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Geotechnical Properties of Shanghai Soils and Engineering Applications

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ABSTRACT: The first part of this paper is an account of the typical layers of Shanghai soils, with empirical formulas correlating different soil parameters. Such has been the result of the writers' effort in geotechnical engineering consultative service and in researches for preparation and revision of foundation engineering codes of practice. It is hoped that these may be useful for others and also for future developments in marine geotechnology in the Donghai Sea (East China Sea) since the seabed soils are in close kindred relationship to land area deposits.

The second part of the paper begins with studies on horizontal permeability and increase of undrained strength with effective overburden pressure for typical soil layers. On these soils, design of the shallow foundation of a 20 000-ton oil tank with scheduling for a water test pre-loading period has resulted in considerable economic savings.

KEY WORDS: statistical analysis, compressibility, permeability, rest pressure coefficient, piles, consolidation

Nomenclature

C_c	Compression index
c_u	Undrained shear strength
c_u/p_o, $(c_u/p_o)_{NC}$, $(c_u/p_o)_{OC}$	Ratio of undrained strength c_u to effective overburden stress p_o; subscripts NC and OC designate normally consolidated and overconsolidated, respectively
c_{vane}	Cohesive strength from vane test
e_o	Natural void ratio
I_p	Plasticity index
K_o	Coefficient of "at-rest" pressure, for total stresses σ_1 and σ_3

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K_o'	Do main for effective stresses σ_1' and σ_3'
K_{on}	K_o for normally consolidated state
K_{ou}	K_o coefficient under rapid continuous loading, simulating instantaneous loading or an undrained condition
K_{od}	K_o coefficient under cyclic loading (frequency less than 1 Hz), as a pseudo-dynamic test for K_o coefficient
k_h, k_v	Permeability in horizontal and vertical directions, respectively
N	Blow count, standard penetration test
OCR	Over-consolidation ratio
p_c	Preconsolidation pressure, from oedometer test
p_o	Effective overburden pressure
p_s	Specific cone penetration resistance, from static cone test
q_u	Unconfined compressive strength
U, U_m	Degree of consolidation; subscript m denotes mean value of a specimen
u, u_b, u_m	Pore pressure, subscripts b and m denote bottom of specimen and mean value, respectively
w_o, w_L, w_P	Natural water content, liquid, and plastic limits, respectively
σ_1, σ_3	Principal stresses; σ_1' and σ_3' denote effective principal stresses

Introduction

The first part of the paper is a brief description of geotechnical properties of Shanghai soils including: (1) a general description of Shanghai soils; (2) empirical formulas for the compression index C_c; and (3) studies of the coefficient of "at-rest" lateral pressure K_o.

The second part on engineering applications includes: (1) evaluation of horizontal permeability; (2) correlation of the strength ratio and plasticity index ($c_u/p_o - I_p$ relationship); and (3) application to oil tank foundation design, with considerable saving in construction cost and shortening of water-test preloading period, as compared with designs at a neighboring site having similar conditions.

Geotechnical Properties of Shanghai Soils

General Description of Shanghai Soils

Shanghai soils may be divided, for convenience, into eight layers, as shown in Table 1. A brief description of the eight soil layers in Table 1 is given as following.

Layer 1—Fill, building debris in the urban, cultivated land or clayey fill in suburbs, and reclaimed land with hydraulic fill from dredging on the banks of the Huangpo River.

Layer 2—Surface crust; yellowish dark brown inorganic clay; low to medium plasticity, medium consistency, medium compressibility; with ferromanganese nodules. Bearing for shallow foundation of low-rise buildings.

TABLE 1—*Soil layers of Shanghai.*

Geological Origin	Sequence of Layers	Description	Soil Type, According to Chinese Codes[a]
		HOLOCENE EPOCH	
River estuary alluvial deposits	1	fill. < 3m, in general	fill
	2	surface crust 2 to 3 m	yellow-dark brown crust
Shallow sea deposits	3	greyish silty clay; 5 to 10 m; sometimes replaced by very fine sand; 3 to 12 m	sub-clay or light sub-clay, muddy; very fine sand
	4	greyish soft clay, highly compressible; 3 to 10 m	muddy clay
Littoral shallow sea marsh deposits; littoral-fluvial deposits	5	greyish silty clay, 5 to 15 m	greyish sub-clay
		NEOPLEISTOCENE EPOCH	
Lacustrine deposits	6	dark green stiff clay, over-consolidated; bearing for piles; 3 m, in general; missing in some localities	dark green stiff layer
Fluvial deposits	7	yellowish very fine to fine sand; Bearing for piles; 5 to 15 m	very fine to fine sand
Shallow sea deposits	8	greyish silty clay; 20 to 30 m missing in certain localities	greyish sub-clay

[a]According to Chinese Code (TJ 7-74), cohesive soils are classified by plastic index as follows: clay ($PI > 17$), sub-clay (10–17), and light sub-clay (3–10). Clays and sub-clays with natural water content greater than liquid limit, and void ratio over unity are described as "muddy" or "mucky."

