UNDRAINED STRENGTH AND STABILITY ANALYSIS OF SOFT IRAQI CLAYS

HIDEO HANZAWA*, TADAE MATSUNO** and KIYOSHI TSUJI**

ABSTRACT

This paper describes (1) the determining procedure of the undrained strength of Iraqi alluvial clays for practical use and (2) the results of stability analysis for sliding of the jetty at Fao and Khor Al-Zubair, located on the mouth of the Shatt Al-Arab and on her old river channel respectively.

From the considerations on the undrained strength for practical use and on the stability analysis (including the field observation), following conclusions were obtained: —

(1) The undrained strength of Iraqi alluvial clays distributed along the Shatt Al-Arab should be fundamentally determined from the in-situ vane tests.

(2) From the comparison of the results of stability analysis and of the field observation, it was suggested that factor of safety for sliding obtained using the undrained compression and extension strength, $S_{u(c)}$ and $S_{u(e)}$ may better represent the actual one.

Key words: anisotropy, clay, compressive strength, consolidated undrained shear, stability analysis, vane shear test

IGC: D6/E6

INTRODUCTION

In the countries along the Arabian Gulf (or the Persian Gulf), a lot of big projects are planning and being under-taken. For development of these projects, it is urgent to expand and to arrange harbor facilities for smooth importation of materials required for the development of projects, so that new harbors have rapidly been developed in this area for a few years.

In the Republic of Iraq which is located at the west end of the Arabian Gulf, new harbor facilities at Ab-Flus, Fao and Khor Al-Zubair have been developed at the same time of the reparation of the old harbor facilities at Basrah. Two of them, jetty at Ab-Flus and Fao have been completed and are under operations, and a big scale of new harbor at Khor Al-Zubair is being completed on May 1978.

It is a characteristic of harbors in the Republic of Iraq that all of them are located along the River Shatt Al-Arab (including her old channel) which is the river after meeting of the River Tigris and the River Euphrates (see Fig.1). The area along the Shatt Al-Arab is composed of soft alluvial clays and they are classified into two clays as follows (Hanzawa, 1977): —

(1) Normally consolidated alluvial clay which is distributed along the present river.

* Soils Laboratory, Toa Harbor Works Co., Ltd., Tsurumi-ku, Yokohama.

** Design Section, Toa Harbor Works Co., Ltd., Tsurumi-ku, Yokohama.

Written discussions on this paper should be submitted before April 1, 1980.

Fig.1. Guide map showing the location of the site

(2) Overconsolidated alluvial clay which is distributed along the old river channel.

Particularly at Fao, located at the mouth of the Shatt Al-Arab, soft alluvial clay more than 30m thick is distributed and a serious problem regarding to its stability for sliding once took place. In these areas, the cost for soil improvement is so vast (the equipment for it must be transported from Japan) and the extension of work period is so difficult that the construction must be sometimes performed under lowest possible safety.

This paper describes the results of stability analyses for sliding of the jetty at Fao and Khor Al-Zubair as well as the determining procedure of the undrained strength of both clays for practical use. Fao clay which is considerably different from Japanese clay was the first experience for us so that the determination of the strength for practical use and the stability analysis were carried out by trial and error during construction. On the other hand, stability analysis of Khor Al-Zubair was carried out after that the shear characteristics of the clay distributed at these areas have almost been grasped. Thus there might be some differences in the determining procedure of the strength of both clays. There must be some questionable points in determining the strength and in evaluating the results of stability analysis, however, the authors report this paper as a record how the engineer dealt with the practical problem when he met with it.

SUMMARY OF SOIL CONDITIONS AND UNDRAINED STRENGTH OF CLAYS AT THE PROPOSED SITES

The soil conditions at Fao and Khor Al-Zubair have been reported in detail by Hanzawa (1977). In this section layout of the soil conditions and the undrained strength of clays at both areas will be briefly described and summarized.

