Odendaalsrus O.F.S.	1 ft. silty sand	50	50 ft.	22·0	0·9	1·44	8·17	40	1·32	6·50	1·97
2	—	—	—	—	14.3	0·5	—	4·85	34	1·05	6·04	1·37
3	—	4 ft.	35	—	12.9	0·6	1·21	6·17	48	0·84	6·16	2·10
4	—	—	30	—	13·6	0·5	1·49	4·01	30	1·10	4·76	1·62
5	—	—	—	—	12·5	0·9	—	3·79	30	0·52	4·72	1·32
6	—	3 ft.	30	—	11·0	0·4	1·20	3·59	32	1·44	5·41	1·32
7	—	—	30	—	12·8	0·7	1·40	4·01	33	1·56	5·26	2·19
8	—	—	35	—	11·6	0·6	1·09	4·49	39	0·78	4·00	1·18
	Averages for Odendaalsrus Site				13·8	0·6	1·3	4·92	36 *	1·07	5·35	1·63
9	Vereeniging Tvl.	silty sand 4 ft.	17	40 ft.	6·5	0·6	1·25	5·56	85 *	0·71	4·58	0·69

* Note : The smaller differential heave at Odendaalsrus is probably due to the provision of flexible joints in the house drains. Flexible joints were provided at Vereeniging only after troubles due to pipe fracture were observed.

eight structures within one half mile of each other have been carefully levelled at approximately three monthly intervals (cases 1-8, Table I). The observed final movement given in Table II is the average movement of the eight structures. In case (c) a number of structures have been founded on underreamed piles at depths varying from 20 ft. to 30 ft. Certain unimportant portions of the buildings such as verandah slabs, kitchen steps and flower bowes have been founded directly in the ground and the relative movements of these portions are clearly visible. Hence, although no proper levels have been observed, it is possible to identify the differential heave between the bottom of the piles and the foundations of the unimportant portions of the buildings. These movements are given in Table II. In case (c) there is no direct means of estimating the heave which has taken place in completed buildings and therefore the case has been omitted from Table II. However, examination of the crack geometry gives an approximate estimate of the differential heave and, usign the data in Table I, it is possible to obtain a rough idea of the total heave which has taken place. The order of movement from these approximate calculations is the same as that predicted from the unit heave date in Fig. 4 (c).

Table II

Comparison between observed and predicted total heave

Site	Observed Final Heave cms.	Predicted Heave cms.	Prediction Error %	Remarks
(a) Vereeniging, Tvl.	6·5	8·15	+ 19	Levels on one building only
(b) Odendaalsrus, O.F.S.	13·8	15·5	+ 11	Obs. heave is average of 8 cases Nos. 1-8. Table I
(d) Coalbrook, O.F.S.	8-11·5	11·3	+ 13	Error calculated on the average observed heave

The detailed results given in this paper refer to subsoils which are predominantly shattered clays. For these materials the double œdometer test appears to provide a very satisfactory basis for estimating the final heave. There is some indication, however, that if a heaving subsoil is sandy or silty and, further, if it is not shattering or microshattered, then the unit heave from laboratory tests may be considerably greater than would be anticipated. In these cases the predicted heave is also greater than that found from rapid ponding tests or from examination of the crack geometry. Shattering of the soil indicates a limiting lateral pressure condition and since such pressure may have an important effect on the resulting heave it is probable that some correction factor based on the presence or absence of shattering should be applied to the estimates of heave made from the laboratory tests. Analytical work by Skempton and Bjerrum (1957) provides an important precedent for the estimation of settlement on precompressed sandy and silty subsoils and work is in hand on a similar approach in the case of heave.

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