According to Shanghai Code (1975), cohesive soils are classified as clay ($PI > 17$), sub-clay (10–17), light sub-clay (7–10), and sub-sand ($PI < 7$). There is also difference in the meaning of "muddy" or "mucky."

Sub-clay and light sub-clay (or sub-sand or both) are sometimes translated as loam and sandy loam, silty clay, and silt, and so forth.

Layer 3—Greyish silty clay; medium plasticity, high compressibility; with inclusions of micaceous flakes and decayed reeds. In some localities, this layer is characterized by greyish very fine sand and silt deposited in buried riverbeds, forming strips 2 to 5 km wide.

Layer 4—Greyish silty clay; medium plasticity, high compressibility; with very fine sand layers and reeds in small amounts. Seat of settlement for buildings.

Layer 5—Greyish silty clay; low to medium plasticity, with calcium nodules in small amounts. In localities where Layer 6 is missing, this layer is characterized with lower plasticity, sometimes with thin layers of very fine sand and silt.

Layer 6—Dark green stiff layer of inorganic clay. Low to medium plasticity, with streaks of ferric oxide; lacustrine deposits during regression by the end of Pleistocene Epoch. Being for some time the ground surface in old days. Overconsolidated, good bearing for pile foundations. Layer 6 is sometimes missing, because of ancient terrain being eroded by water courses.

Layer 7—Very fine to fine sand; yellow or bluish grey; medium density. Good bearing for piles under heavy constructions.

Layer 8—Silty clay with laminations of sand layers. Seat of settlement under pile foundations.

A plot of Shanghai soils on the plasticity chart is shown in Fig. 1. Figure 2 is the key plan for soil profiles shown in Figs. 3 through 7 and Tables 2 and 3. Figures 3 and 4 show variation of physical properties, penetration resistance, undrained strength, and preconsolidation pressure with depth.

Empirical Formulas for the Compression Index C_c

During the last ten years, the writers have endeavored to collect available test data on Shanghai soils, in addition to innovation of apparatus and running tests; thus empirical formulas based upon regression analysis have been derived, which may be used advantageously in evaluating certain design parameters from routine test indices that can be more easily determined [*1*].

