Settlement Analyses for Areas of Continuing Subsidence

Études sur les Emplacements où les Tassements sont Continus

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Summary

A particularly complicated type of settlement problem is one which has already progressed over a period of years and which is continuing at an appreciable rate at the time of making the first soil study. The authors describe the procedures used in such a study of settlement in the concrete paved seaplane apron at Coco Solo, Panama Canal Zone. In this case a large, marshy area was covered by two fills, one in 1943 and one in 1948. At the time of borings and soils study (1955), the 80 ft. of compressible clay was 30 per cent consolidated under the first and 23 per cent consolidated under the second fill. The authors show computed past settlements as compared with the observed ones over a period of years and show also the future time–settlement curve.

Sommaire

Le tassement qui progresse déjà depuis plusieurs années et continue encore au moment de la première étude du sol, constitue un problème très compliqué. Les auteurs exposent les méthodes employées au cours d'une étude de la piste d'envol de Coco-Solo, zone du Canal de Panama. Il s'agit ici de deux couches de remblai, la première en 1943, la seconde en 1948 sur une zone marécageuse. Au moment des forages et de l'étude du sol (1955), la couche d'argile compressible, épaisse de 24 m (80 pieds) avait été consolidée à 30 pour cent par le premier remblai et à 23 pour cent par le second. Les auteurs font la comparaison entre les tassements antérieurs calculés et les tassements observés sur plusieurs années et présentent également la courbe de tassement en fonction du temps pour l'avenir.

Introduction

A problem frequently encountered in waterfront construction by the Bureau of Yards and Docks, U.S. Department of the Navy, is that of subsidence within extensive low lying areas of soft soil, covered with several feet of fill. In a few instances during wartime construction it was not expedient to cope with the problems of settlement and settlement studies were made only after the continuance of subsidence over a period of years.

In such cases, one must look both backward and forward in one's analysis to estimate the past and future settlements. Such problems are usually complicated by incomplete records of fill construction and subsequent observed settlements. Even where structures are pile-supported in such areas, settlements may yet cause costly damage to buried conduits and to pavements.

Settlement of Aircraft Parking Apron

General description—A concrete pavement was constructed in 1943 at U.S. Naval Station, Coco Solo, Canal Zone, on fills placed on deep, compressible deposits. The original fill was placed in 1943 and additional fill was added in 1948 after five years of settlement. Fill was placed hydraulically behind a perimeter bulkhead. The settlement study was made in 1955 to determine the magnitude and rate of future settlement as a basis for recommendations for rehabilitating the paved seaplane parking area. The initial pavement and fill elevations were known but no settlement observations were made prior to 1948. The original, natural ground elevation was not recorded and the depth of fill could be estimated only from boring data. The problem of rate of settlement by consolidation was complicated by the placement of two fills at different times and by the fact that so much settlement was already completed. In such cases, meticulous procedures must be supplanted by judgment and experience.

A typical boring is shown by Fig. 1. This shows two distinct clay strata which had different values of the coefficient of consolidation c_v. Locations of undisturbed samples are shown in the figure. The water table was immediately below the pavement and the combined load of pavement and fill was 0·80 tons per sq. ft.

The analytical procedure; general description—The authors have studied many problems of this general nature, one feature being common to all; the analysis is made at a time when a very appreciable amount of settlement by consolidation has already taken place. The approach in each case has differed from those followed in all others.

To simplify the problem of rate of consolidation of the two different clay layers shown in Fig. 1a the two strata are converted to a single stratum having properties identical to one of the two. Thus the lower of the two layers, Fig. 1a, is converted to a layer of the same material as that of the upper layer by decreasing its thickness to compensate for its larger c_v. This procedure is best adapted to the conditions shown in Fig 1a with only one pervious boundary (at the top). The lower firm sandy clay underlying the soft material is impervious and over-consolidated.

Since the time required for any given percentage of consolidation of the compressible soil is inversely proportional to the values of c_v and directly proportional to the square of the thickness, then

$$\frac{H_2^2}{c_{v(2)}} = \frac{H_3^2}{c_{v(1)}} \quad \text{or} \quad H_3 = H_2\left[\frac{c_{v(1)}}{c_{v(2)}}\right]^{\frac{1}{2}} \qquad \ldots.(1)$$

in which H_2 is the thickness of the layer in place and H_3 is its converted thickness. Apply this to the conditions of Fig. 1a and convert the lower layer, having a thickness $H_2 = 44$ ft. and a c_v of 0·12 cm²/min. to a thickness H_3 and a c_v of 0·04 cm²/min. Then

$$H = \text{equivalent thickness} = H_1 + H_3 = 36{\cdot}5 + 44\left[\frac{0{\cdot}04}{0{\cdot}12}\right]^{\frac{1}{2}} = 62 \text{ ft.}$$

Thus the single layer, 62 ft. thick and having a c_v of 0·04, is considered as equivalent in overall rate of consolidation to the two separate layers, Fig. 1a.

