STRUT LOADS RECORDED IN A DEEP EXCAVATION IN CLAY

MESURE DES EFFORTS DANS LES ETRESILLONS D'UNE EXCAVATION PROFONDE EN ARGILE

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SYNOPSIS. The paper deals primarily with the measured loads in the struts supporting a deep excavation through a sensitive and soft clay. The results obtained during the various excavation stages are compared with those computed according to the existing empirical rules with the purpose of determining their applicability to the above soil.

INTRODUCTION

During the excavation to construct a siphon at the intersection of the Mexico City subway with a sewage colector (Fig. 1) measurements were taken of the strut loads and of the horizontal soil deformations. The excavation for the siphon was 7.00 m wide, 22.00 m long and 11.30 m deep and it was supported by a steel sheet piling and four strut levels.

The soil profile at the site and the mechanical properties of the subsoil, as well as the excavation procedure and the instrumentation installed are described in this paper, together with the strut loads data and the measured horizontal soil deformations.

Finally, a comparison among the measured strut loads and the loads estimated using the criteria of Peck (1967) and Brinch Hansen (1953) is discussed.

SOIL PROFILE AND MECHANICAL PROPERTIES OF THE SUBSOIL

The available subsurface information of the zone indicated the existence, in most of the explored depth, of lake deposits formed by soft clays. This initial information was confirmed by 4 continuous borings made at the site and located as shown in Fig. 2-a. Undisturbed samples were obtained with a Shelby-type sampler 10.16 cm inside diameter.

The soil profile at the site is shown in Fig. 3-b, as well as the values of the natural water content (w) and plasticity limits corresponding to boring M-2. Values of the unit weight (γ) and of the unconfined compression strength (q_u), for the 4 borings made, are also shown in such figure.

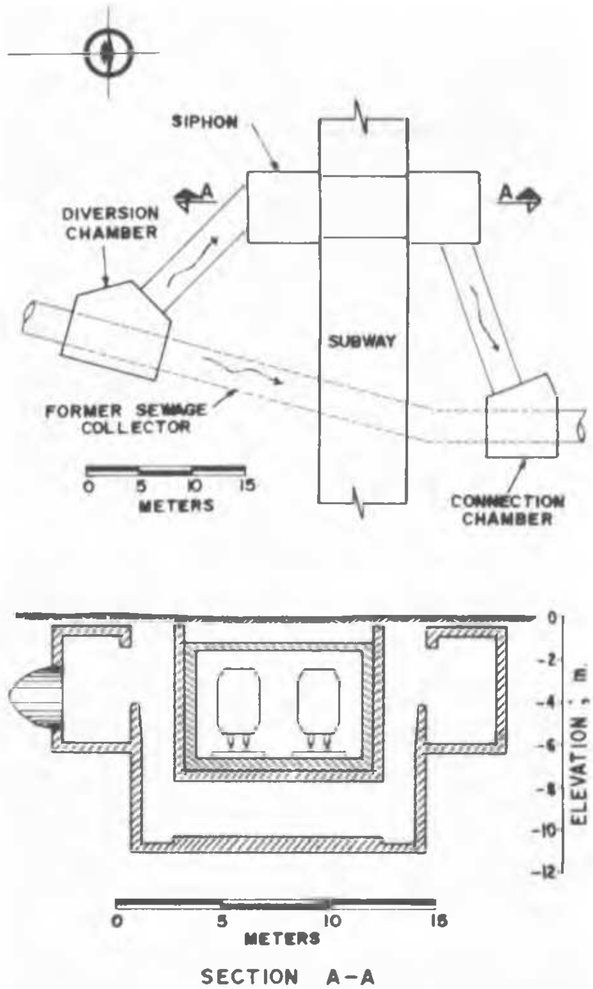

FIG. 1. INTERSECTION BETWEEN THE SUBWAY AND A SEWAGE COLLECTOR.