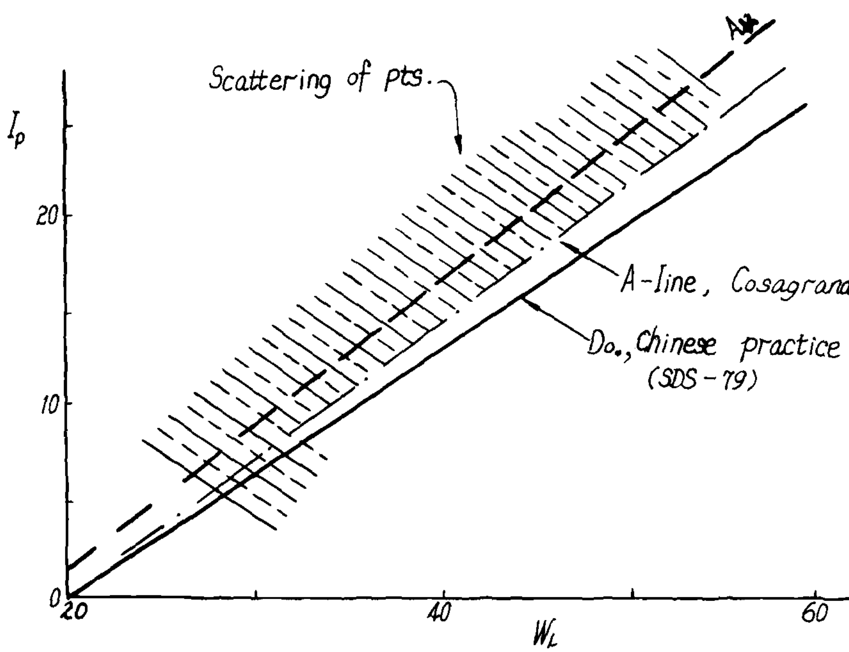

FIG. 1—*Plot of Shanghai soils on the plasticity chart.*

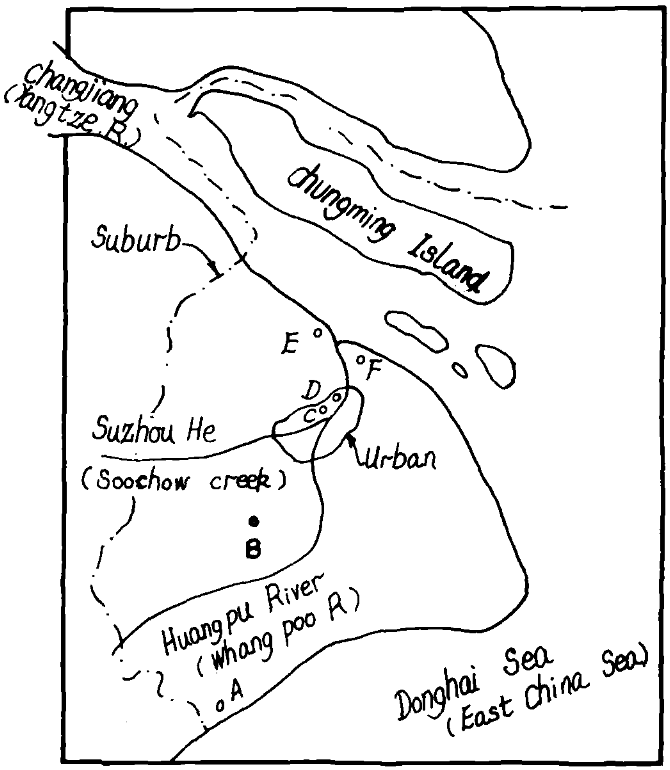

FIG. 2—*City of Shanghai: key plan for soil profiles shown in Figs. 3 through 7 and Tables 2 and 3.*

Some of these formulas relating to the compression index C_c, which are rather preliminary, are given in Table 4.

In Table 4, correlation of C_c and e_o appears to be satisfactory, and the C_c-w_L relationship is at variance with the formulas proposed by Skempton et al. [*2,3*]

$$C_c' = 0.009\,(w_L - 10) \tag{1}$$

$$C_c = 0.007\,(w_L - 10) \tag{2}$$

where C_c' are compressive indices for undisturbed and remolded samples, respectively.

Studies of the Coefficient of "At-Rest" Lateral Pressure K_0

Since the 1950s, there has been much research work done in China in laboratory studies of the "at-rest" earth pressure coefficient. An early design of

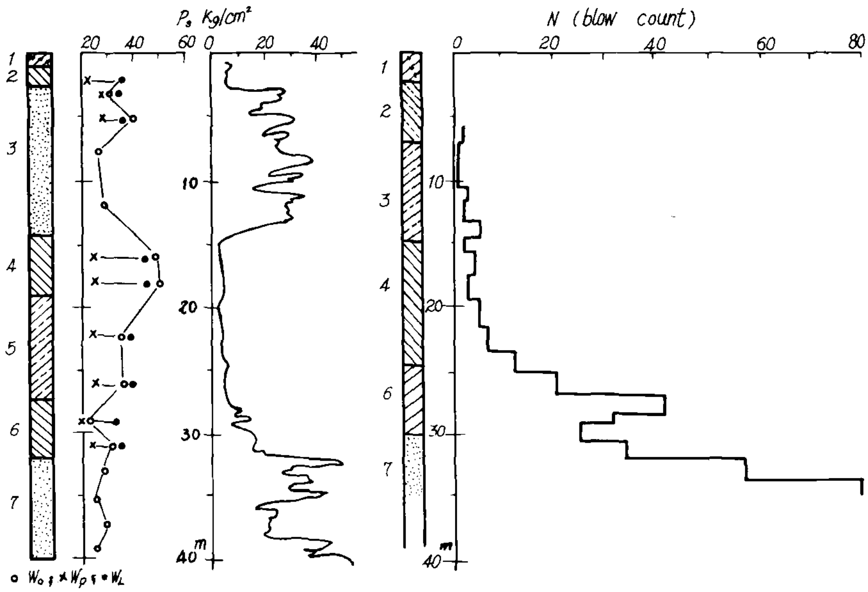

FIG. 3—*Typical profiles of physical properties and penetration resistance data for Site B in Fig. 2:*

w_o, w_P, w_L = *natural water content, plastic limit and liquid limit, respectively;*
p_s = *specific cone penetration resistance; and*
N = *SPT blow count.*

Note: See Table 1 for sequence of soil layers.

K_o meter [*4*] resembles Hveem's stabilometer [*5*] and the "cell test" apparatus then in common use in European countries [*6, 7*]. K_o studies for Shanghai soils began with laboratory tests with application to settlement analysis [*8*] and this was followed by more elaborated laboratory tests and innovations in instrument design, leading to the design of an automatized apparatus [*9*]. A diagrammatic sketch of the apparatus is shown in Fig. 8. The test specimen with rubber membrane is prevented from lateral expansion by ambient liquid pressure, has drainage at the top, and a pore-pressure measurement at bottom, and may be tested in a stress- or strain-controlled condition with an automatized recording device (not shown in Fig. 5).

