SETTLEMENT AND CRACK OBSERVATION OF STRUCTURES

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SYNOPSIS

In this paper a comparison of computed and observed settlements of actual buildings is attempted for the purpose of making a contribution to the accumulation of similar data. Buildings selected include seventeen apartment buildings, five school buildings and two hospital buildings, all of which are located in Hiroshima city.

In addition, this paper also deals with the problem of crack formation due to differential settlement of the structure.

INTRODUCTION

The theories required for computing the settlements of structures above deposits of soft clay were made available by Terzaghi in about 1925, and many settlement computations have been made since that time on the basis of those theories. Nevertheless, it seems that few attempts have been made for some time to confirm the reliability of such computations under various conditions by making a comparison of computed and observed settlements of actual buildings. To the knowledge of the writer, the bulletin written by Peck and Uyanik is the first comprehensive report dealing with the problem of this nature.

In this report here, the writer attempted to take up the problem of the same nature as written in Peck and Uyanik's bulletin for the purpose of making a contribution to the accumulation of similar data.

Twenty-four buildings in Hiroshima City were chosen as the objects of this investigation, and computed and observed settlements of those buildings were compared. The reasons why the city of Hiroshima was selected as the field of this investigation are:

(1) Under the whole area of this city, subsurface conditions are quite simple and uniform. That is, almost everywhere in this city, the top 10 m. of soil consists of sandy material of medium relative density, and soft silty clay is deposited thereunder down to the elevation of about -30 m. from the ground surface, at which elevation a bed of highly dense gravel is found.

(2) Without anticipation of injurious effect of the underlying soft clay deposit, shallow foundations were formed in the past relying upon the fairly high bearing capacity of the top sandy stratum. As a consequence, a large number of buildings in this city have suffered remarkable settlements over a long period.

(3) The Hiroshima Prefectural Office made available for the writer invaluable information on soil properties and records of observed settlements of many structures in this city.

In addition to a comparison of computed and observed settlements of structures,

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this report also deals with the problem of crack formation due to differential settlement of the structure. Together with the observation of settlement, as many visible cracks as possible in individual structures were carefully observed and recorded. Furthermore, the limits of differential settlement without any formation of cracks in the structure are discussed in the later part of this paper on the basis of these crack observations.

SOIL CONDITIONS AND GEOTECHNICAL PROPERTIES

The city of Hiroshima is located near south-western part of Japan Proper (Fig. 1)

Fig. 1. Location of Hiroshima City

and is seated upon the delta developed by the Ohta River as shown in Fig. 2.

The surface of this delta, having an area of about 20 sq. km., is nearly flat and is at the elevation of 0 to 5 m. above the average sea level except for a few scattered, elevated areas which once were small islands in the sea.

The subsoil of this city has been explored rather extensively up to the present time by means of test borings, and fiftyseven boring logs have been made available for the writer by courtesy of the Prefectural Office as acknowledged above. The writer reviewed those boring logs in detail and ascertained that the top thirty meters of the subsoil consisted of three major strata extending continuously in the horizontal direction with little inclination under almost the whole area of this city. Figs. 3-1 and 3-2 show two representative subsoil profiles which were schematically drawn along N-S and E-W sections, respectively, in Fig. 2 on the basis of above mentioned boring data.

Fig. 2. Map of Hiroshima City; Location of Borings Shown in Fig. 3.

Fig. 3-1. Subsoil Profile Along N-S Section

Fig. 3-2. Subsoil Profile Along E-W Section

The descriptions for these three major strata are:

- (1) The first stratum, which lies just below the top soil down to the depth of about 7 m. in the central part of the city, consists of sandy material with the color varying

from light brown to brownish grey. Grain size of this sand stratum is, in general, intermediate between coarse and fine, and it contains some fine gravel and small shells. The ground water table under this city is at the level of -0.4 m. to ± 0 m. and, therefore, almost the entire stratum is submerged and completely saturated. Natural density, void ratio and degree of saturation of this stratum are as shown in Fig. 4. Number of blows per foot for this sand stratum obtained from standard penetration tests lies between 10 and 15 except near the lower boundary. According to the results of a few bearing tests performed upon the surface of this sand stratum using a loading plate of 45 cm. square, bearing capacity differs in different localities and is within the range of 15 to 30 t. per sq. m.

(2) The second stratum is a deep deposit of soft clayey material extending from the elevation of about -7 m. to the elevation of -27 m.; that is, the thickness is around 20 m. This soil shows a bluish or dark grey color, and smells bad since it contains much of organic matters. Number of blows for this deposit is usually 3 to 4 and various geotechnical properties will be seen in Fig. 4 through Fig. 8.

