Swelling Characteristics of a Transported Soil Profile at Leeuhof Vereeniging (Transvaal)

Caractéristiques de gonflement d'un profil de terrain transporté à Leeuhof, Vereeniging (Transvaal)

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Summary

As part of a research programme on the mechanism of heaving of expansive soils on the South African highveld, the relation between the moisture content and the equilibrium volume under the appropriate overburden pressure, for a number of samples taken from a typical expansive soil profile, was determined by means of a volumenometer method.

The present paper describes in detail the instruments that were used in this investigation and the procedure adopted.

The use of partial specific volumes is explained, when describing volume changes of unsaturated soils through moisture uptake. It is shown how the swelling characteristics of an expansive soil profile may be presented in terms of either the virginal or the residual potential expansiveness of the soil, together with the swelling limits of the moisture content, all as a function of depth below the soil surface.

The results obtained for the Leeuhof profile are compared with the clay mineral composition of the soil.

Values of 32·0 cm for the virginal potential heave and 3·7 cm for the residual potential heave were calculated for the profile, assuming that no lateral movements can take place. These results are compared with those obtained by other investigators.

Sommaire

La relation entre la teneur en eau et le volume d'équilibre sous une pression de couverture appropriée fut déterminée au moyen d'une méthode volumétrique pour un certain nombre de prélèvements pris dans un profil de terre typiquement expansif. Cette étude faisait partie du programme de recherche sur le mécanisme du soulèvement des terres gonflantes du highveld (Landes) d'Afrique du Sud.

Le présent rapport décrit en détail les instruments qui furent utilisés pour cette recherche, ainsi que la méthode qui fut adoptée.

L'usage des volumes spécifiques partiels est expliqué en décrivant les variations de volume d'un sol non saturé en présence d'eau. Les caractéristiques de gonflement d'une terre meuble peuvent être exprimées comme l'expansibilité potentielle vierge du sol ainsi que l'expansibilité potentielle résiduelle, en combinaison avec les limites de gonflement de la teneur d'humidité, l'ensemble étant fonction de la profondeur sous la surface du sol.

Les résultats obtenus pour le profil de Leeuhof sont comparés à la composition minérale de l'argile de ce sol.

Les valeurs de 32·0 cm pour le soulèvement potentiel vierge et de 3·7 cm pour le soulèvement potentiel résiduel furent obtenus en supposant qu'aucun mouvement latéral ne se produise. Ces résultats sont comparés avec ceux obtenus par d'autres chercheurs.

Introduction

The serious foundation problems which are often encountered in connection with expansive soils on the highveld of Southern Africa have been discussed by several authors (Jennings [1, 2], Collins [3], Jennings and Williams [4]).

As part of a research programme on the mechanism of heaving of such soils (de Bruijn [5]) a detailed investigation was undertaken by the author to establish the relation between the moisture content and the equilibrium volume for a number of typical expansive soil profiles. Estimates of the potential heave of these profiles could then be made on the basis of these data together with a knowledge of any variation in moisture content.

As was observed by Brink [6], expansive characteristics may be developed by pedogenic processes in either residual or transported soils. The present report deals with results obtained by means of volumenometer tests on a transported soil of fluvio-lacustrine origin at Leeuhof, Vereeniging (Transvaal).

Geology of the Vereeniging profile

A detailed description of this profile has been given by Brink [6, 7]. Its expansive part is made up of a layer of grey, or mottled yellow-grey, sandy clay which extends, at Leeuhof, to a depth of about 6.8 m. This layer is characterized by an abundance of well developed slip planes, known as slickensides, along which movement is thought to have taken place to accommodate volume changes due to seasonal variations in moisture content. A lateritic zone of iron and aluminium sesquioxide accumulation has developed at the top of the clay layer, just below the sandy top soil, and ferruginous concretions extend from this zone downwards into the clay, progressively decreasing in concentration with depth. Lime nodules are scattered throughout the profile.

The base of the clay layer is demarcated by a bed of water-worn gravel with a thickness of about 0·5 m, known as the pebble marker. It represents the gravel terrace of the Vaal river which deposited the overlying material. The formations below the pebble marker originated in pre-quaternary times and are not expansive.