Some of the results of laboratory tests using the new apparatus [*10*] are as follows:

1. Formulas for effective stress coefficient ($K_o' = \sigma_3'/\sigma_1'$) (Table 5). It is seen that K_o'-sin ϕ' relationship agrees very well with Jacky's formula

$$K_o' = 1 - \sin \phi' \tag{3}$$

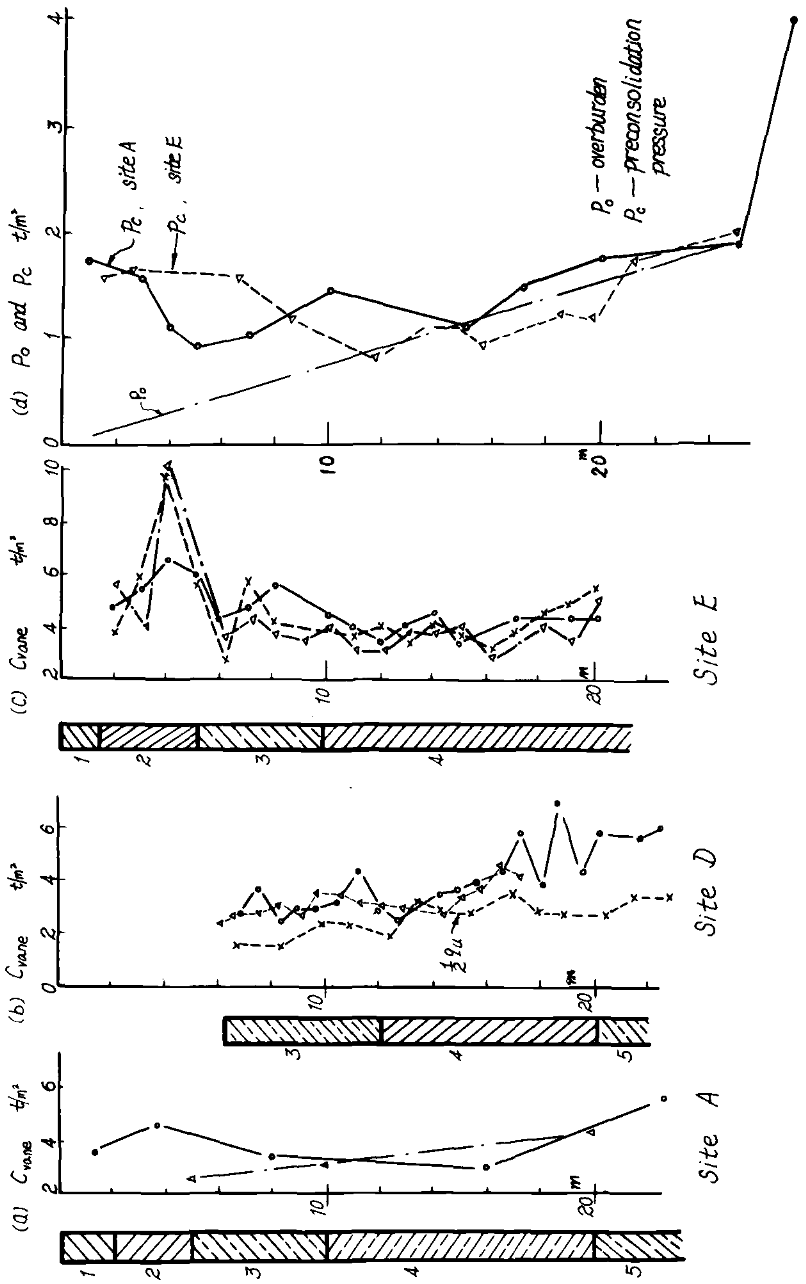

FIG. 4—*Typical profiles showing variation of strength and preconsolidation pressure at Sites A, D, and E in Fig. 2. See Table 1 for sequence of soil layers.*

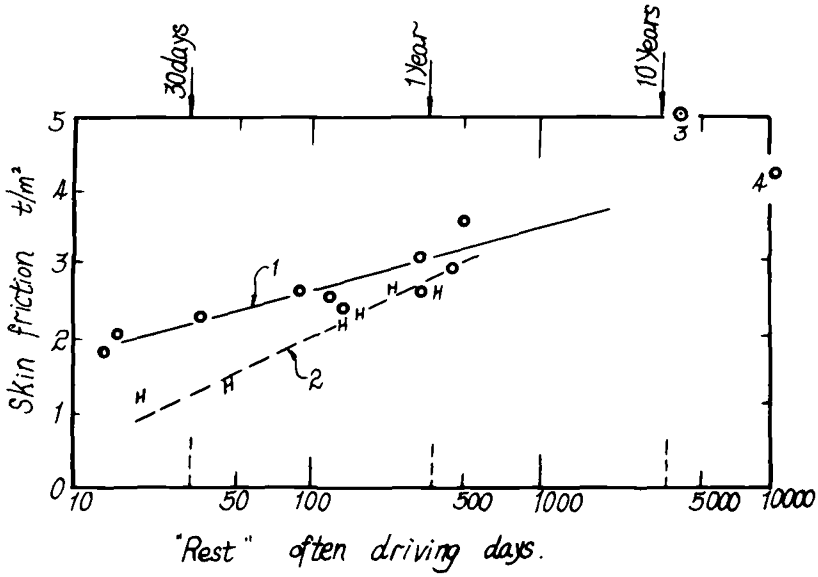

FIG. 5—*Gain of fractional resistance with time of driven piles in Shanghai soils* [18,19]*:* (1) *square RC piles, at Site D, Fig. 2; based upon data reported by the late Gu Bai-Sheng et al.;* (2) *H-shaped RC piles;* (3) *square RC pile; and* (4) *timber pile.*