Fig. 4. Natural Density, Void Ratio and Degree of Saturation of Top Sand and Hiroshima Clay

The characteristics of this soil stratum vary quite widely; however, in general, it is soft, compressible and fairly sensitive to remolding, the sensitivity thereof varying from 4 to 30 in different locations. The comparison between precompression stresses and effective overburden pressures indicates that this deposit is normally loaded. This stratum is usually referred to as Hiroshima Clay in this locality and, evidently, is responsible for the remarkable settlements of heavy structures constructed in this city.

(3) The deposit of Hiroshima Clay is underlain by a highly dense bed of sandy gravel, and the boundary of these two strata is at the depth of 22 m. to 27 m. under the sea level as shown in Fig. 3-1 or 3-2.

BUILDINGS CONSIDERED

As the area of investigation, three blocks in Hiroshima city were selected; they are (1) Hijiya Block, (2) Sendamachi Block and (3) Yoshijima Block.

Fig. 5. Plasticity Chart for Hiroshima Clay

Fig. 6. Unconfined Compression Strength of Hiroshima Clay

Fig. 7. Compression Ratio of Hiroshima Clay

Fig. 8. Relation Between Degree of Consolidation and Time

Settlement observations were made for twenty-four buildings, consisting of seventeen apartment houses, five school buildings and two hospital buildings. All of these buildings are located within each of the three blocks above mentioned.

The name, type of construction, number of stories and elapsed years since the completion of construction up to the date of settlement observation for each observed building are summarized in Table 1.

OBSERVATION OF SETTLEMENTS

In discussing settlements of structures, three different ways of representation of settlement are distinguished in this report and they are referred to as "total" settlement, "differential" settlement and "relative" settlement, respectively.

Suppose that a structure ABCED has made settlement and deformed as schematically shown in Fig. 9 (a) and points A, B and C fixed to the structure have moved to A', B' and C' from each initial position at a date of settlement survey. Then, the magni-

Fig. 9. Representations of Settlement

tude of real settlements shown in Fig. 9 (b) is referred to as “total” settlement.

If, as shown in Fig. 9 (c), the magnitude of the settlements is represented in taking as the reference point one end, say A', of the structure which has experienced the least settlement, it is referred to as “differential” settlement.

Furthermore, it may be possible to represent the settlements in reference to an imaginary line connecting both ends of the settled structure, A' and C', in Fig. 9 (c). The magnitude of settlement thus represented is given in Fig. 9 (d) and is specifically referred to in this report as “relative” settlement. “Relative” settlement is obtained by eliminating the tilt of the structure from “differential” settlement and is directly related to deformation stresses set up in the structure due to the settlement.

Settlement observations of all structures were made by means of a telescopic level placed on the ground surface nearby. Since, unfortunately, no special settlement reference points were set for any structure at the stage of construction, the elevations of the window sill or the base course line at the exterior wall measured at appropriate intervals, and in some cases the elevations of the finished floor surface inside the structure were observed.

COMPUTATION OF SETTLEMENTS

Steps and assumptions taken in determining the amount of settlements by computation are as follows:

(1) It is assumed that the stratum of Top Sand is perfectly incompressible in contrast to far larger compressibility of the underlying deposit of Hiroshima Clay. Consequently, the deposit of Hiroshima Clay is assumed in this report as the only source of settlements of the structures.

(2) Among three principal components constituting the settlement of a structure, only the primary settlement has been computed which is due to squeezing excess water