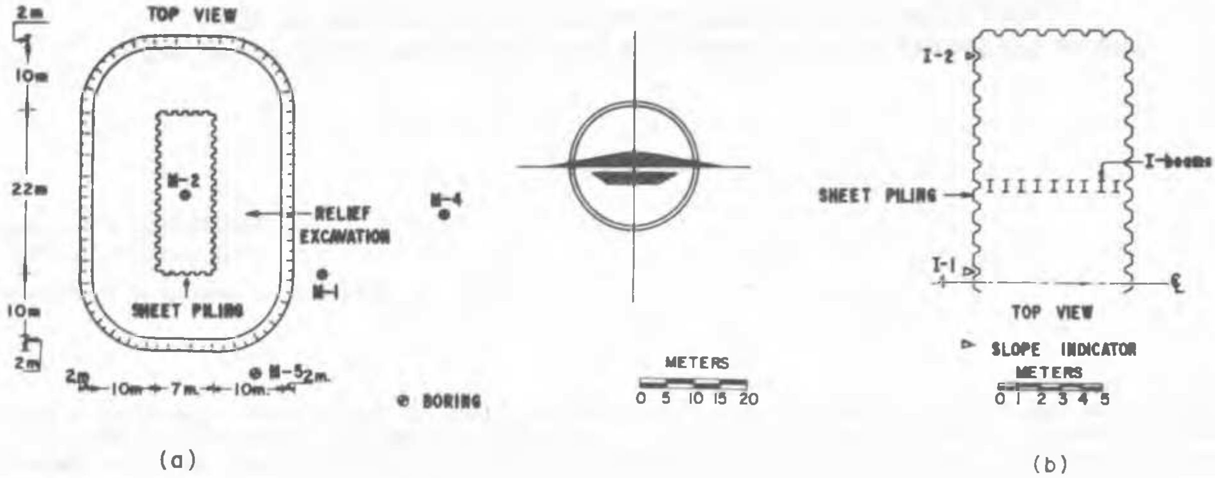

FIG. 2. (a) SITE LAYOUT AND LOCATION OF SOIL BORINGS.
(b) LOCATION OF SLOPE INDICATORS.

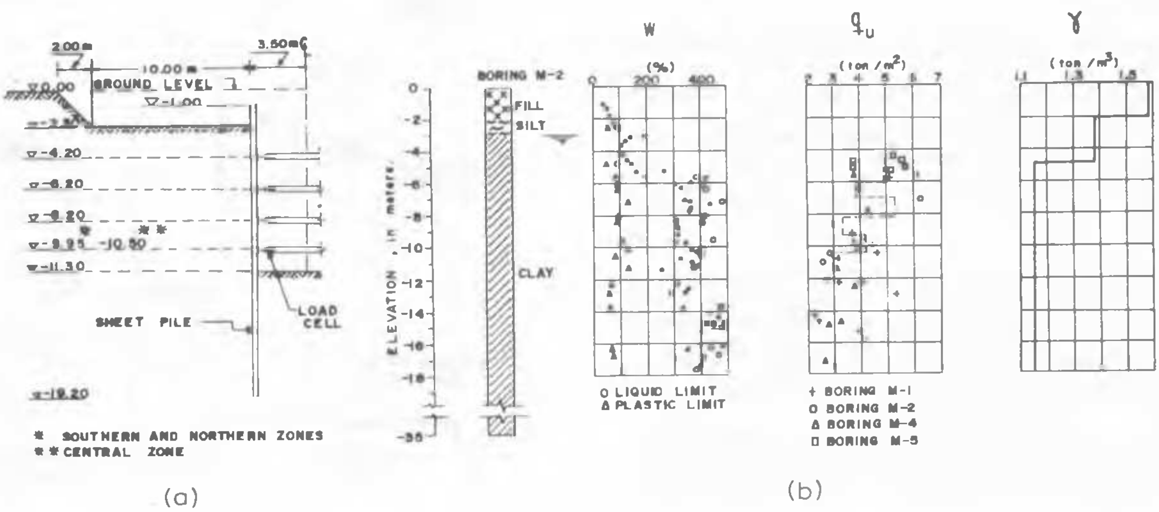

FIG. 3. (a) CROSS SECTIONAL VIEW OF EXCAVATION.
(b) SOIL PROFILE AND SOIL PROPERTIES.