Fao

Fao Jetty, 10km west from Fao city, is located on the right bank of the Shatt Al-Arab. The upper 35m is composed of alluvial clay overlying diluvium. A thin sand layer and sandy soil, and sandy clay 2m to 3m thick are distributed at (-) 11m to (-) 13m elevation and at the lowest level of the alluvial clay respectively. The diluvium is composed of alternating of sand and clay, with N values ranging from 30 to 50 in sand and from 15 to 40 in clay. Clay at the proposed site was 1.7t/m^3 to 1.9t/m^3 in unit weight, γ_t (average 1.8t/m^3), 30% to 50% in water content, w_c (average 40%) and had a plasticity

Fig.2. Typical soil profile at Fao and physical properties of Fao clay

Fig.3. $S_{u(v)}/p_0$ and $q_u/2p_0$ values of Fao clay plotted versus elevation

index, PI of 15% to 30% (average 20%). It may be classified as a clay of low to medium plasticity. The typical soil profile at the site and the physical properties of Fao clay are shown in Fig.2.

A lot of in-situ vane tests and unconfined compression tests on undisturbed samples were carried out for determining the undrained strength of this clay for practical use. The undrained strength ratio, S_u/p_0 (S_u =undrained strength and p_0 =effective overburden pressure) for both in-situ vane strength, $S_{u(v)}$ and unconfined compression strength, q_u plotted versus elevation are shown in Fig.3. Following notes may be pointed out as follows:—

- (1) There is great difference between $S_{u(v)}/p_0$ and $q_u/2p_0$ values.
- (2) The S_u/p_0 values are not constant through the depth.

These two problems will be discussed later.

On the other hand a series of triaxial tests on undisturbed samples obtained by the use of stationary piston sampler were also performed as follows:—

(a) CK_0UC_1 tests in which specimens were consolidated under a K_0 (coefficient of lateral earth pressure at rest) conditions where σ_{1c} is equal to the effective overburden pressure, p_0 which the specimen carried in the field and then brought into shear by compression (σ_{1c} is vertical consolidation pressure).

(b) CK_0UE_1 tests in which specimen were consolidated under a K_0 conditions ($\sigma_{1c}=p_0$) and then brought into shear by extension.

(c) CK_0UC_2 tests in which specimen were consolidated under a K_0 conditions (σ_{1c} is considerably greater than p_0) and then brought into shear by compression.

From these triaxial tests, the ratio between compression strength, $S_{u(c)}$, extension strength, $S_{u(e)}$ and in-situ vane strength, $S_{u(v)}$, and the undrained compression strength

ratio under a normally consolidated state, $S_{un(c)}/p_0$ were obtained as follows : —

$$\left. \begin{aligned} S_{u(c)} &= 1.27 S_{u(v)} \\ S_{u(e)} &= 0.75 S_{u(c)} = 0.95 S_{u(v)} \\ S_{un(c)}/p_0 &= 0.39 \\ S_{un(c)} &= \text{undrained compression strength under a normally} \\ &\quad \text{consolidated state} \end{aligned} \right\} \text{Eq. (1)}$$

Khor Al-Zubair

Layout of soil conditions and physical properties of Khor Al-Zubair clay obtained from an investigation which was carried out at the boundary between No.2 and No.4 Jetty are shown in Fig.4. As shown in Fig.4, the clay in this area was about 15m to 16m thick, was 1.8t/m^3 in γ_t , and had values of PI of 33% to 36% (average 35%).

In-situ vane, unconfined compression, CK_0 , UC_1 , CK_0UC_2 , and CK_0UE_1 tests were carried out as same as for Fao clay and following strength ratio were obtained : —

$$\left. \begin{aligned} S_{u(c)} &= 1.43 S_{u(v)} \\ S_{u(e)} &= 0.55 S_{u(c)} = 0.78 S_{u(v)} \\ S_{un(c)}/p_0 &= 0.355 \end{aligned} \right\} \text{Eq. (2)}$$

A total of 24 in-situ vane tests were carried out and the $S_{u(v)}/p_0$ values versus depth were obtained. When $S_{u(v)}/p_0$ values are multiplied by the above ratio, the $S_{u(c)}/p_0$ and $S_{u(e)}/p_0$ values can be obtained. The undrained strength ratio, S_u/p_0 versus elevation are shown in Fig.5 in which $S_{u(c)}/p_0$ and $S_{u(e)}/p_0$ were determined with above operations.