2. Total-stress coefficient ($K_o = \sigma_3/\sigma_1$) as effected by the overconsolidation ratio (OCR). It has been known that K_o coefficient is not constant but depends on the OCR

$$K_o = K_{on}\,(\text{OCR})^m \tag{4}$$

with $m \leq 0.41$, where K_{on} is the K_o coefficient for a normally consolidated sample [*11*]. This applies to the case when the specimen is unloaded (with OCR increasing). When the specimen is reloaded (with OCR decreasing), K_o values will be much smaller than those of Eq 4. For the latter case, empirical formulas have been established and given in Table 6.

3. Total-stress coefficients K_o as effected by pore-water pressure dissipation. Analysis of test results led to the following formulas

$$K_o = 0.54 + 0.40\,(u_b/\sigma_1) \tag{5}$$

$$K_o = 1.01 - 0.46\,U_m \tag{6}$$

where

u_b = monitored pore-water pressure at bottom, with drainage at top,

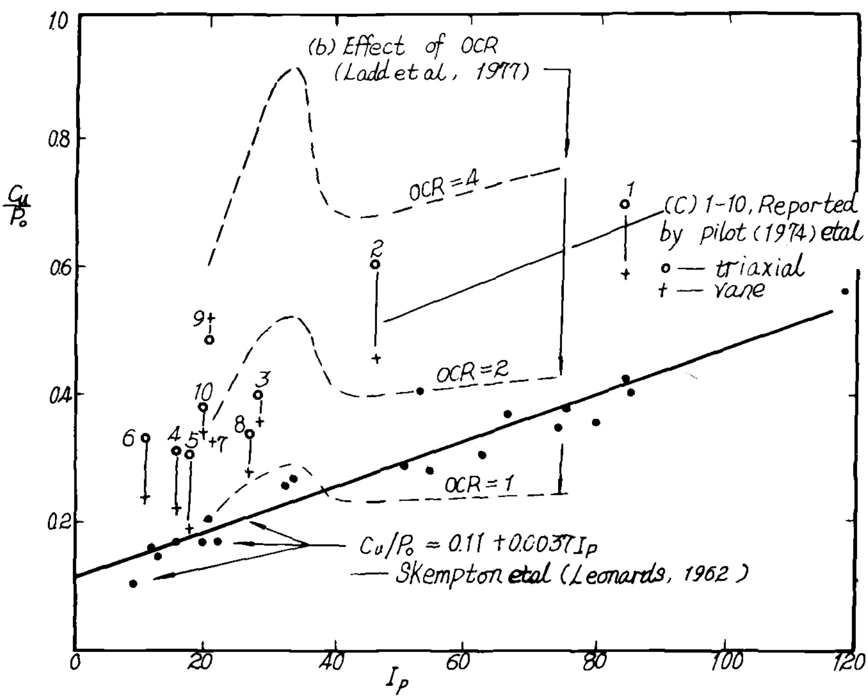

FIG. 6—*Correlation of strength ratio and plasticity index* (c_u/p_o — I_p *relationship):* (a) *Skempton's empirical formula, with scattering of data* [20]*;* (b) *Effect of overconsolidation, replotted from data reported by Ladd et al.* [11]*; and* (c) *Data reported by Pilot* [21] *(see Table 2).*

σ_1 = applied load at top of specimen, and
U_m = average degree of consolidation of the specimen.

4. On the instantaneous loading and cyclic loading coefficients (K_{ou}, K_{od}). Loading conditions are K_{ou} rapid continuous loading, simulating instantaneous loading or undrained condition, and K_{od} cyclic loading, at frequency less than 1 Hz, which may be considered a pseudo-dynamic test for the K_o coefficient.

It has been found for Shanghai soils that

$$K_{od} \approx 0.8\ K_{ou} \qquad (7)$$

Application to Oil Tank Foundation Design

A 20 000-ton oil tank, at Site F in Fig. 2, was planned to be built with foundation pressure over 20 ton/m^2, while local practice is to allow not more than 8 to 10 ton/m^2 for buildings and structures on shallow foundations [12].