The mineral composition of the soil above the pebble marker, as far as it could be determined by means of quantitative *X*-ray analysis, is presented in Table 1. The predominant clay mineral was found to be montmorillonite in amounts up to 20 per cent. This mineral is probably mainly responsible for the potential expansiveness of the soil. Only small amounts, less than 5 per cent, of kaolinite were detected. The percentage of the material, labeled amorphous in Table 1,

Table 1

Mineral composition and specific surface area of soil samples from profile at Leeuhof

Composition minéralogique et surface spécifique d'échantillons du sol à Leeuhof

Sample number / *Sample depth*	m	*A1* 0·08	*A2* 0·63	*A3* 1·30	*A4* 1·93	*A5* 2·48	*A6* 3·08	*A7* 3·63	*A8* 4·28	*A9* 4·88	*A10* 5·50	*A11* 6·08	*A12* 6·76
Quartz	%	96	53	57	62	53	43	49	59	61	56	38	46
Kaolinite	%	0	0	< 5	< 2	0	< 2	< 2	< 5	< 2	< 2	< 5	< 5
Montmorillonite	%	0	0	0	5	14	17	13	12	8	11	20	15
Amorhous (incl. kaolinite)	%	4	47	43	38	33	40	38	29	31	33	42	39
Montmorillonite plus amorphous	%	4	47	43	38	47	57	51	41	39	44	62	54
External specific surface	m^2/gm	18	59	80	99	142	132	96	71	92	98	117	100
Internal specific surface	m^2/gm	29	64	96	111	183	189	194	157	137	151	215	166
Total specific surface	m^2/gm	47	123	176	210	323	321	290	228	229	249	332	266

was obtained by subtracting the combined percentages of montmorillonite and quartz from 100. It includes the small amounts of kaolinite. This material could not be identified further by means of *X*-rays. It is suspected that it may also contribute to the expansiveness.

In a case like this, where a detailed mineral analysis presented serious difficulties, determination of the specific surface of the soil, e.g. with the glycol method (Bower and Gschwend [8], was found to be a valuable indicator test for potential expansiveness. According to the tentative classification, laid down in a previous publication (de Bruijn, Collins, and Williams [9]', samples *A5*, *A6* and *A11*, taken from the profile would have to be designated as "bad" (total specific surface more than 300 m^2/gm) and the others, except for sample *A1*, as "medium" (total specific surface more than 70 m^2/gm, but less than 300 m^2/gm). See Table 1.

The use of specific and partial specific volumes

When dealing with the expansion of soils through moisture uptake (*sorptional expansion*), it has been found convenient to express the *specific volume* v of a soil element (volume per unit mass of grains) as

$$v = v_1 m + v_2 \tag{1}$$

where m is the moisture content (mass of water per unit mass of grains) and v_1, v_2 the are *partial specific volumes* of water and grains respectively. This method is similar to the description of mixtures in terms of partial molar quantities commonly employed in chemical thermodynamics (see e.g. Rutgers [10]).

In the case of a *geometrically unsaturated* soil, a term introduced here to indicate a soil of which the pore volume is not completely occupied by water, both v_1 and v_2 vary with m, v_1 becoming equal to the specific volume of water, and v_2 to that of the grains at saturation. In addition v_1 and v_2 depend on soil composition and overburden pressure in a soil profile.

The coefficient v_1 can be written as the differential quotient

$$v_1 = dv/dm \tag{2}$$

which applies to a soil element of constant grain mass. v_1 is thus represented by the slope of the curve $v = v(m)$ for this case. Differentiation of (1) gives in general

$$dv = v_1 dm + m dv_1 + dv_2$$

so that for a soil element of constant grain mass

$$m dv_1 + dv_2 = 0 \tag{3}$$

from (3) one can deduce

(*i*) that the curve $v_2 = v_2\,(m)$ has a horizontal tangent at $m = 0$, because at this value $dv_2 = 0$ for finite values of dv_1,

(*ii*) that at the same value of m the slopes of the curves $v_1 = v_1\,(m)$ and $v_2 = v_2\,(m)$ have opposite sign, and

(*iii*) that v_2 is a minimum when v_1 is a maximum, and vice versa.