The above soil profile can be summarized as follows: a recent fill extends from the surface to the elevation -2.00 m and it is underlaid by a sandy silt located between elevations -2.00 and -3.00 m. The ground water table was found at an elevation of -3.00 m where the clay formation also starts continuing uniformly down to the maximum elevation of -35.00 m; thin strata of silts and sands were encountered between the elevations -20.00 and -35.00 m.

The clay is normally consolidated within the depth influenced by the excavation, with the exception of the soil located between the elevations -3.00 and -6.00 m which shows a preconsolidation due to desiccation.

EXCAVATION PROCEDURE

Based on the analysis of bottom stability of the excavation, the project designer decided to drive a steel sheet pile 18.20 m high to a depth of 19.20 m from ground level. The sheet piles had a Z-shape section and a section modulus of 1688 cm³/m. It was also decided to perform a "relief excavation" 2.30 m deep covering a width of 10.00 m around the perimeter of the excavation (Figs. 2-a and 3-a). For the reason mentioned above the designer also recommended to divide the excavation in three zones, starting at a depth of 6.50 m, to be supported by a combined sheet piling; it was then necessary to drive two rows of vertical I-beams between the elevations -6.70 and -14.00 m, as shown in Fig. 2-b.

The ground water level was lowered inside the sheet piling by using and electro-osmotic pumping system (Fig. 4-a); the excavation started when the water table had been lowered to the elevation -8.00 m. When the excavation reached a depth of 4.70 m, the 1st strut level was placed at the elevation -4.20 m and upon arriving to a depth of 6.50 m the 2nd strut level was installed at the elevation -6.20 m. The excavation was then continued by zones, starting with the central zone, following the southern zone and ending with the northern zone.

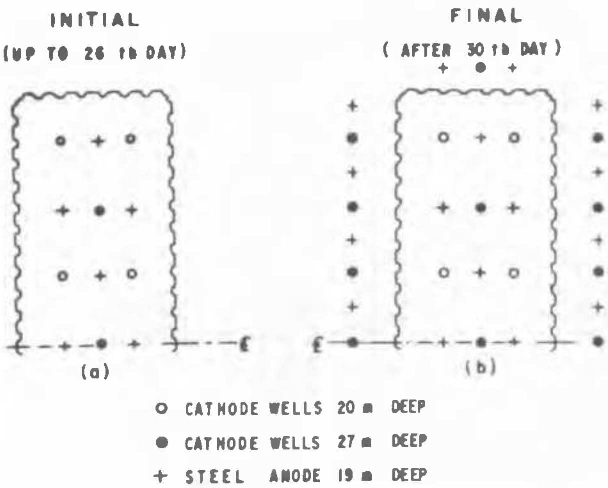

FIG. 4. ELECTRO-OSMOTIC PUMPING SYSTEM.

In the central zone the excavation had three additional stages limited by the elevations -8.80 , -10.70 and -11.30 m respectively and the two remaining strut levels were installed at the elevations -8.20 and -10.50 m respectively. It should be mentioned that the excavation process had to be suspended during six days due to the high pore pressures observed when it had reached the elevation -8.80 m. The process was resumed once new pumping elements were added outside the sheet piling (Fig. 4-b). When the final depth was reached, a bottom slab 1.10 m thick was constructed leaving the last strut level embedded in the concrete. The 3rd strut level was then removed and the part of the siphon corresponding to this zone was constructed up to a height approximately equal to the elevation of the 2nd strut level.

The rest of the zones was excavated with identical number of stages; however, for the fourth stage the excavation reached a final elevation of -10.30 m in both zones since the measurements taken at the central zone showed that it was possible to install the 4th strut level at an elevation of -9.95 m instead of -10.50 m without risking the stability of the project and by doing so the struts could be saved during the pouring process of the bottom slab.

All the struts were pre-loaded with 12 ton prior to their placement.

INSTRUMENTATION

In order to prevent a bottom failure of the excavation even considering a safety factor of 1.25[1], it was decided to install special devices so any incipient failure could be detected and thus prevented. Thirteen deep bench marks were installed at an elevation of -19.50 m inside the excavation and at an elevation of -13.50 m on the outside. Shallow bench marks were placed around the excavation.