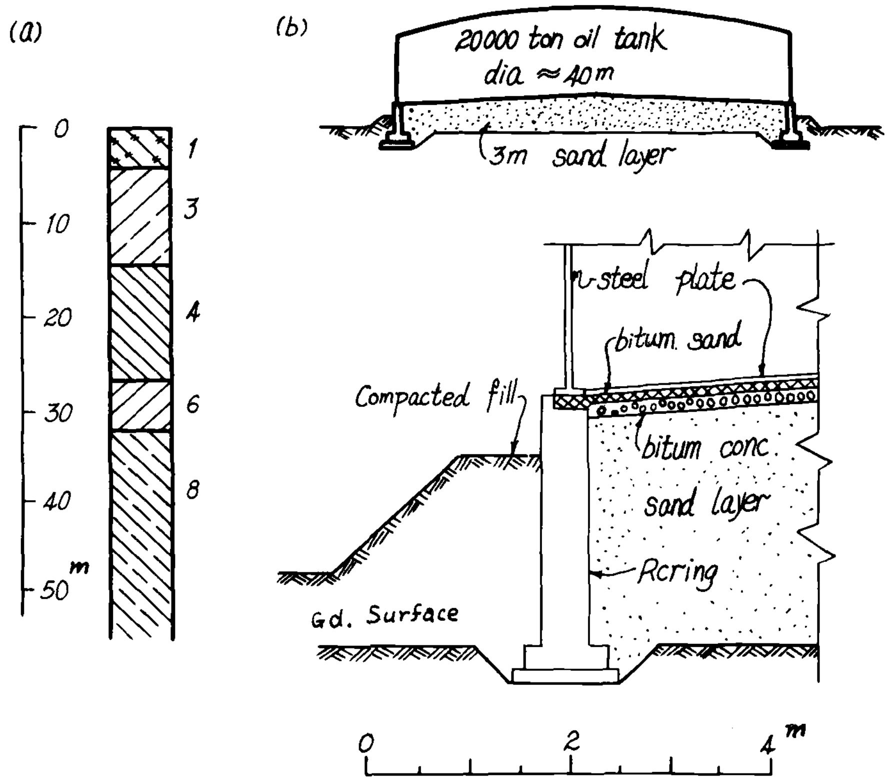

FIG. 7—*20 000-ton oil tank on hydraulic fill, at Site F, Fig. 2:* (a) *soil profile, see Table 1 for sequence of layers;* (b) *sketch of tank; and* (c) *reinforced concrete ring, berm, and sand layer.*

It is known that Terzaghi proposed, more than 50 years ago, that piles for oil tanks on soft ground are unnecessary [*13*] and that water-test pre-loading [*14*] has been tried in Shanghai with satisfactory results, in spite of large settlements. Yet there are engineers who insist on piling or some sort of treatment to insure stability and reduce settlement. Thus, the following theories have been considered: (1) theory of consolidation with due consideration for horizontal drainage in varved soils; (2) proper evaluation of permeability in horizontal as well as a vertical direction, and (3) a reasonable estimate of an increase in undrained strength with effective pressure (and therefore with consolidation).

With reference to the first point mentioned above, Gibson, Davis, and Lumb et al. have given rather elaborated numerical solutions in the 1950s and 1960s [*15*]. In China, Lu [*16*] has presented formulas and charts based upon rather simplified assumptions and making use of the "equivalent soil layer

TABLE 2—*Notes on data of* c_u/p_o *ratio, quoted from Pilot* [21] *(Fig. 6c).*

Number	Description	I_p	$q_u/2$	Triaxial	Vane	OCR	Literature
1	Bangkok clay	85	...	0.70	0.59	...	Pilot [21]
2	Matagami clay	47	...	0.61	0.46	...	...
3	Dramen plastic clay	29	...	0.40	0.36	...	...
4	Vaterland clay	16	...	0.32	0.22	...	...
5	Studenterlunden	18	...	0.31	0.18	...	...
6	Dramen lean clay	11	...	0.34	0.24	...	...
7	Boston blue clay	21	...	0.33	...	...	Lin [22]
8	Da-chen clay, Zhejiang	27	...	0.344	0.274	...	...
9	Peaty clay, Sri Lanka	21	...	0.49	0.52	...	Hydrogen & Power Engineering Research Institute [23]
10	Shanghai soft clay, Site E in Fig. 2	20	0.20	0.39	0.34	1.1	East China Electric Power Design Institute

TABLE 3—*Alternative foundation designs for 20 000-ton oil tank on Shanghai soft soil.*

Number	Location	Description of Foundation	Pre-Loading Period	Relative Cost of Foundation, with No. I Taken as Unity
I	At Site F, Fig. 2	with reinforced concrete ring and 3-m sand layer, see Fig. 7	50 days	1
II	at Site E, Fig. 2, near to Site F, but on the west bank	360 to ϕ 550 by 30-m RC piles, 1.83-m centers, with RC mat	...	...
III	...	121 to ϕ 409 by 65-m steel tubular piles, 3.3-m centers, with RC mat	...	6
IV	...	1712 to ϕ 400 by 20-m sand drains; 1.5-m centers	...	...
V	...	271 to ϕ 400 by 20-m sand drains; 3.2-m centers	120 days	2

NOTE: (1) Soil conditions are essentially the same for Site F (foundation design I) and Site E (foundation designs II, III, IV, and V). (2) Both No. I and No. V have been in use. (3) Alternative designs II, III, and IV are foreign designs that have not been constructed. Design V seems to be a compromise between overconservative and bold designs.