Substitution of (2) in (1) gives

$$v_2 = v - m\,(dv/dm)$$

which leads to a simple geometrical interpretation of v_2. The values of v_2 are presented by the segments cut by the tangents to the curve $v = v\,(m)$ from the ordinate for $m = 0$. Fig. 1 shows an exemple of a $v = v\,(m)$ curve of an expansive

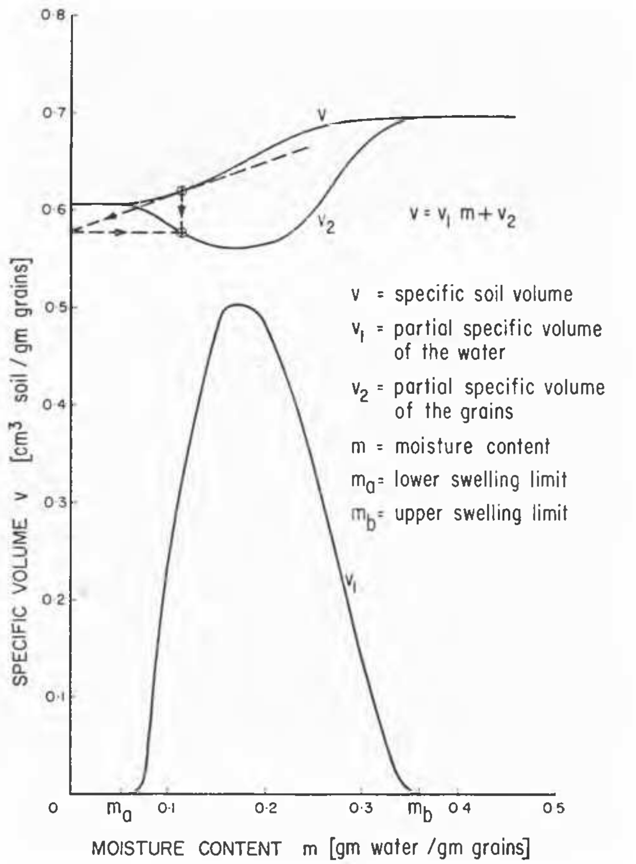

Fig. 1 Swelling diagram of an expansive soil.
Diagramme de gonflement d'un sol expansif.

soil, as determined by means of the volumenometer method (see below).

Apparatus and procedure

A schematic diagram of the volumenometers used in the present investigation for determining $v = v\ (m)$ curves (*swelling diagrams*) at a definite confining pressure is presented in Fig. 2. The volumenometer cells were made of brass. An air dry cylindrical soil specimen *S* (diameter 7·6 cm, height 2·5 cm) was packed between the porous plates *A* and *B* within the waterproofed latex sleeve C. The cell was then tightly closed, the flexible outlet *D*, made of thin spirally wound copper tubing, being fitted to the to plate, and the remaining space completely filled with water.