Four slope indicators were installed down to the elevation -28.00 m to measure the horizontal soil deformations throughout the influence depth affected by a probable bottom failure. Readings were taken every 8 hours at every 1.50 m in depth with a 200-B Recorder having and approximation of 0.0009 radians and manufactured by the Slope Indicator Co.

Pumping was controlled with 31 pneumatic piezometers of the C.F.E.[2] type and with 4 Casagrande open-type piezometers. These instruments were conveniently located and their depth selected according to the theoretical flow net analyzed. The open-type piezometers were only used at the sand strata and measurements were taken with an electric probe; readings were taken at the pneumatic ones with a calibrated pressure gage.

The rest of the instruments consisted of Freyssinet pressure cells installed in a closed circuit to measure the strut loads by means of a calibrated pressure gage with a rated capacity of 140 kg/cm^2 . Readings were taken every 6 hours with an approximation, given by the previous calibration, of about 1.0 ton.

MEASUREMENTS DATA

In order to facilitate the presentation and interpretation of the results obtained, a series of numbers was assigned to the days elapsed from the beginning of the slope indicator readings. This date was arbitrarily named Day No. 1.

The development of the strut loads as the excavation progressed is shown in Fig. 5. For simplicity sake, only one of the four daily readings is reported and it corresponds to the one taken at noon. Any other exceptional reading at other time is included in the graphs.

It is convenient to notice that a different influence area corresponds to each strut, since this fact accounts for the varied magnitudes of the measured loads.

The horizontal soil deformations during the main excavation stages are shown in Fig. 6. Due to space shortage the soil deformations occurred below the bottom of the sheet piling are not indicated.