TABLE 4—*Empirical formulas for compressive index* C_c *of cohesive soils of Shanghai.*

Correlation of Soil Parameters	Soil Type	Empirical Formulas	Soil Layers (see Table 1)
$C_c - e_o$	silty clay and soft clay	$C_c = A(e_o - B)$	soil layers 3 and 4
		$A = 0.52 - 0.55$	
		$B = 0.5 - 0.53$	
		$C_c = 0.486\ (e_o - 0.523)$	soil layer 5
$C_c - w_o$	...	$C_c = C(0.01 w_o - D)$	soil layers 3 and 4
		$C = 1.4 - 1.9$	
		$D = 0.15 - 0.21$	
$C_c - w_L$	...	$C_c = 1.80\ (0.01\ w_L - 0.22)$	soil layers 3 and 4

method" [*17*]. It is interesting to note that there is not much difference in the results of either of the consolidation computations, whether using more sophisticated procedures or doing it in a crude way. This is especially true when scattering in permeability and difference in opinion as to gain in strength with consolidation are taken into consideration, and the latter points will be discussed in the following paragraphs.

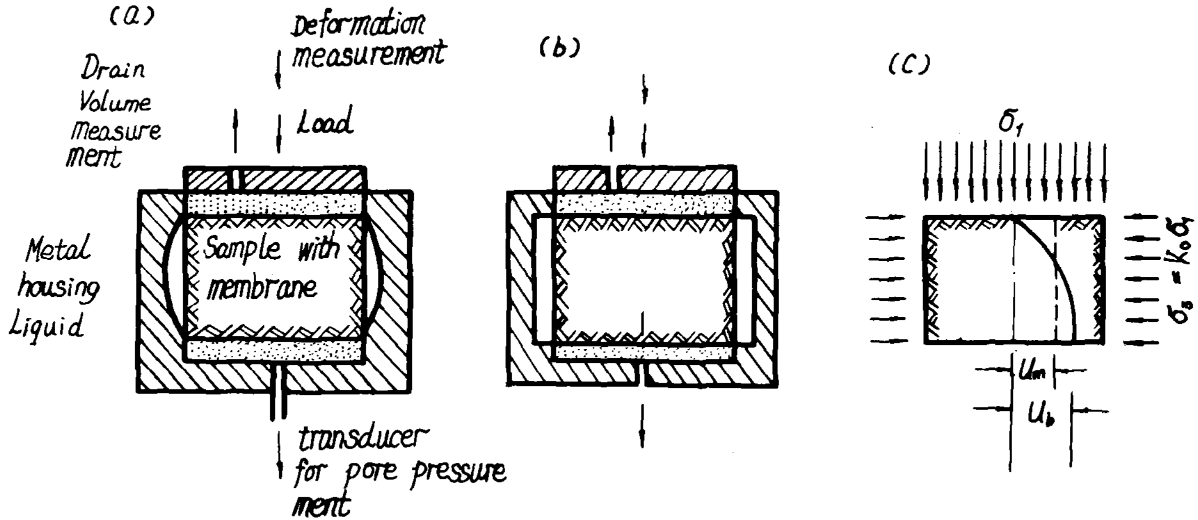

FIG. 8—(a) *Sketch of the* K_0 *meter (automatized device not shown).* (b) *Sketch of the apparatus in use in the 1950s and 1960s. Notice that the cylindrical cavity of the metal housing had been replaced by one with a concave surface as in Fig. 8*a, *and this reduces the possibility of air bubbles being entrapped in the cavity.* (c) *Stresses and pore pressures: principal stresses* σ_1, $\sigma_3 = K_0\sigma_1$*; pore pressure at the bottom* u_b *and mean pore pressure* $u_m \approx 0.7\ u_b$.

TABLE 5—*Formulas for* K_o' *coefficients.*

Correlation of Soil Parameters	Soil Type	Empirical Formulas	Soil Layers, see Table 1
$K_o' - \sin \phi'$	silty clay and soft clay	$K_o' = 0.999 - 0.993 \sin \phi'$	Soil layers 3 and 4
$K_o' - I_p$	...	$K_o' = 0.155 - 0.021\, I_p$	...

NOTE: ϕ' = angle of internal friction for effective stresses;
I_p = plasticity index.