Table 1. List of Considered Buildings

Block	No.	Name	Type*	Number of Stories		Elapsed Years
				Above Ground	Base-ment	
Hijiyama	1	Hijiyama Apartment House No. 1	C.B.	2	—	6.0
	2	Hijiyama Apartment House No. 2	C.B.	2	—	6.0
	3	Hijiyama Apartment House No. 6	C.B.	2	—	1.5
	4	Minamimachi Apartment House. RA	R.C.	4	—	6.2
	5	Minamimachi Apartment House. RB	R.C.	4	—	6.2
	6	Minamimachi Apartment House. RC	R.C.	4	—	6.2
	7	Minami High School, North Building	B.	3	—	41.5
	8	Minami High School, Center Building	B.	3	—	41.5
	9	Minami High School, South Building	B.	3	—	41.5
Sendamachi	10	Faculty of Physics Building, Hiroshima University	R.C.	3	—	25.0
	11	Attached Elementary School Building, Hiroshima University	R.C.	3	—	18.0
	12	Hiroshima Red Cross Hospital, Main Building	R.C.	3	1	15.0
	13	Hiroshima Red Cross Hospital, North Annex	R.C.	3	1	15.0
Yoshijima	14	Yoshijima Apartment House. RD	R.C.	3	—	2.0
	15	Yoshijima Apartment House. No. 4	R.C.	3	—	2.0
	16	Yoshijima Apartment House. No. 5	R.C.	3	—	2.0
	17	Yoshijima Apartment House. No. 9	R.C.	3	—	1.0
	18	Yoshijima Apartment House. No. 10	R.C.	3	—	1.0
	19	Yoshijima Apartment House. No. 11	C.B.	2	—	1.0
	20	Yoshijima Apartment House. No. 13	C.B.	2	—	1.0
	21	Yoshijima Apartment House. No. 16	C.B.	2	—	1.0
	22	Yoshijima Apartment House. No. 18	C.B.	2	—	1.0
	23	Municipal Apartment House. No. 3	R.C.	4	—	1.0
	24	Municipal Apartment House. No. 4	R.C.	4	—	1.0

*C.B: Concrete block construction

R.C: Reinforced concrete construction

B. : Brick construction

from the pores of the soil. The secondary settlement probably caused by readjustment of grain positions to change in stress and the settlement due to lateral displacement of the loaded clay were both disregarded.

(3) For top sand,

unit weight $\gamma=1.64$ t. per cu. m.

submerged unit weight $\bar{\gamma}=0.65$ t. per cu. m.

were used in computations. These values correspond to the average of test results shown in Fig. 4.

(4) Similarly, for Hiroshima Clay, index properties obtained by laboratory tests were averaged and the following values were used for theoretical computations:

submerged unit weight $\bar{\gamma}=0.58$ t. per cu. m.

void ratio $e=1.79$

compression index $C_c=0.65$

In addition, upon the assumption that the deposit of Hiroshima Clay is normally loaded as stated before, the precompression stress is considered equal to the overburden pressure at each elevation.

(5) As to the elevation of the ground water table, the depth of the lower boundary of top sand stratum, and the thickness of Hiroshima Clay deposit, the boring logs obtained from the nearest site of each structure in question were referred to.

(6) In computing the weight of the structure, dead load was estimated from the copies of design for each building, whereas no information was available as to how live load should be dealt with in settlement computations. Nevertheless, just as a matter of convenience, an appropriate value was estimated and adopted in the present discussion as live load for each building so that it might be interpreted as an average, constant load continuously occupying the area covered by the structure and contributing to long lasting settlement of the structure. Although more or less inaccuracy in computed settlements may result from this arbitrary assumption, it is expected not to be so significant since the values of thus assumed live load are far smaller than the dead load for the cases of usual apartment, school or hospital buildings.

When the soil was excavated for the construction of basement, the weight of the excavated soil was subtracted from the building weight.

(7) The building load thus obtained is assumed to distribute uniformly and act upon the soil mass over a plane which is located at the elevation of footing base or, when piles are driven under the structure, at the elevation of pile tip.

(8) The stresses in the mass of soil were computed by means of Boussinesq's equation or Newmark's graphical procedure, wherein the soil was assumed to be elastic, isotropic, homogeneous and semi-infinite in extent and, at the same time, the structure was assumed to be perfectly flexible.

(9) According to the theory of consolidation, the time required for a soil layer to reach a certain degree of consolidation is proportional to the square of the thickness of the layer.

Now let

H : The thickness of a natural soil stratum,

h : The thickness of specimen for consolidation test ($=2.54$ cm.)

- T : The time for a natural soil stratum to reach a certain degree of consolidation,
 t : The time for laboratory specimen to reach the same degree of consolidation

then

$$t = T (h/H)^2 \dots\dots\dots (1)$$

Putting into Eq. (1)

- H = The thickness of Hiroshima Clay stratum at each location
 T = The time elapsing from the construction of each structure to the date of settlement observation,

the time t can be obtained, which, in turn, determines the degree of consolidation U on the basis of Fig. 8.

In connection with this procedure Prof. Ralph B. Peck, University of Illinois, U.S.A., has pointed out to the writer that the relationship given by Eq. (1) is not even approximately valid for highly organic materials such as Hiroshima Clay. However, to the knowledge of the writer, no alternative procedure seems to be available under the present circumstances.