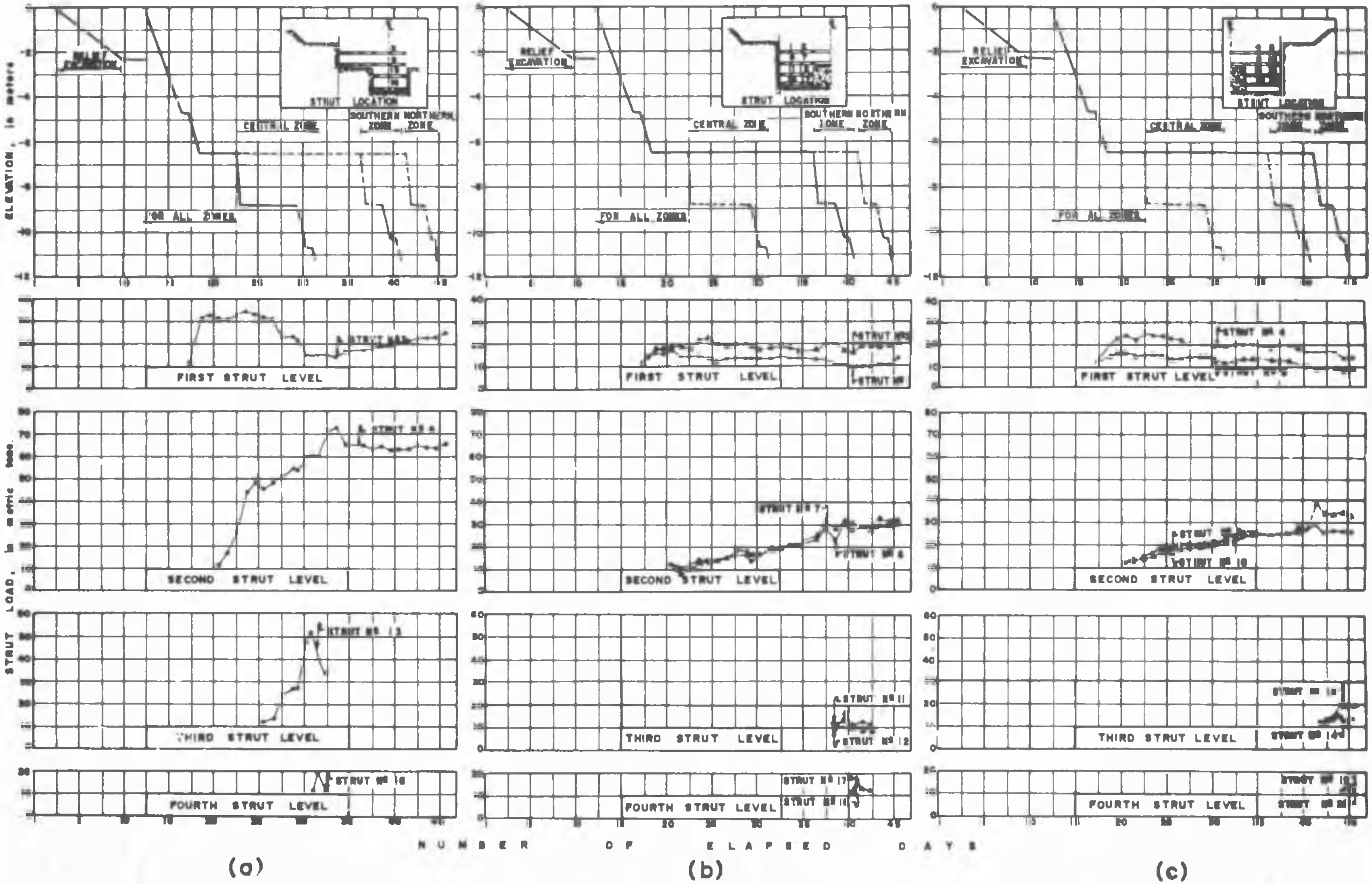

FIG. 5. EXCAVATION PROGRESS AND STRUT LOADS.
(a) CENTRAL ZONE.
(b) SOUTHERN ZONE.
(c) NORTHERN ZONE.