Fig. 1a was a typical and also an actual boring at the site. The location of the numbered undisturbed samples are shown here. Fig. 1b shows the division of the entire combined depth of the two strata into depth intervals, ΔH, of variable

Table
Essential data for settlement analysis
Données essentielles pour les etudes de tassement

Sample number	*Estimated initial over-burden pressure* (1943)	*e_1 of sample*	*e_2 of sample*	*ΔH repre-sented by sample*	*Decrease in ΔH from e_1 to e_2 condition*	*e_3 of sample*	*e_4 of sample*	*Decrease in ΔH from e_3 to e_4 condition*	*Consoli-dation of ΔH as of 1955—due to 1943 fill only*	*Consoli-dation of ΔH as of 1955—due to 1948 fill only*	*e_5 of sample*	$\frac{e_1 - e_5}{1 + e_1}\Delta H$
	tons/sq. ft.			ft.	ft.			ft.	%	%		
4	0·050	2·17	1·60	5·0	0·898	1·66	1·62	0·075	95	93	1·60	0·90
5	0·156	2·59	2·00	6·0	0·985	2·19	2·12	0·132	79	73	2·08	0·85
6	0·250	2·13	1·73	6·0	0·768	1·95	1·88	0·142	67	62	1·83	0·58
7	0·370	2·10	1·78	5·0	0·520	2·04	1·97	0·115	50	36	1·91	0·31
8	0·470	1·91	1·65	8·0	0·706	1·91	1·84	0·192	36	17·5	1·81	0·27
10	0·670	2·17	1·92	6·5	0·514	2·17	2·10	0·144	9	0	2·14	0·06
11	0·820	2·47	2·22	15·0	1·085	2·47	2·41	0·259	0	0	2·47	0
13	1·075	1·86	1·70	13·5	0·758	1·86	1·83	0·142	0	0	1·86	0
14	1·195	1·89	1·74	15·5	0·808	1·89	1·85	0·215	0	0	1·89	0
				Total	7·04		Total	1·42			Total	2·97 S from all sources as of 1955

thickness, each ΔH being assumed as having the same voids ratio throughout, as the sample taken from within it. These several depth intervals are shown in column 5 of the table and the corresponding samples are listed in column 1.

Obviously, for any given percentage consolidation of the

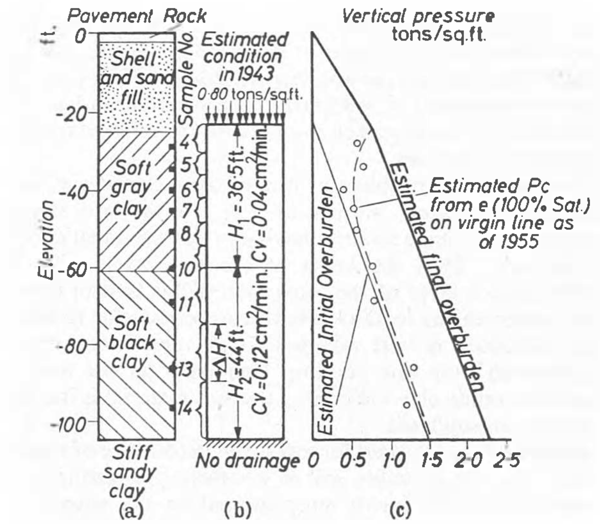

Fig. 1 Typical boring log and pressure diagram
Sondage caractéristique et schéma de pression du sol

62-ft. equivalent layer, occurring in a time, t, in years, according to the expression,

$$t\text{ (years)} = \frac{T_v H_e^2}{c_v} \quad \ldots . (2)$$

those depth intervals nearest to the upper boundary (pervious fill) have consolidated to a greater degree than the lower layers. It is also obvious that since the soil in the upper layers tends to be more compressible than the soil in the lower ones, the percentage of total ultimate *settlement* occurring at any given time subsequent to fill placement differs from the percentage consolidation as a whole, as will be shown.