On the other hand, from the comparison of $S_{u(c)}/p_0$ and $S_{un(c)}/p_0$ in CK_0UC_1 and CK_0UC_2 tests and also from the comparison of p_c/p_0 values in consolidation tests (p_c is preconsolidation pressure), it was found that Khor Al-Zubair clay is an overconsolidated clay with overconsolidation ratio (O.C.R) being higher in upper part and decreasing with increasing depth.

O.C.R values versus elevation obtained from various kinds of strength tests and from consolidation tests are shown in Fig.6 in which O.C.R values were obtained as follows : —

$$\begin{aligned} \text{O.C.R from in-situ vane tests} &= S_{u(v)}/p_0 \div 0.355 \div 1.43 \\ \text{O.C.R from } CK_0UC \text{ tests} &= S_{u(c)}/p_0 \div 0.355 \\ \text{O.C.R from } q_u \text{ tests} &= q_u/2 p_0 \div 0.355 \\ \text{O.C.R from consolidation tests} &= p_c/p_0 \end{aligned}$$

As shown in the figure, O.C.R values from each method showed good agreement each other except those values from q_u tests below E.L (—) 10m. Since O.C.R values from q_u tests below E.L (—) 10m are less than 1.0, q_u values were not used for any kind of practical purpose.

Fig.4. Typical soil profile at Khor Al-Zubair and physical properties of Khor Al-Zubair clay

LAYOUT OF THE STRUCTURE OF THE JETTY AT PROPOSED SITES

As previously described, all of harbors in the Republic of Iraq are situated along the Shatt Al-Arab and they are designed using their existing ground. Thus the zone in front of the jetty is dredged to the proposed depth and the back side is filled with sandy soils. Layout of the structure of the jetty at Fao and Khor Al-Zubair are shown in Fig.7 and Fig.8 in which originally existing ground is also shown. As shown in the figure, the proposed dredging depth at Fao and Khor Al-Zubair are E.L (-) 10.5m and E.L (-) 12m respectively, and the thickness of back fill are 2m to 3m in Fao and about 2m

Fig.5. Undrained strength ratio, S_u/p_0 obtained from in-situ vane, CK_0UC_1 , q_u and CK_0UE_1 tests plotted versus elevation

Fig.6. Overconsolidation ratio, O.C.R. obtained from consolidation tests and various undrained shear strength tests plotted versus elevation

in Khor Al-Zubair. Each zone in the figure will be described later.

DETERMINING PROCEDURE OF THE UNDRAINED STRENGTH FOR PRACTICAL USE

In carrying out the stability analysis it is most important how to determine the reasonable strength for it. In this section the determining procedure of the undrained strength of both Fao and Khor Al-Zubair clays for practical use will be discussed.

Fao Clay

When the $q_u/2p_0$ values shown in Fig.3 (b) are compared with the $S_{un(c)}/p_0 (=0.39)$, it can easily pointed out that Fao clay has not been completed in consolidation by its own weight. Actually p_c values obtained from consolidation tests in preboring were smaller than p_0 values ($p_c=0.7p_0$) (Hanzawa, 1977). It is obvious that this problem is very important for the development of Fao jetty in relation to the stability for sliding and for settlement. To make this problem clear, an inquiry regarding to the history of Fao city and the ground set-

Fig.7. Layout of the jetty at Fao

Fig.8. Layout of the jetty at Khor Al-Zubair

tlement in this city was carried out and following facts were obtained : —

(1) Fao city was developed about 200 years ago—it is not normal for clay aged for hundreds of years since deposition should still continue to settle under its own weight.