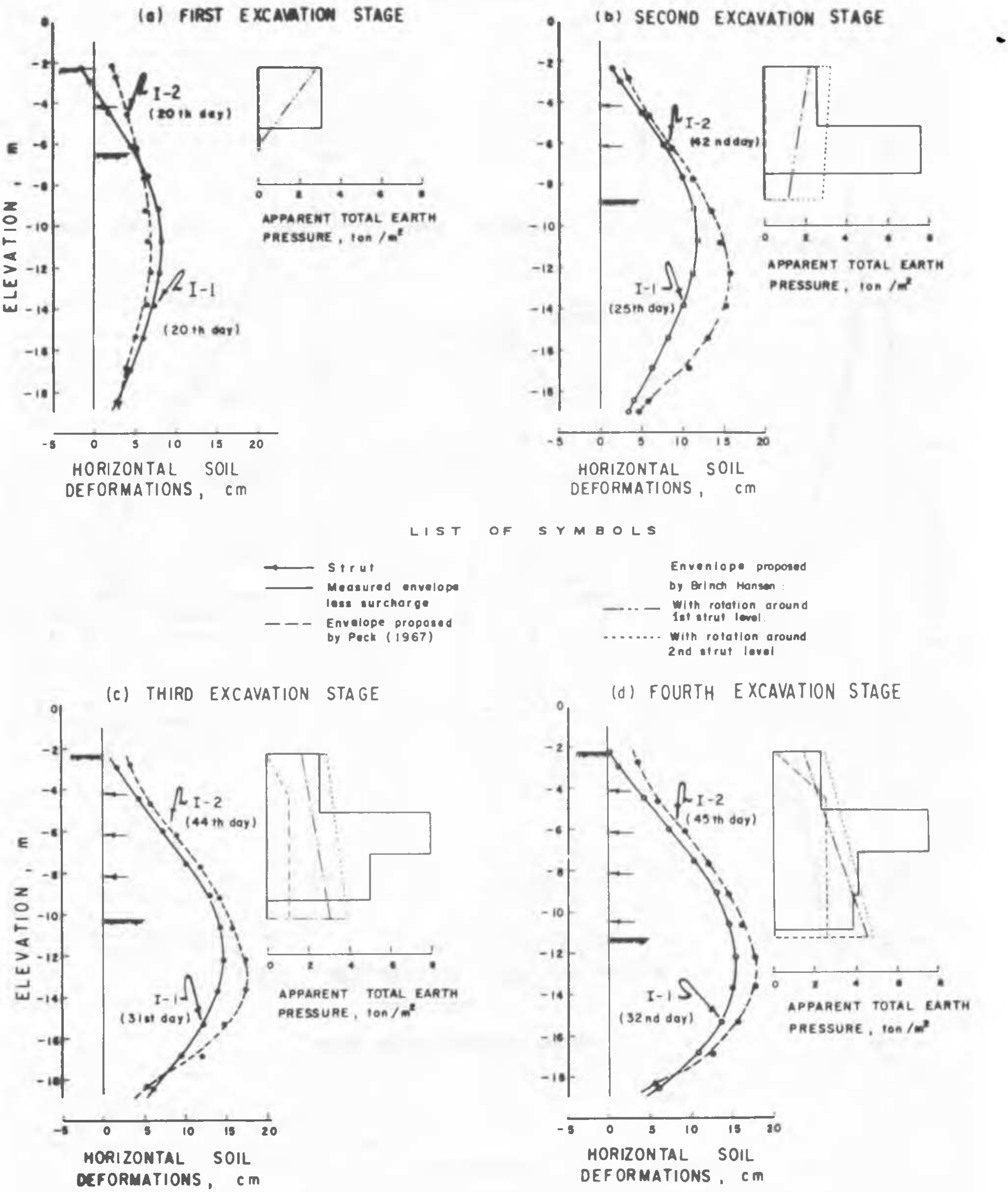

FIG. 6. HORIZONTAL SOIL DEFORMATIONS AND TOTAL APPARENT EARTH PRESSURE MEASURED IN THE MAIN EXCAVATION STAGES.