In equation 2, T_v is the time factor as defined by TAYLOR (1942) and H_e is the thickness of the equivalent layer. Fig. 1c shows the estimated p_c (pre-consolidation pressure) of the samples. In this particular project, the p_c was taken as that value of p in the *e versus* log *p* curve, Fig. 2, at which the samples became 100 per cent saturated. It was not possible to estimate p_c values in this study by the graphical method of CASAGRANDE (1940). In the authors' long experience, undisturbed samples from below ground water level are almost never completely saturated and they become so at points on

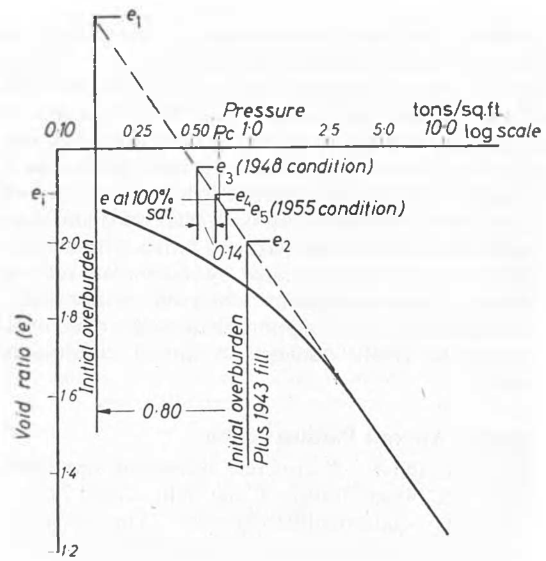

Fig. 2 Typical consolidation test curve
Résultat typique d'essai de consolidation

the *e versus* log *p* curve that are slightly above the points of sharpest curvature. The data of Fig. 1c served in this case to indicate clearly the existence of only one (the upper) pervious boundary and to show that samples nearest to the top in 1955 when the study was made had consolidated appreciably whereas consolidation was barely begun in the lower depth intervals.

Application of the General Procedure

In the analysis of test data, the following actual and hypothetical voids ratios were defined and used.

Defined voids ratios	*Conditions corresponding to defined e*
e_1	The initial e of each sample consolidated by the weight of compressible soil overburden before any fill was placed

e_2	Corresponds to a hypothetical condition; all samples fully consolidated under weight of compressible soil plus 1943 fill
$e_3 = e_1 - (U_v$ of sample in 1948) $(e_1 - e_2)$	Just prior to adding 1948 fill with the soil 18 per cent consolidated by load of 1943 fill
e_4	A hypothetical condition; 18 per cent consolidation completed under 1943 fill and 100 per cent consolidation under 1948 fill
$e_5 = e_1 - (U_v$ of sample in 1955 by 1943 fill) $(e_1 - e_2)$. $e_5 = e_1 - (U_v$ of sample in 1955 by 1948 fill) $(e_3 - e_4)$	Conditions as of 1955, the entire depth of compressible soil in place being 30 per cent consolidated by 1943 fill and 23 per cent by 1948 fill
e_f = ultimate e of samples $= e_2 - (e_3 - e_4)$	Completed primary consolidation under both fills
U_v	Denotes degree of consolidation and varies from 0 to 1.

It was assumed that prior to placing the first fill in 1943, the compressible soil was 100 per cent consolidated under its own weight at all depths and Fig. 1b shows the estimated elevations of strata at this time.

The estimated apportionments of computed past and future decreases of the several ΔH intervals (Fig. 1b and column 5 of the Table) are contained in columns 6 and 9 of the Table and the degrees of completed consolidation (expressed as per cent) of the intervals appear in columns 10 and 11.

For any given degree of consolidation, U_v, of the entire deposit, the distribution of U_v is shown, for example, by a triangular area, ABC, of Fig. 3 which represents intergranular pressure distribution; the area $ACED$ representing pore pressure. Thus at 18 per cent consolidation of the layer as a whole, the horizontal distance, $A'B'$, Fig. 3, is the estimated U_v of sample 5, the condition in 1948, five years after placing the first fill and prior to placing the second. At this time, sample 8 and those below it (Fig. 3) showed no consolidation under this loading.

The ultimate decrease in thickness of each ΔH is obtained thus:

$$\Delta S = \frac{e_1 - e_f}{1 + e_1}\Delta H \quad .... (3)$$

and the sum of all ΔS values is the ultimate settlement by primary consolidation of the entire layer. From the expression,

$$e_f = e_2 - (e_3 - e_4) \quad .... (4)$$

and using the e and ΔH values of the Table,

$$S = \Sigma\Delta S = 8{\cdot}43 \text{ ft.}$$

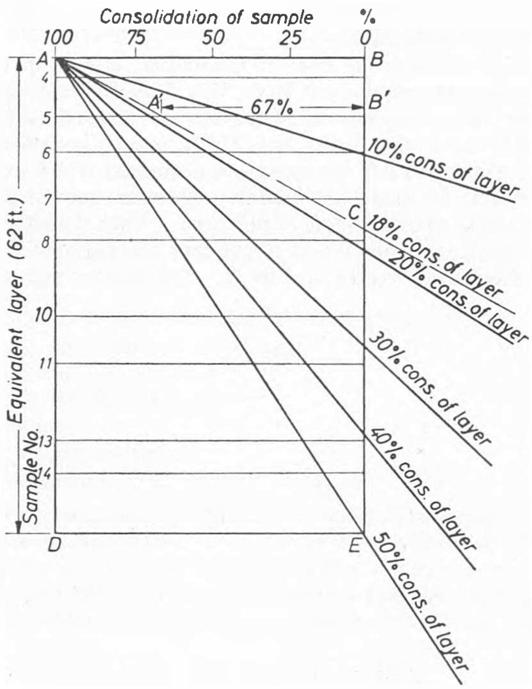

Fig. 3 Approximate method for computing U_v of individual samples corresponding to given U_v values of entire layer