(2) Ground settlement has not been observed in Fao city. In addition from the examination of the $S_{u(v)}$ values, it was suggested that Fao clay cannot be in an underconsolidated state and that the underconsolidation must have been produced by a special geotechnical property of this clay. Thus two kinds of consolidation tests were performed in check boring as follows : —

(a) Standard consolidation tests in which each consolidation load was applied by doubling the previous load.

(b) Special consolidation tests in which consolidation loads approximating p_0 were applied in small increments.

p_c values obtained from both tests are shown in Fig.9. As illustrated p_c values from the standard tests also indicated that Fao clay is in the underconsolidated state, however, p_c values from the special tests showed good agreement with, or were slightly higher than the values of p_0 , which is corresponding to the results obtained from the inquiry previously described.

Following three points were suggested from the consolidation tests results : —

(3) Fao clay is seriously disturbed and expanded in structure during sampling.

(4) However when the sample is gradually reconsolidated under the same stresses which the sample carried in the field, the structure in the field may be restored.

(5) The undisturbed structure may not be completely restored in the standard tests because of its larger increment in consolidation load.

From these suggestions following important conclusions regarding to the strength of Fao clay for practical use were obtained.

(6) The undrained strength of Fao clay for practical use shouldn't be determined from q_u tests but should be determined from in-situ vane tests.

(7) The strength, $S_{u(c)}$ and $S_{u(e)}$ from CK_0UC_1 and CK_0UE_1 tests are recommended for the compression and the extension strength for practical use.

Next problem regarding to the determination of strength of Fao clay is how to deal with the undrained strength ratio, S_u/p_0 . When $S_{u(v)}/p_0$ values for each boring point is expressed by a single value throughout the stratum, following $S_{u(v)}/p_0$ values were obtained.

No. A	$S_{u(v)}/p_0 = 0.26$	} Eq. (3)
1	" = 0.33	
2	" = 0.33	
3	" = 0.30	

The following problems should be pointed out : —

(8) It is questionable to express the $S_{u(v)}/p_0$ value by a single value in such a thick layer.

(9) How to determine, for practical use, the strength value of this clay from above expressions.

In the authors' opinion the following two points should be considered in determining the strength of Fao clay.

(10) Such thick layer cannot be entirely homogeneous throughout the stratum. That is, the strength cannot be expressed by a single $S_{u(v)}/p_0$ value throughout the stratum.

(11) Since the stratified conditions of this clay is very flat, it can be suggested that all clay deposited at the same elevation must possess very similar geotechnical properties.

In view of this, $S_{u(v)}/p_0$ values were plotted versus elevation, which was already shown in Fig.3(a). As illustrated it can be clearly be seen that the values are not the same throughout the stratum and $S_{u(v)}/p_0$ values shown by the solid line in the figure were used to obtain the $S_{u(v)}$ values for practical use.

As shown in Fig.7, Fao jetty is subjected to excavation to the depth of (—) 10.5m elevation in front of the jetty. Thus clay in front of the jetty is decreased in strength. The strength decrease due to the stress release is uniquely determined from the overconsolidation ratio, O.C.R (Nakase et al., 1971). To obtain the strength decrease due to

Fig.9. Comparison of preconsolidation pressure, p_c values obtained from the standard and the special consolidation tests on Fao clay and their relations to the effective overburden pressure

Fig. 10. Change in the undrained strength with overconsolidation ratio, O.C.R. of Fao and Khor Al-Zubair clays obtained from CIRIUC tests

Fig. 11 Change in the undrained strength ratio with time to failure for Khor Al-Zubair clay

excavation, a series of CIRIUC tests in which the specimens were first isotropically consolidated under a pressure considerably greater than p_c , then isotropically rebounded under various pressures at different O.C.R. and finally was brought to shear by compression, was carried out. Strength change with O.C.R., S_{u0}/S_{un} -O.C.R. relationship obtained from this tests is shown in Fig. 10.