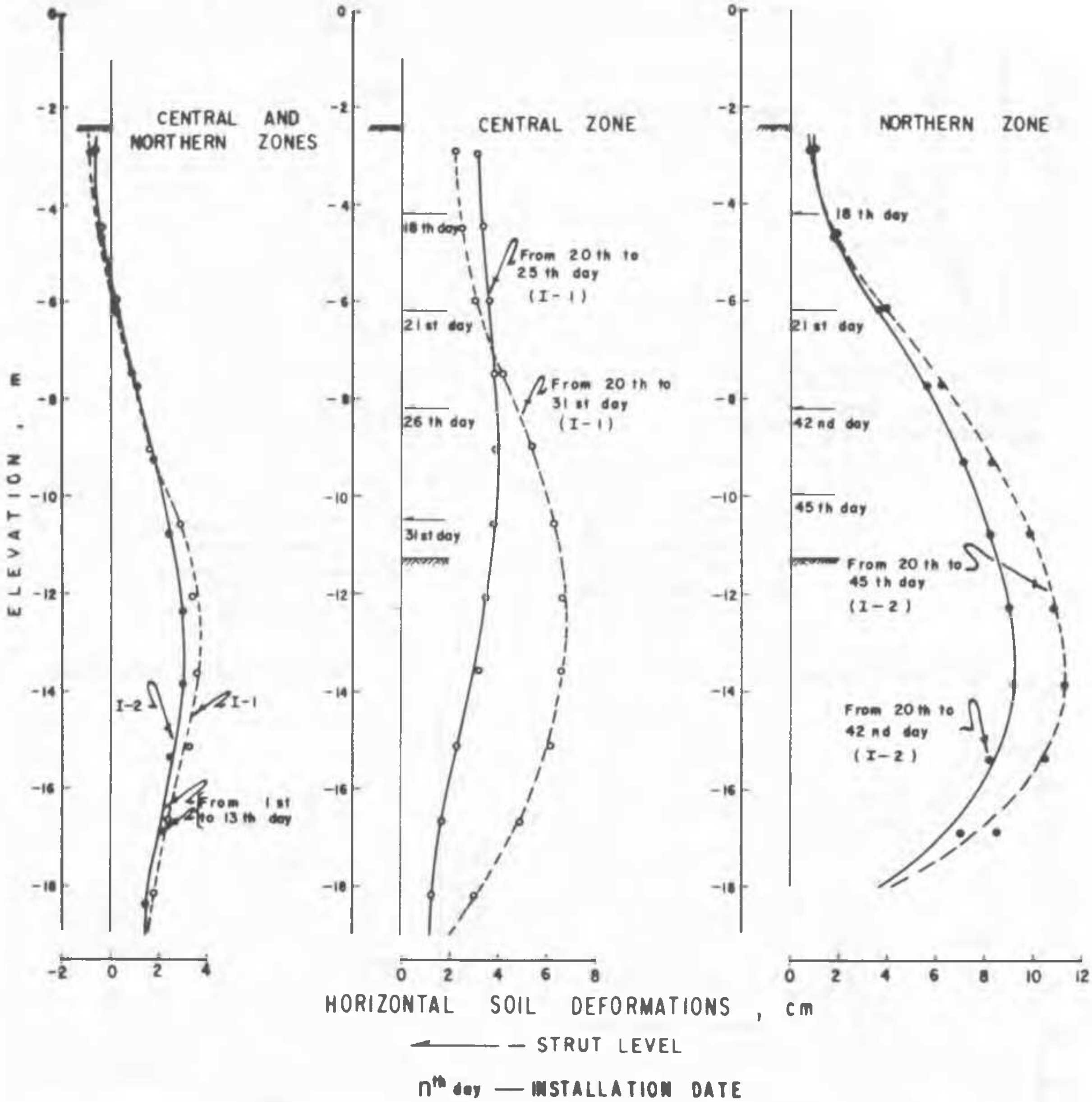

FIG. 7. HORIZONTAL SOIL DEFORMATIONS.

ANALYSIS OF RESULTS

The following analysis will be reported in terms of the total stresses acting inside the soil mass since it was not possible, although it would had been desirable, to perform the analysis in terms of effective stresses; this was impossible because the number of installed piezometers was not sufficient and the precision of their readings was not the required one for the latter type of analysis. It is also worth mentioning that the presence of nearby excavations with an intense pumping contributed to the lowering of the water table at the site of the siphon, from its original level of -3.00 m to an approximate elevation of -8.00 m.

The analytical computation of the apparent earth pressure envelopes[4] was accomplished considering the top of the excavation at an elevation of -2.30 m which corresponds to the ground level after the relief excavation was made.

In order to compare the theoretical envelopes with those determined from the measurements taken, the influence of the surcharge due to the soil not affected by the relief excavation was subtracted from the measured envelopes. The criterion used to evaluate such an influence has been suggested by Carothers[3], in spite of the fact that Terzaghi recommends to use twice the value of the horizontal stress (σ_H) obtained with the first criterion in order to take into account the small sheet piling deformation under the action of the surcharge. Such recommendation is not valid in this case since the relief excavation by itself produced important lateral displacements and in addition such deformations were even higher during the subsequent excavation stages.

Using the above criterion the theoretical envelopes corresponding to the main excavation stages were calculated (Fig. 6). For the envelopes determined with Peck's criterion[4] the reduction factor "m" was supposed to be equal to unity whereas for those computed with Brinch Hansen's criterion[5] the undrained shearing strength was reduced by the specified safety factor of 1.5. Each one of the measured envelopes of the various excavation stages was obtained from the recorded loads corresponding exclusively to the stage being analyzed.

For the 1st and 2nd excavation stages (Figs. 6-a and 6-b) Peck's envelope was found to be null whereas Brinch Hansen's shows values which decrease as the depth increases. In both stages the theoretical apparent pressure is appreciably lower than the measured one, specially at the second strut level during the 2nd excavation stage.

In the two remaining excavation stages (Figs. 6-c and 6-d) Peck's envelopes are now developed although the pressures obtained are lower than those observed in Brinch Hansen's envelopes. The pressures in the theoretical envelopes become again appreciably smaller than the measured values and once again the critical case corresponds to the second strut level.