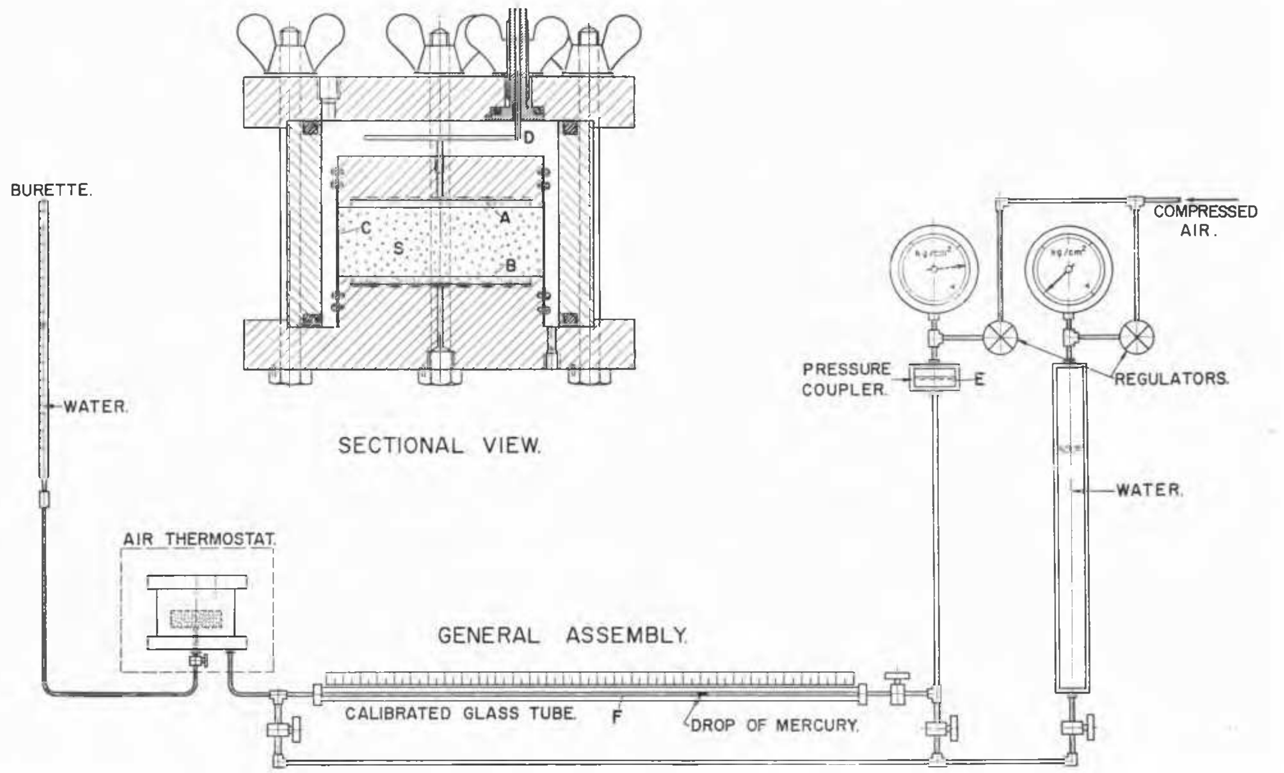

Fig. 2 Diagrammatic sketch of volumenometer.
Dessin schématique du voluménomètre.

A constant confining pressure, calculated from the weight of the overburden soil, was then applied by means of regulated air pressure via the pressure coupler *E* and the horizontal glass tube *F*. This glass tube contained a drop of mercury to act as a pointer on a volume scale.

Using a sample volume of about 116 cm^3 and a tube of 0·2 cm internal diameter, the sensitivity of the volume measuring system amounted to a relative expansion of about 0·003 per cent of the sample volume per mm displacement of the mercury.

Fig. 3 shows a bank of 8 volumenometers.

Undisturbed soil samples were usually air dried or vacuum dried at room temperature before putting then into the volumenometers. After the confining pressure had been applied and an equilibrium volume obtained, small amounts of water were successively added via the lower porous plate by means of a burette (e.g. 5 cm^3 at a time) and the resulting final expansions recorded. The tests were regarded as complete when no additional expansion could be detected. The dry weight of the sample was then obtained by oven drying so that the variations in the moisture content could be calculated. All tests were carried out in a room at a controlled temperature of 22 $\pm$ 1° C. Complete tests often lasted as long as three months.

Fig. 3 Photograph of bank of 8 volumenometers.
Photographie d'une batterie de 8 voluménomètres.

Swelling diagrams of the Leeuhof profile

Swelling diagrams showing the *specific expansion* (expansion per unit mass of grains) as a function of moisture content for each sample at the appropriate confining pressure, are presented in Fig. 4.