From these discussions and tests results, it was finally concluded that the undrained strength of Fao clay for practical use should be determined as follows:—

(12) Since Fao clay is seriously expanded during sampling, q_u value should not be used but $S_{u(v)}$ value which is the strength under the field stress conditions should be used for practical problem.

(13) $S_{u(v)}$ values are obtained using the solid line shown in Fig. 3(a).

(14) The strength of clay subjected to excavation is obtained from S_{u0}/S_{un} -O.C.R. relationship shown in Fig. 10.

(15) $S_{u(c)}$ and $S_{u(e)}$ are obtained by multiplying strength ratio shown in Eq. (1) by $S_{u(v)}$ as follows:—

$$S_{u(c)} = 1.27 S_{u(v)}$$

$$S_{u(e)} = 0.95 S_{u(v)}$$

Khor Al-Zubair

Geotechnical properties of Khor Al-Zubair clay are shown in Fig. 4, 5, 6, 10 and 11. Following notes may be pointed out:—

(16) The undrained strength ratio, S_u/p_0 is higher in upper part and decreases with increasing depth.

(17) Strength ratio between various strengths are as follows (Fig. 5)

$$S_{u(c)} = 1.43 S_{u(v)}$$

$$S_{u(e)} = 0.55 S_{u(c)} = 0.78 S_{u(v)}$$

$$S_{un(c)}/p_0 = 0.355$$

$$S_{un(v)}/p_0 = 0.25$$

(18) This clay is an overconsolidated clay with overconsolidation being higher in upper part and decreasing with depth. O.C.R. values from various kinds of undrained strength tests and consolidation tests show good agreement each other (Fig. 6).

(19) Undrained strength of Khor Al-Zubair clay is almost independent on the strain rate at which the clay is brought to failure (Fig. 11).

As already reported (Hanzawa, 1977), the overconsolidated state of Khor Al-Zubair clay was not caused by geologic stress release but may be caused by another factors such as aging effects, capillary forces and seepage forces. Now let us divide the strength into two components, S_{u1} and S_{u2} resulting from the effective overburden pressure and from the other factors described above respectively.

The procedure is as follows : —

(20) S_u/p_0 values are obtained from Fig.5.

(21) When this value at a proposed depth is $S_{u(v)}/p_0$, S_{u2}/p_0 may be shown by " $S_{u(v)}/p_0 - S_{un(v)}/p_0$ ". The ratio between S_{u1} and S_{u2} versus elevation obtained with this operation is shown in Fig.12. It is not evident that strength resulting from other factors than p_0 is maintained or not when clay is subjected to stress release.

When this problem is treated from practical view point, following two methods are probably possible : —

(22) S_{u2} is independent on the stress release, that is, strength after rebound, S_{u0} is expressed as below.

$$S_{u0} = \alpha S_{u1} + S_{u2}$$

(23) S_{u2} is dependent on the stress release and follows the S_{u0}/S_{un} -O.C.R relationship.

$$S_{u0} = \alpha (S_{u1} + S_{u2})$$

α = strength ratio between S_{u0} and S_{un} at a corresponding O.C.R.

From these discussions and tests results, it was finally concluded that the undrained strength of Khor Al-Zubair clay for practical use should be determined as follows : —

(24) The undrained strength ratio are obtained using Fig.5. When a value corresponding to $S_{u(v)}$ is obtained, $S_{u(c)}$ and $S_{u(e)}$ values are obtained by multiplying strength ratio shown in Eq. (3) by $S_{u(v)}$ as follows.

$$S_{u(c)} = 1.43 S_{u(v)}$$

$$S_{u(e)} = 0.78 S_{u(v)}$$

(25) The strength of clay subjected to excavation is obtained by the two methods described in (22) and (23).