TABLE 6—*Effect of OCR on* K_o *coefficient of cohesive soils of Shanghai.*

Description of Soil	Empirical Formulas for K_o-OCR Relationship, When Specimen is Re-Loaded (OCR Decreasing)	Soil Layer, in Table 1
Surface crust	$K_o = 0.541 + 0.685 \log (OCR)$	Layer 2
Dark green stiff clay	$K_o = 0.447 + 0.377 \log (OCR)$	Layer 6
Greyish silty clay, muddy	$K_o = 0.523 + 0.094\,(OCR)$	Layer 3
Greenish silty clay, soft clay, muddy, with thin layers of very fine sand	$K_o = 0.445\,(OCR)^{0.565}$	Layers 4, 5
Light sub-clay	$K_o = 0.335\,(OCR)^{0.517}$	Layer 3

TABLE 7—*Laboratory permeability (cm/day) of soil layers 3 and 4* [25] *(Fig. 5, Table 1).*

Soil Layer, see Table 1	Laboratory Values			Estimated Values for Use in Design	
(1)	k_h (2)	k_v (3)	k_h/k_v (4)	k_h (5)	k_v (6)
Layer 3	range: 0.12 to 0.22 average = 0.16	range: 0.005 to 0.032 average = 0.014	12	10	0.5
Layer 4	range: 0.014 to 0.026 average = 0.020	range: 0.004 to 0.009 average = 0.008	3	0.6	0.005

Evaluation of Horizontal Permeability

For the oil tank foundation under question, the soft soil layers (Fig. 7, Table 1) are of particular significance. Results of laboratory tests are quoted in Table 7, with estimated values for design purpose in Columns 5 and 6 for reference. It is seen that design values of k_h are much larger than laboratory values; this is reasonable, for there is much evidence that field permeability exceeds laboratory values greatly, for instance, values of horizontal permeability given in the Shanghai Code [12]

- clay and sub-clay, muddy, varved with thin layers of fine sand, k_h = 0.17 to 0.35 cm/day;
- sub-sand (or light sub-clay), 17 to 35 cm/day; and
- very fine sand, 170 to 350 cm/day.

Correlation of Strength Ratio and Plasticity Index

It has been known from experience that Shanghai soft soils increase in strength on consolidation; one example being gain in skin friction of driven piles, as shown in Fig. 5 [18,19].

Yet there is a point of practical interest as to how much increase in undrained strength c_u for a certain increment in effective stress p_o can be considered in design; the reason for raising this question is that field vane shear strength sometimes greatly exceeds that given by the formula of Skempton and Henkel [2] and those of other authors [20]

$$c_u/p_o = 0.11 + 0.0037\ I_p \tag{8}$$

There are engineers who are inclined to reject such test results. Facing this situation, it is significant that Skempton's relationship applies only to clayey soils that are normally consolidated, fairly uniform, and of low activity and sensitivity, as illustrated in Fig. 6.

In connection with Fig. 6*b*, Ladd et al. [11] suggested the following relationship

$$(c_u/p_o)_{\rm OC}/(c_u/p_o)_{\rm NC} = ({\rm OCR})^m \tag{9}$$

where the subscripts OC and NC designate overconsolidated and normally consolidated soils, respectively; m = 0.75 to 0.85 and may be taken as equal to 0.8. So, it has been demonstrated, by the plotting in Fig. 6*b* that overconsolidated exercises influence on c_u/p_o ratio to a much greater degree than I_P values. Notes for data quoted from Pilot [21] et al., in Fig. 6*c* are given in Table 2. From Fig. 6*c* and Table 2, it is seen that values of strength ratio (c_u/p_o) based upon triaxial tests are in general higher than those from vane tests; this is in agreement with the well-known fact that conventional triaxial consolidated isotropically undrained test (CIU) tests usually give higher strength compared with CK_oU tests or field vane tests.

Soil 4 (Shanghai soft clay) has a vane strength ratio of 0.34, which is nearly twice as predicted by Skempton's Formula 8 for I_P = 20, and this cannot be explained by Formula 9 since the OCR is only 1.1; this should be attributed to the presence of thin sand and silt layers.

Application to Oil Tank Foundation Design

As shown in Fig. 7, the foundation for a 20 000-ton oil tank has a 3-m sand layer with a RC ring (a usual practice). With proper knowledge of horizontal drainage and a c_u/p_o ratio as mentioned above and with careful monitoring of displacement and pore pressure, the construction has proceeded economically and quickly, as can be seen in comparison with alternative designs given in Table 3.

From Table 3, use of piled foundation (Designs II and III) is at variance with Terzahi's suggestion [*12*] and local experience, resulting in a terribly extravagant design. Also, the water-test pre-loading period for the sand-drain foundation (V), lasting 120 days, as compared with 50 days for the untreated foundation soil (I) seems to be due to lack of proper understanding of the behavior of Shanghai soft soil in horizontal permeability k_h and strength ratio (c_u/p_o).

Closing Remarks

It is hoped that the writers' experience with Shanghai soft soils may be helpful to the geotechnical engineering profession, and it has been made clear that proper evaluation of soil parameters (k_h, c_u/p_o-ratio, and so forth) may be rewarding.

The writers feel very much indebted to all who have helped to collect experimental data and case records of all sorts, and to Prof. Yu Tiao-Mei for his encouragement and valuable suggestions in revising the manuscript.

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