Méthode approximative pour calculer U_v de specimens individuels s'accordant avec la valeur U_v de l'ensemble de la couche

This is very slightly less than the sum, 8·46 ft., obtained by adding the totals of columns 6 and 9 of the Table. The last column of the Table shows computed decreases in ΔH as of 1955 and their sum is 2·97 ft. which is 35·2 per cent of the ultimate settlement.

The problem now is to apportion this settlement to two

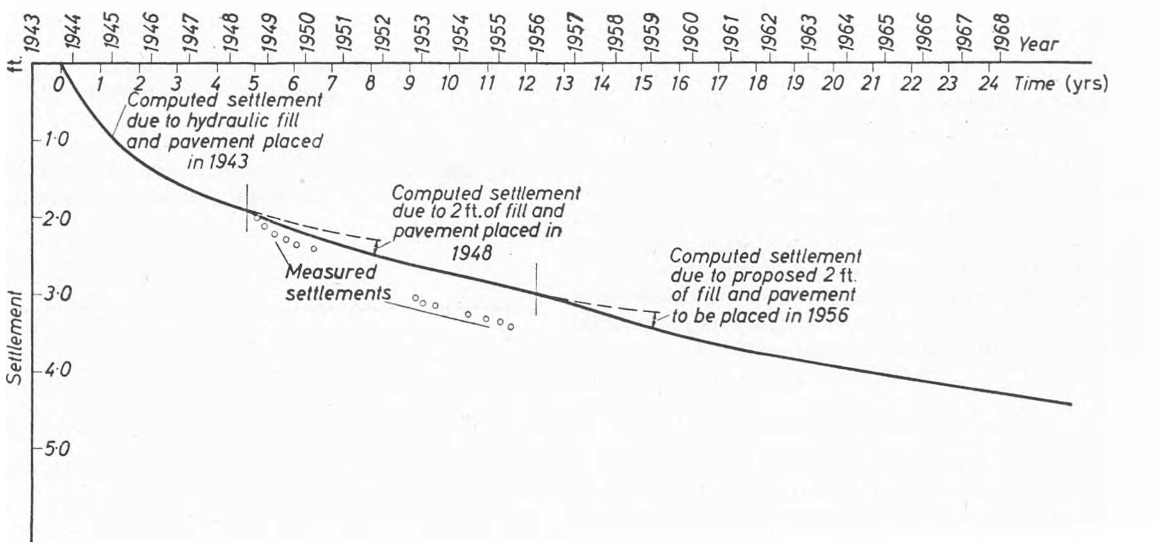

Fig. 4 Composite time–settlement curve

Tassement en fonction du temps (courbe composée) separate causes; the 1943 and 1948 fills. This requires approximate methods since the actual times when filling was accomplished in these years and the durations of filling operations are not known.

The U_v for the entire deposit subsequent to 1948 can be computed separately for each fill load by using equation 2. The U_v under 1943 fill was 18 per cent in 1948 and 30 per cent in 1955. However, these were not the percentages of final settlement as completed on these dates.

Example—Considering 1943 fill load alone, at a U_v of 10 per cent for the entire equivalent layer, Fig. 3, the ΔH represented by sample 5 was consolidated 38 per cent and hence the decrease in this ΔH was $0{\cdot}38 \times 0{\cdot}985$ or 0·374 ft. (see column 6 of the Table). Similarly, ΔH for sample 4 decreased 0·695 and for sample 6, the ΔH decreased 0·20 ft. All other depth intervals had not begun to consolidate at this time. Thus the settlement of the entire layer when it was 10 per cent consolidated was the sum of these three values or 1·09 ft. This is 15·5 per cent of the ultimate settlement (7·04 ft., total of values in column 6 of the Table) caused by the 1943 fill alone. Note that 10 per cent of the ultimate, 7·04 ft., under 1943 fill is only 0·70 ft.

In this manner, settlement *versus* time is plotted as shown in Fig. 4. The procedure is applied separately for each fill; that of 1943, 0·80 tons/sq. ft. and 1948, 0·14 tons/sq. ft. Starting with 1948, Fig. 4, computed settlements for both loads are superposed to continue the curve beyond 1948. The observed settlements made during the period 1948 to 1955 are also shown in Fig. 4. The maximum divergence observed from computed settlements tends to be less than 17 per cent. This is the final test of the validity of the procedure.

References

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