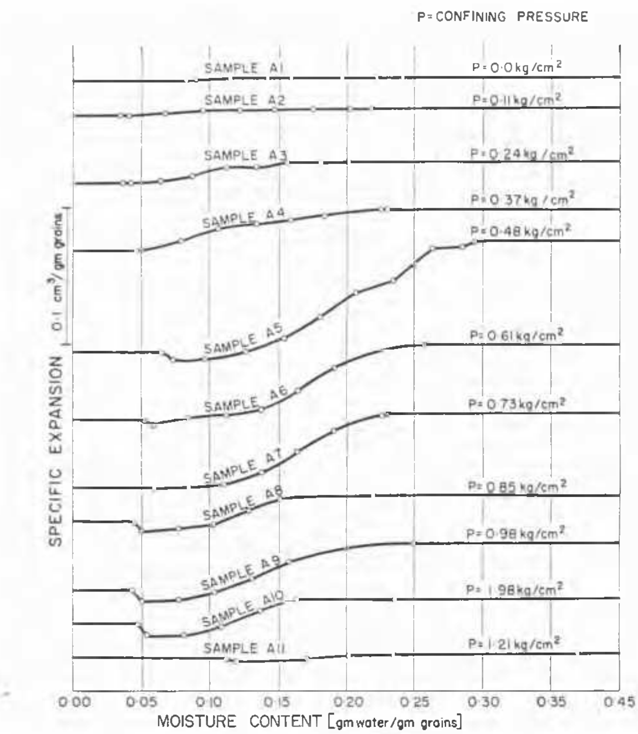

Fig. 4 Swelling diagrams of soil profile at Leeuhof (Borehole 1).
Diagrammes de gonflement du sol à Leeuhof (trou de sonde nº 1).

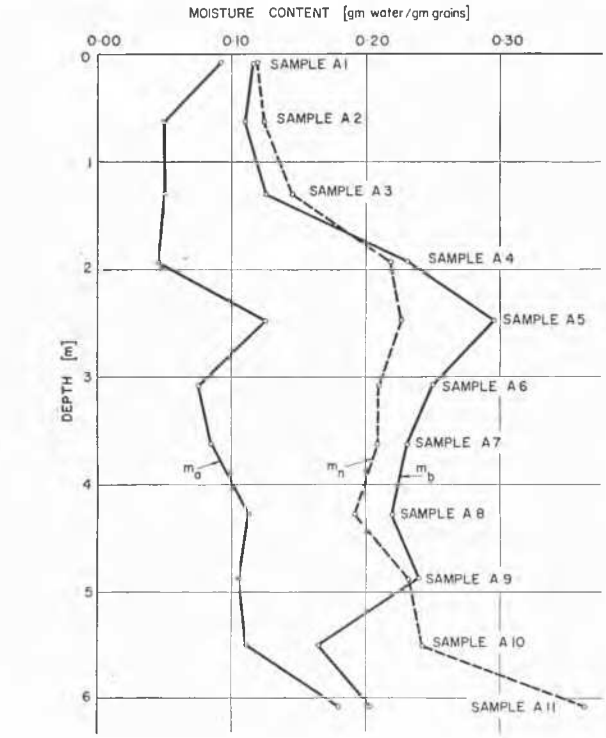

Fig. 5 Lower swelling limit (m_a), upper swelling limit (m_b), and natural moisture content (m_n) of soil profile at Leeuhof (Borehole 1).
Limite inférieure de gonflement (m_a), limite supérieure de gonflement (m_b) et teneur en eau naturelle (m_n) du profil du sol à Leeuhof (trou de sonde nº 1).

As was also the case with a weathered diabase profile at Lynnwood, Pretoria (DE BRUIJN [11]), there appeared to be a restricted range of moisture content within which swelling could take place. Fig. 5 shows the *lower swelling limit* m_a and the *upper swelling limit* m_b of the moisture content for this profile as a function of depth. The difference between these moisture contents has been termed the *swelling index* (cf. plasticity index).

In a number of cases, especially at the higher confining pressures, it was found that the addition of the initial amounts of water to the dry samples resulted in some shrinkage. This effect is tentatively attributed to capillary forces and the term *capillary contraction* seems appropriate. With sandy materials the effect may be associated with a collapse of the bridges made up of finely divided particles of clay minerals and oxides between the larger grains (collapsing sands, KNIGHT [12].

Potential expansiveness and potential heave

In order to calculate the potential heave of a soil profile the *relative expansion* or *volume dilatation* (expansion per unit soil volume) should be used instead of the specific expansion. Considering a moisture content change from m_i to m_j the corresponding relative expansion e of the soil at the depth z would be

$$e(z) = \int_{v_i}^{v_j} (1/v)dv = \log_e (v_j/v_i) \qquad \ldots. \quad (4)$$

where v_i and v_j are the specific soil volumes at the moisture contents m_i and m_j respectively.