The above series of computations is summarized in Fig. 10 in a tabular form.

$$T = 6 \times 365 \times 24 \times 60 = 3.16 \times 10^6 \text{ min.}$$

$$H = 1600 \text{ cm} \quad h = 2.54 \text{ cm}$$

$$t = 3.16 \times 10^6 \times (2.54 / 1600)^2 = 8 \text{ min.}$$

$$U = 0.65$$

Fig. 10. Computation of Settlements

COMPARISON OF OBSERVED AND COMPUTED SETTLEMENTS

The settlement computations in the above mentioned procedure have been made with respect to every building listed in Table 1 and compared with actually measured differential settlements.

Take the case of Hiroshima Red Cross Hospital Building (Fig. 11) as an example, and then the comparisons between observed (full line) and computed (dash line) settlements are as illustrated in Fig. 12 through Fig. 14. In addition, cracks observed at the exterior walls of the structure are recorded in these figures.

Fig. 11. Plan View of Hiroshima Red Cross Hospital Buildings

Fig. 12. Hiroshima Red Cross Hospital Building, along A-B

Fig. 13. Hiroshima Red Cross Hospital Building, along C-D

Fig. 14. Hiroshima Red Cross Hospital Building, Along E-F

The review of these results of comparison with respect to all twenty-four buildings has indicated that

- (1) for some buildings the computed settlements show good agreement with the observed ones,
- (2) for other buildings, however, there are fairly large discrepancies between observed and computed settlements,
- (3) in general, it may be said that the magnitudes of observed and computed settlements are of the same order.

In order to make the comparison a little more quantitatively, let us refer to Fig. 15 where the relative settlement profile of a structure is schematically shown for illustra-

Angle of deformation between points i and $i-1$

$$\theta_i = \frac{\delta_i(\text{obs}) - \delta_{i-1}(\text{obs})}{L_i}$$

Ratio of observed and computed settlements

$$\alpha = \frac{1}{n-1} \sum_{i=1}^{n-1} \frac{\delta_i(\text{obs})}{\delta_i(\text{com})}$$

Fig. 15. Ratio of Observed and Computed Settlements and Angle of Deformation

tion. Suppose that the relative settlements were observed at points 1, 2, 3,, $n-1$ and the relative settlement curve was obtained as shown by solid broken line.

First, at a certain point i , the ratio of observed relative settlement δ_i (OBS) to computed one δ_i (COM) is determined. Then such ratios at every individual points are averaged throughout the structure to obtain the index α ;

$$\alpha = \frac{1}{n-1} \sum_{i=1}^{n-1} \frac{\delta_i(\text{OBS})}{\delta_i(\text{COM})} \dots\dots\dots (2)$$

which may roughly represent the extent of agreement between observed and computed relative settlement profiles of the structure.

The value of this averaged ratio α for each investigated structure is collectively plotted in Fig. 16. In Fig. 16, the ordinate is the ratio α and the abscissa is the number of story of the structure. White circle represents the ratio α for the structure of concrete block construction, which lies within the range of 0.6 to 1.1; while black circle represents the ratio α for reinforced concrete structures, which is in the range of 0.2 to 0.7.

It is a well known fact that, in spite of the assumption of perfect flexibility of the structure in theoretical settlement computations, actual buildings have more or less rigidity, and that the structural rigidity has an effect of reducing the magnitude of the relative settlement from what is computed under the assumption of perfect flexibility.

On the other hand, it will not be out of order to presume that a taller building possesses larger vertical rigidity than another lower building; hence, in Fig. 16, the number of story on the abscissa was used as a simple measure of structural rigidity.

Fig. 16. Comparison of Observed and Computed Settlements

It will be immediately seen from Fig. 16 that the settlement ratios for concrete block constructions are definitely larger than those for reinforced concrete constructions, presumably, because of two reasons; (1) the lower height of investigated buildings of concrete block construction, and (2) the lower rigidity essential to concrete block construction itself when compared with reinforced concrete.

Another finding in these settlement observations is that the settlement of the structure is evidently reduced where the basement is constructed as shown, for instance, in Figs. 12, 13 and 14. This fact is quite significant in the sense that it has verified the concept of "effective" stress increment in the mass of soil and, at the same time, it provides a mean of reducing or eliminating the settlement of a structure to be constructed upon the compressible soil stratum.