Fig.12. Comparison of strength ratio between S_{u1} and S_{u2} and their distribution with elevation

RESULTS OF STABILITY ANALYSIS

Preconditions in Stability Analysis

In the previous sections, the undrained strength characteristics and the determining procedure of the undrained strength of Fao and Khor Al-Zubair clays for practical use were described. In this section the results of stability analysis for sliding of both jetties will be reported and discussed. Before the results are reported, various preconditions used in stability analysis will be described as follows : —

- (1) Circular arc method was used in stability analysis.
- (2) The resistance of foundation piles and sheet piled walls was neglected.
- (3) Strength increase resulting from consolidation due to back fill was neglected because additional load with back fill was relatively small as shown in Fig.7 and Fig.8.

(4) Slopes of both Jetties were divided into zone A to zone G and zone A to zone I for Fao and for Khor Al-Zubair respectively as shown in Fig.7 and Fig.8. The strength of each zone were represented by the strength at the center part of each zone.

(5) The $S_{u(v)}$ values of each zone were first obtained using $S_{u(v)}/p_0$ -elevation relationship shown in Fig.3(a) and Fig.5.

Fig.13. Diagrammatic showing of the method in using $S_{u(c)}$ and $S_{u(e)}$ for stability analysis in this paper

(6) When the zone is the one subjected to excavation, $S_{u(v)}$ values were corrected by the use of S_{u0}/S_{un} -O.C.R relationship.

(7) When $S_{u(c)}$ and $S_{u(e)}$ are used, they were obtained by multiplying the strength ratio shown in Eq. (1) and (2) by $S_{u(v)}$ for Fao and for Khor Al-Zubair clays respectively.

(8) As already reported (Bjerrum, 1973 ; Ladd and Foott, 1974), relevant laboratory tests results should be used for stability problems. Thus

Fig.14. $S_{u(v)}$ and $q_u/2$ values of each zone shown in Fig.7 plotted versus elevation

$S_{u(c)}$ and $S_{u(e)}$ were used for the right side and for the left side of the center of the circle as shown in Fig.13. Shear strength, $S_{u(s)}$ should be used for the area in which $S_{u(s)}$ is mobilized (Bjerrum, 1973 ; Ladd and Foott, 1974) (see Fig.13), however, shear tests were not carried out in this investigation so that such technique above described was adopted.

(9) Residual and low water level adopted in the stability analysis were as follows

Fao Jetty R.W.L = +3.0m L.W.L = ± 0.0 m

Khor Al-Zubair Jetty R.W.L = +5.0m L.W.L = ± 0.0 m

(10) Unit weight of soils and internal friction angle of back fills were as shown in Fig.16 and 17.

The vane strength of each zone for both jetties are shown in Fig.14 and Fig.15 in which $q_u/2$ values obtained from Fig.3(b) and the strength for two cases described in (22) and (23) are also shown for Fao and for Khor Al-Zubair respectively.

Results of Stability Analysis for Sliding

Stability analysis of the jetty at Fao and Khor Al-Zubair were carried out using circular arc method for two cases without and with surcharge ($2t/m^2$). The undrained strength used in the analysis were as follows: (1) $S_{u(v)}$, $q_u/2$, and $S_{u(c)}$ and $S_{u(e)}$ for Fao and (2) $S_{u(v)}$, and $S_{u(c)}$ and $S_{u(e)}$ for Khor Al-Zubair.

In this section of the paper the results of stability analysis will be discussed and evaluated also considering the results obtained in the field observation. Fig.15 and Fig.16 show the

Fig.15. In-situ vane strength a) $\alpha S_{u1(v)} + S_{u2(v)}$ and b) $\alpha(S_{u1(v)} + S_{u2(v)})$ of each zone shown in Fig.8 plotted versus elevation

Fig.16. Results of stability analysis of the jetty at Fao for sliding

Fig.17 Results of stability analysis of the jetty at Khor Al-Zubair for sliding

results of stability analysis for sliding of the jetty at Fao and Khor Al-Zubair respectively. Examining the factor of safety shown in both figures, following notes will be pointed out : —

Fao Jetty

(1) Minimum factor of safety, $S.F_{min}$ from $q_u/2$ values were 0.684 and 0.606 for both cases without and with surcharge.