Assuming simple heaving to occur in the case of a laterally confined soil body, the heave becomes

$$H = \int_{z_2}^{z_1} e\,dz \qquad \ldots. \quad (5)$$

if the expansive layer extends from z_1 to z_2. This relation no longer holds as soon as lateral movements can take place. However, observations on the swelling of soil samples under conditions of different vertical and lateral confining stresses have not yet been made.

When estimating potential values for the expansion and the heave of soil layers, the moisture content changes that are liable to occur in the profile have to be considered (DE BRUIJN [5]). They in turn depend on the permeability characteristics and the boundary conditions of the soil body concerned. These considerations fall outside the scope of the present paper.

When m_i is the lower swelling limit m_a and m_j the upper swelling limit m_b, the corresponding values for e and H will be termed the *virginal potential expansiveness* e_{vp} and the *virginal potential heave* H_{vp}. Although these values may be unrealistic for technical purposes, they are useful for the characterization of expansive soil profiles. More realistic but still conservative values can be obtained if the natural moisture content m_n is chosen for m_i instead of the lower swelling limit m_a. The corresponding values for e and H vill be termed the *residual potential expansiveness* e_{rp} and *residual potential heave* H_{rp}.

Values for e_{vp} and e_{rp} for the profile at Leeuhof are presented in Table 2 and Fig. 6. The initial volumes of all samples were calculated after measuring their diameter and height prior to the tests and in order to obtain v_a, allowance was made for the measured compression due to the confining pressure.

Table 2

Swelling characteristics of soil profile at Leeuhof

Caractéristiques de gonflement du profil de sol à Leeuhof

Sample number *Sample depth*	*m*	*A1* 0·08	*A2* 0·63	*A3* 1·30	*A4* 1·93	*A5* 2·48	*A6* 3·08	*A7* 3·63	*A8* 4·28	*A9* 4·88	*A10* 5·50	*A11* 6·08	*A12* 6·76
Natural moisture content (m_n)	gm/gm	0·119	0·124	0·145	0·219	0·227	0·210	0·209	0·192	0·233	0·242	0·363	0·383
Natural density	gm/cm³	1·80	1·80	2·14	1·98	1·96	1·99	1·99	2·01	2·00	1·96	1·86	—
Confining pressure[1]	kg/cm²	0·02	0·11	0·24	0·37	0·48	0·61	0·73	0·85	0·98	1·10	1·20	—
Specific volume before compression[2]	cm³/gm	0·621	0·633	0·551	0·551	0·589	0·569	0·567	0·588	0·606	0·553	0·659	—
Specific volume after compression (v_a)	cm³/gm	0·621	0·629	0·547	0·543	0·575	0·561	0·546	0·575	0·583	0·536	0·642	—
Final specific volume (v_b)	cm³/gm	0·624	0·633	0·562	0·573	0·656	0·616	0·601	0·594	0·617	0·555	0·646	—
Virginal specific expansion ($v_b - v_a$)	cm³/gm	0·003	0·004	0·015	0·030	0·081	0·055	0·055	0·019	0·034	0·019	0·004	—
Virginal potential expansiveness (e_{vp})	cm³/cm³	0·005	0·006	0·026	0·054	0·132	0·094	0·095	0·033	0·057	0·034	0·006	—
Lower swelling limit (m_a)	gm/gm	0·091	0·050	0·050	0·045	0·125	0·075	0·085	0·113	0·105	0·110	0·180	—
Upper swelling limit (m_b)	gm/gm	0·116	0·110	0·125	0·231	0·295	0·250	0·231	0·220	0·240	0·164	0·203	—
Swelling index ($m_b - m_a$)	gm/gm	0·025	0·060	0·075	0·186	0·170	0·175	0·146	0·107	0·135	0·054	0·023	—
Residual potential expansiveness (e_{rp})	cm³/cm³	0·000	0·000	0·000	0·002	0·042	0·012	0·008	0·000	0·001	0·000	0·000	—

[1] In calculating the confining pressure from the natural density of the overburden soil the compression due to the confining pressure has been neglected.
[2] From sample dimensions.