LIMITING DEFORMATION OF STRUCTURE FOR CRACK FORMATION

Observed settlement profiles of actual buildings have evidently shown that the differential settlement of a structure consists of two components of different nature; the tilt of the structure as a rigid body and the deformation of the structure as a flexible body. The latter has been referred to as "relative" settlement in this report as defined previously in Fig. 9, and, obviously, it constitutes the origin of deformation stresses set up in the structure.

As the relative settlement of a structure advances, the deformation of the structure is increased. In the meantime, if the deformation at a portion of the structure exceeds a certain critical value, formation of cracks occurs at that portion. Information on limiting deformation of a structure at which the structure is cracked, in other words, the extent to which a structure can safely be deformed without formation of any crack, will be a matter of direct concern for both structural and foundation engineers.

To discuss the problem of this nature on the basis of settlement observation data, refer to Fig. 15 again.

In order to represent the extent of deformation at a portion of the structure, we now compute the slope of this relative settlement line at the corresponding portion. For instance, the value of θ_i indicated in Fig. 15 is computed by

Fig. 17. Angle of Deformation Critical to Crack Formation in Reinforced Concrete Construction

$$\theta_i = \frac{\delta_i (\text{OBS}) - \delta_{i-1} (\text{OBS})}{L_i} \dots\dots\dots (3)$$

and is used as an index to represent the extent of deformation of the structure at the interval between i and $i-1$.

The slope θ thus computed is referred to in this report as "angle of deformation".

Then, a cross mark or a small circle is plotted for each observation interval of all reinforced concrete structures corresponding to whether the interval is cracked or not, respectively; Fig. 17 has been thus obtained.

It might now be possible to estimate, if any, the limiting angle of deformation for crack formation in reinforced concrete structures. In the range between two lines indicated by upper limit and lower limit in Fig. 17, the ratio of the number of points for "cracked" to "not cracked" is 17 to 16, while in the range above the upper limit line the ratio is 24 to 5 and in the range below the lower limit it is 6 to 18. Then it might be roughly concluded that the most probable value of critical angle of deformation would lie between these two limiting lines, that is,

$$\theta_{\text{critical}} = 1 \sim 2 \times 10^{-3} \dots\dots\dots (4)$$

for reinforced concrete structures.

Two essential inaccuracies will be pointed out in relation to the above reasoning:

- (1) It is unknown whether observed cracks were formed due to the settlement as assumed in this paper or due to some other causes such as shrinkage or temperature stresses, and
 - (2) the effect of openings in the observed exterior walls is not taken into account in estimating the above critical value.
- With respect to the first question, it

should be emphasized that, in general, the amounts of relative settlements observed in the structures under discussion were as large as might have overwhelmed other causes of crack formation. As to the effect of openings, any detailed discussion seems to be impossible under the present situation.

In 1954 the writer made a series of shearing tests of reinforced concrete full walls to investigate their behaviors under the action of lateral forces. The size of eleven tested walls was 2.70 m. $\times$ 1.90 m. with the thickness of 6, 8 and 10 cm. As one of the results of this series of tests, an information was obtained that crack was formed when the angle of deformation in the range of

$$\theta_{critical} = 0.13 \sim 0.27 \times 10^{-3} \dots\dots\dots (5)$$

was reached.

If this value is compared with the limiting angle of deformation in Eq. (4), it will be learned that the latter is only a small fraction of the former.

As the cause of such a difference of crack-resisting capacities under both conditions, following matters may be pointed out:

- (1) Since the deformation of the structure due to the settlement occurred slowly in quite a long time, flow of concrete accompanied the deformation making the material more plastic, whereas shearing forces were applied upon test specimens quite rapidly by means of a testing machine.
- (2) Some fraction of actually observed settlement occurred during or immediately after the construction of the structure before the concrete was not completely solidified; and, therefore, actual stresses set up in the structure are not so large as expected to correspond to the amount of total deformation.
- (3) While pure shear was applied to test specimens, effects of both shearing and

Fig. 18. Angle of Deformation Critical to Crack Formation in Concrete Block Construction

bending deformation are involved in the concept of angle of deformation for actual buildings ; hence, in a strict sense, θ 's in Eq. (4) and in Eq. (5) are of somewhat different implication, so that they are not to be directly compared.

In Fig. 18 are plotted similar data for structures of concrete block construction. Within the range between two lines indicated as upper and lower limit, the ratio of "cracked" to "not cracked" is 9 to 10 ; in the range above the upper limit line, the ratio is 17 to 4 ; and below the lower limit line, it is 5 to 12. Then, it may roughly be concluded that, as to the value of angle of deformation critical to crack formation in concrete block construction, the same expression holds as Eq. (4).