(2) $S.F_{min}$ from $S_{u(v)}$ were 1.244 and 1.098 for both cases in surcharge.

(3) $S.F_{min}$ from $S_{u(c)}$ and $S_{u(e)}$ were 1.432 and 1.264 for both cases in surcharge.

Excavation and backfilling at Fao Jetty were terminated on Dec.1976 and field observation has been made up to the present time.

(4) During this observation the symptom of sliding has not been observed except that the top of sheet piled wall showed about 20cm displacement in maximum (this displacement was mostly terminated on March 1977).

(5) Thus it should be concluded that S.F from $S_{u(v)}$, and from $S_{u(c)}$ and $S_{u(e)}$ show good correspondence with the actual one.

Khor Al-Zubair Jetty

(6) $S.F_{min}$ from $S_{u(v)}$ was 1.156 in the case of surcharge=0.

(7) When surcharge is $2t/m^2$, the center of the circle giving $S.F_{min}$ moved and a value of 1.025 was obtained.

(8) $S.F_{min}$ from $S_{u(c)}$ and $S_{u(e)}$ were 1.466 and 1.262 for both cases in surcharge.

Excavation and backfilling were terminated on Dec. 1976 at some parts of this jetty and field observation has also been made up to the present time.

(9) During this observation the symptom of sliding has not been observed and only a few displacement was observed at L-shaped bulk head shown in Fig.8.

(10) If S.F from $S_{u(v)}$ is corresponding with the actual one, it could be thought that the displacement must show such values obviously observed in the field survey.

(11) Thus it might be suggested that S.F from $S_{u(c)}$ and $S_{u(e)}$ probably represents the actual one for Khor Al-Zubair.

CONCLUSIONS

The determining procedures of the undrained strength of Iraqi alluvial clays for practical use and the results of stability analysis for sliding of the jetty at Fao and Khor Al-Zubair, located on the mouth of the Shatt Al-Arab and on her old river channel, were reported.

From the considerations on the undrained strength and on the results of stability analysis (including field observations) following conclusions were obtained : —

(1) The undrained strength of Iraqi alluvial clays distributed along the Shatt Al-Arab should be fundamentally determined from the in-situ vane tests.

(2) Considering the results both of stability analysis and of field observation it was suggested that S.F obtained using $S_{u(c)}$ and $S_{u(e)}$ may better represent the actual one.

NOTATION

CIRIUC=isotropically consolidated and rebounded-undrained compression tests

$CK_0UC_1=K_0$ consolidated-undrained compression tests ($\sigma_{1c}=p_0$)

$CK_0UE_1=K_0$ consolidated-undrained extension tests ($\sigma_{1c}=p_0$)

$CK_0UC_2=K_0$ consolidated-undrained compression tests ($\sigma_{1c}>p_0$)

K_0 =coefficient of lateral earth pressure at rest

O.C.R=overconsolidation ratio

PI=plasticity index

p_0 =effective overburden pressure

- p_c = pre-consolidation pressure
 S.F = factor of safety
 S_u = undrained strength
 S_{un} = undrained strength under a normally consolidated state
 $S_{u(c)}$ = undrained compression strength
 $S_{u(e)}$ = undrained extension strength
 S_{u0} = undrained strength under an overconsolidated state
 $S_{u(v)}$ = in-situ vane strength
 S_{u1} = undrained strength resulting from effective overburden pressure
 S_{u2} = undrained strength resulting from other factors than p_0
 q_u = unconfined compression strength
 wc = water content
 γ_t = unit weight of soils
 α = strength ratio shown by S_{u0}/S_{un} -O.C.R relationship

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(Received June 21, 1978)