The fact that the second strut level shows the maximum pressures in all the excavation stages can be explained by observing the horizontal deformations of the surrounding soil. In this way, from the date of installation of the second strut level (20th day) to immediately before placement of the third strut level (25th day) the central zone experienced soil deformations which increased with time, as shown by the continuous curve of Fig. 7-b, whereas their increase just before the placement of the fourth strut level is represented by the broken curve. Since both curves intercept at an approximate elevation of -7.00 m, it can be observed that the deformation increments become negative at shallow depths and this means that the sheet piling rotated around the second strut level and as a consequence a passive earth pressure state was induced in the surrounding soil. The behavior of the northern zone (Fig. 7-c) is not quite clear although it can be observed that the deformation increment at the second strut level is almost negligible. Knowing that Brinch Hansen assumes that the sheet piling rotates around the first supporting element, it was considered convenient to apply this criterion to determine the envelopes for the real rotation condition. However, even for this case the theoretical envelopes resulted considerably smaller than those measured in the influence area of the second strut level (Figs. 6-b, c & d).

The average and maximum ratio between the observed horizontal (σ_H) and vertical (σ_V) total pressures during the main excavation stages are given in columns 7 and 8 of Table I. If the variation of the above ratio σ_H/σ_V is plotted against the ratio between the excavation depth H and the critical depth $H_{crit} = 4c/\gamma$, approximate linear relationships are obtained (Fig. 8).

The computed pressure center[4] "n" varies within a narrow range from 0.49 to 0.50; these values fall along the upper limit of the variation range recorded in other places[4].

T A B L E I

ZONE	EXCAVATION STAGE	TOTAL THRUST ABOVE EXCAVATION LEVEL (ton/m) MEASURED AVE.	MEASURED MAX.	DUE TO SURCHARGE	(1)-(3)	(2)-(3)	$\frac{1}{2}\gamma H^2$	RATIO σ_h/σ_v AVE. (4)/(6)	MAX. (5)/(6)	n_a
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
All	1st	8.94	10.42	0.92	8.02	9.50	11.50	0.697	0.826	——
All	2nd	20.37	23.10	2.58	17.79	20.52	26.35	0.675	0.779	0.50
NORTHERN AND SOUTHERN	3rd	26.74	32.01	4.35	22.39	27.66	39.30	0.569	0.704	0.49
CENTRAL	3rd	——	33.96	4.60	——	29.36	43.00	——	0.683	0.49
All	4th	32.44	39.24	6.17	26.27	33.07	49.40	0.532	0.669	0.49

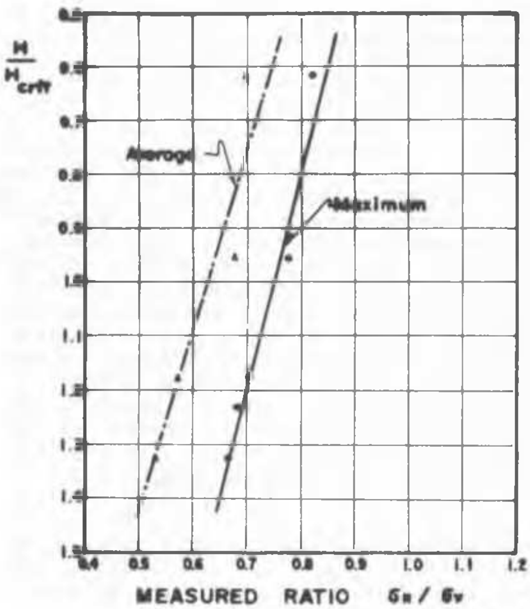

FIG. 8. VARIATION OF THE RATIO σ_h/σ_v WITH THE RATIO H/H_{crit}

CONCLUSIONS

The total pressures obtained from the theoretical envelopes are appreciably lower than those deduced from the measured loads of the struts particularly at the influence area of the second strut level that corresponds approximately to the real rotation axis of the sheet piling.

The envelopes obtained with Brinch Hansen's criterion, considering that the sheet piling rotates around the first strut level, give values which are closer to the measured pressures than those obtained with Peck's criterion.

The envelopes obtained applying Brinch Hansen's criterion to the real rotation condition result with a satisfactory approximation of about 30% with respect to the measured envelopes, except at the influence area of the second strut level.

For the case being reported, the measured envelopes only differ about ± 20% from the envelopes similar to those proposed by Peck, in which the horizontal pressure is defined by the product of the total vertical pressure (σ_v) times the maximum ratio σ_h/σ_v obtained from Fig. 8.

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