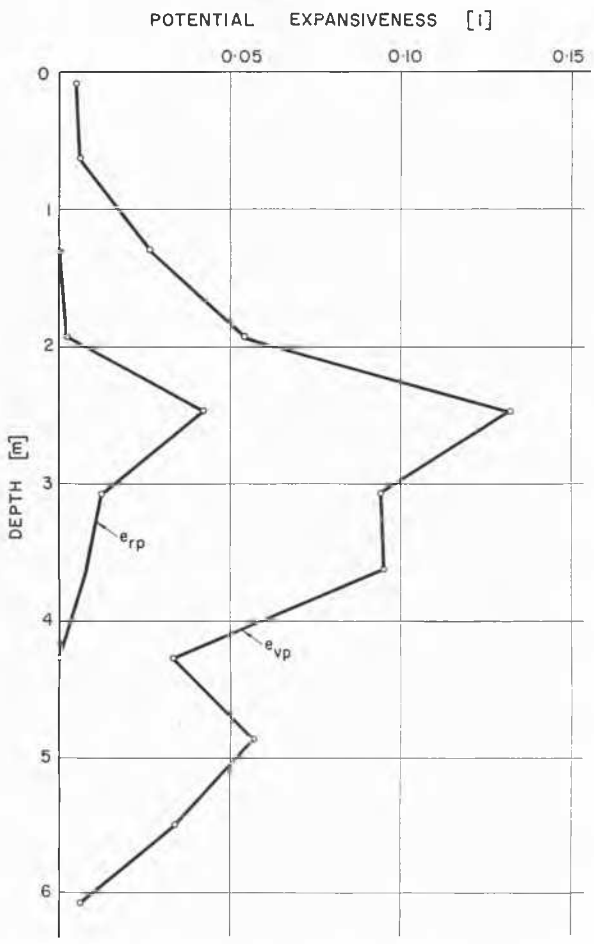

Fig. 6 Virginal potential expansiveness (e_{vp}) and residual potential expansiveness (e_{rp}) of soil profile at Leeuhof (Borehole 1).

Expansibilité potentielle vierge (e_{vp}) et expansibilité potentielle résiduelle (e_{rp}) du profil de sol à Leeuhof (trou de sonde n° 1).

Discussion

Results indicated that the virginal potential expansiveness of the profile extends to a depth of about 6 m. The residual potential expansiveness at the time of sampling (3rd March 1959), however, appeared to be limited to the soil layer between 1·8 and 4·3 m. Maximal values were found at a depth of 2·5 m. Below this level the potential expansiveness gradually decreased, which was probably mainly due to the increase of the overburden pressure with depth. In a previous study (DE BRUIJN [11]) it was observed that both the potential expansiveness and the swelling index decreased when the confining pressure in the volumenometer was increased. It should, however, be noted that the montmorillonite content of the soil decreases below a depth of 3·1 m until a minimum is reached at about 5·0 m (see Table 1). This was reflected in the values of the internal and total specific surface areas of the soil as determined by means of the glycol method. Below about 5.0 m the montmorillonite content increases again but the increased overburden pressure apparently prevents the soil *in situ* from being more than only slightly expansive.

Both the virginad and the residual potential heave for the unloaded soil surface and for imaginary depth points at the centres of the various samples *in situ* have been plotted as a function of depth in Fig. 7. The virginal potential heave of the soil surface amounted to 32.0 cm and the residual potential heave 3·7 cm. The same figure includes data collected by COLLINS [3], DE WET [13], and JENNINGS and KNIGHT [14].

The values given by COLLINS [3] (Table 1 of his paper) were based on level observations of depth points, situated under a test house at a distance of about 21 m from the borehole from which the samples used in this work were taken. COLLINS also found that the top soil layer to a depth of 1·8 m had practically no residual potential expansiveness and that the soil layer from 1·8 — 3·6 m was by far the most expansive layer in the profile.

The values determined for the residual potential heave in this work are, however, considerably lower than the level observations by COLLINS [3] would indicate. The observed average heave of the external walls of the test house was 6 cm and of the centre points in the house 7 cm. This discre-

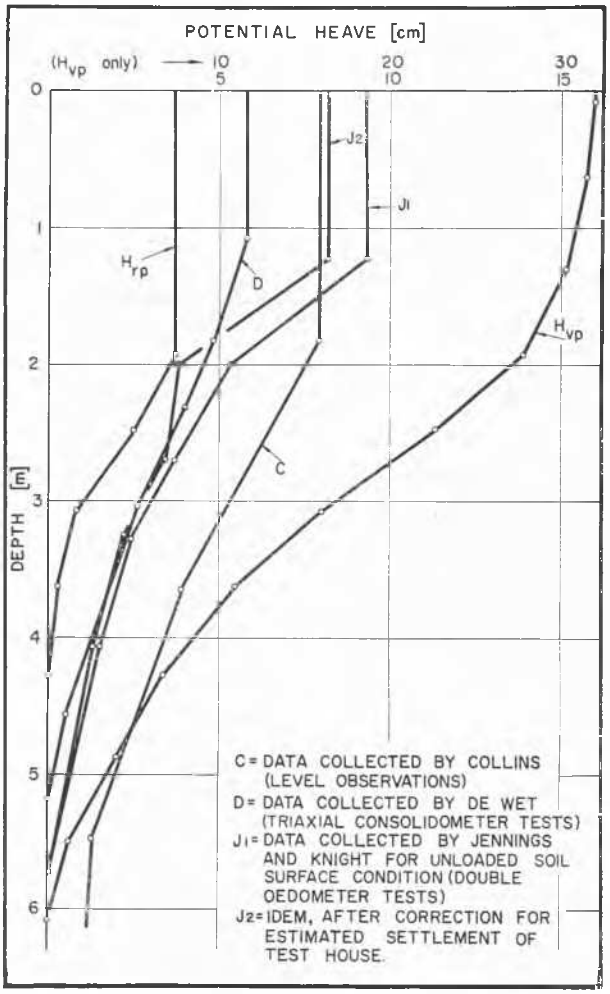

Fig. 7 Comparison of virginal potential heave (H_{vp}) and residual potential heave (H_{rp}) of soil profile at Leeuhof, as determined by different investigators.

Comparaison du soulèvement potentiel vierge (H_{vp}) et du soulèvement potentiel résiduel (H_{rp}) du profil de sol à Leeuhof, déterminé par différents chercheurs.

pancy might be due to a rather high natural moisture content at the time of sampling which was towards the end of the rainy season. Another explanation might be that, as BRINK [7] has pointed out, although a general uniformity of profile throughout the Vereeniging region is observed, wide variations exist within comparatively small areas.

Experimental values for the residual potential expansiveness of the Leeuhof profile have also been obtained by DE WET [13] by means of a three-dimensional consolidometer. Taking into account that the top layer in the profile is not expansive, his calculated value of 6.7 cm for the residual potential heave of the unloaded soil surface should be reduced to 5·8 cm, as was found by more precise graphical integration. Heaves of about 5 cm were observed after flooding the site (DE WET [15]).

Double œdometer tests, carried out by JENNINGS and KNIGHT [14], resulted in a value of 9·3 cm for the residual potential heave of the unloaded surface of the Leeuhof profile, and 8.2 cm after a correction for the estimated settlement of the test house had been applied. These high values were largely influence by one extremely expansive sample taken from a depth of only 1·6 m.

Conclusion

The volumenometer method provides detailed information on the swelling characteristics of an expansive soil profile. On the basis of these data the potentiel expansiveness of the soil can be estimated if the initial moisture content is accurately known and also the moisture content changes governed by the permeability characteristics and the boundary conditions of the soil body concerned. The upper limit of the potential expansiveness, the virginal potential expansiveness, is useful for the characterization and the classification of expansive soil profiles. The residual potential expansiveness, associated with moisture content changes from the natural moisture content at the time of sampling up to the upper swelling limit is of great importance for civil engineering purposes.

In estimating the virginal and the residual potential heave, the assumption that simple heaving occurs without lateral movements may need modification when data become available on the swelling of soil samples under deviator stress conditions. At present this assumption can only lead to too conservative values.

As is the case with all soil tests in the laboratory, the interpretation of volumenometer results for engineering purposes may present serious difficulties when the soil body concerned has a very heterogeneous composition. The difficulty can only be overcome by increasing the number of boreholes and the number of samples from each hole.

Acknowledgement

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