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Experimental Study on the Method of Rebound and Recompression Deformation Calculation in Deep and Large Foundation Design

Etude expérimentale sur la méthode de calcul des déformations de résilience et de recompression pour les fondations larges et profondes

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ABSTRACT: By analyzing the data from the consolidation-rebound-recompression test of in-situ soil, bearing test, model experiment and field measurement test, the calculating methods of rebound and recompression deformation are proposed, which based on stress history of ground soil, the loading and unloading conditions. Some conclusions can be drawn: i) the progress of rebound deformation exhibits three-phases characteristics, and the critical unloading ratio could be used to determine the calculating depth of rebound deformation; ii) the recompression deformation of foundation soil can be computed as two-phase mode, in fact, the controlled deformation emerges when the reloading ratio exceed the critical reloading ratio; iii) the recompression deformation is larger than rebound one, and the increase proportion varies with different kinds of soil; iv) in actual constructions, the parameters of rebound and recompression deformation can be gotten by compression-rebound-recompression test on in-situ soil of corresponding depth in the site, or bearing test in site that include the process of load-unload-reload. Then the recompression deformation can be calculated by using the parameters responding to the real stress history. According to model experiment and in-situ tests, the calculated rebound and recompression deformation has a well agreement with measured datum, and the accuracy of predicted deformation is improved.

RÉSUMÉ : Par une analyse de données d'essai de compression sur sol intact, de test de portance, d'expérimentation à grande échelle, et de mesure faites in situ, il est possible de proposer une méthode de calcul des déformations de résilience et de recompression pour fondation profonde et large sur la base de l'histoire des contraintes (conditions de chargement et déchargement lors de l'exécution des travaux). Les résultats importants de cette étude se synthétisent comme suit: 1. l'évolution de la résilience et de la recompression du sol de fondation se caractérisent par trois phases et la profondeur de résilience calculée peut être utilisée pour déterminer celle de profondeur critique; 2. La déformation de recompression du sol de fondation est calculée en deux phases; en fait au cours de la réalisation des travaux les grandes déformations se produisent durant la phase où la charge excède la recharge critique; 3. La valeur de la déformation globale de recompression est supérieure à celle de déformation de résilience; 4. Dans un cas réel de réalisation des travaux, le calcul de déformation de recompression de sol de fondation se fait suivant les paramètres recueillis de l'épreuve dite compression-rebond-recompression avec un échantillon du sol original prélevé in situ par sondage à une profondeur convenable, ou de l'essai s'applique in situ soit chargement-déchargement-rechargement sur le bloc de charge du sol de fondation, avec ces paramètres de résilience et de recompression, on peut procéder au calcul de déformation dans l'état réel des chargements de travaux. L'affirmation des résultats de l'essai de modèle et de l'épreuve in situ, les paramètres obtenus par calcul de déformation de résilience et de recompression correspondent bien à ceux recueillis par les essais in situ; dans ce cas-là, on peut dire que la précision de prédiction de déformation est acceptable.

KEYWORDS: deformation control design, rebound-recompression deformation, critical depth, critical reloading ratio.

1 INTRODUCTION

In the past decades, with the developing of engineering technique, building foundation engineering in china shows some new features such as bulky, deeply buried, large load differences, multiple-storey buildings or high-rise buildings built on the basis of the same large area raft foundation. For this kind of buildings, the deformation-controlled foundation design is very important, and some deformation index should be pay more attention to prevent structure from cracking or damaging, such as overall deflection of main buildings, differential settlement between the main and podium buildings, etc. In the process of construction and normal service of this kind of buildings, the foundation soil deformation usually includes rebound deformation of foundation soil caused by the excavation of deep foundation pit, recompression deformation and consolidation deformation caused by additional stress. The deeper the foundation buried, the proportion of recompression deformation to total settlement is larger. So the calculation of foundation deformation is more complicated. There are some mature methods to calculate consolidation deformation caused by additional stress, but the reasearch and calculating method to rebound-recompression deformation are seldom reported. In this paper, the calculating methods of rebound and recompression deformation are proposed by analyzing the data from the consolidation-rebound-recompression test of in-situ soil, bearing test, model experiment and field measurement test. According to model experiment and in-situ tests, the calculated rebound and recompression deformation has a well agreement

with measured datum, and the accuracy of predicted deformation is improved.

2 THE LAW OF REBOUND AND RECOMPRESSION DEFORMATION

2.1 The Law of Rebound Deformation

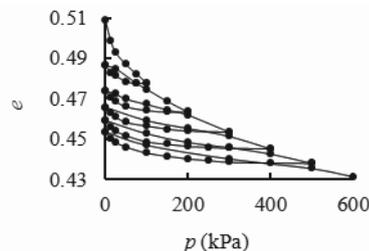


Figure 1. The typical $e-p$ curves of soil.

The typical $e-p$ curves of soil by the consolidation-rebound-recompression test are shown as figure 1. The basic law of rebound deformation under unloading condition and recompression deformation under reloading condition, usually can be described by some parameters such as unloading ratio R , modulus of resilience E_c , rebound ratio, critical unloading ratio R_{cr} , limit unloading ratio R_{lu} , and some new parameters^[1, 2] such as rebound proportion, reloading ratio R' , recompression ratio r' are proposed, and some relation curves can be used to analyze

rebound deformation and recompression deformation, such as the relation curves of unloading ratio-rebound proportion, the relation curves of unloading ratio- modulus of resilience, the relation curves of reloading ratio-recompression ratio etc.

(1) The relation curves of unloading ratio-rebound proportion
In the process of unloading, figure 2 shows that: i) as the unloading ratio is less than 0.4, the rebound deformation is less than 10% of the total rebound deformation; ii) as the unloading ratio increases to 0.8, the rebound deformation is about 40% of the total one; iii) as the unloading ratio increases from 0.8 to 1.0, the rebound deformation is about of 60% of the total one. So unloading ratio is the key influencing factor of rebound deformation.

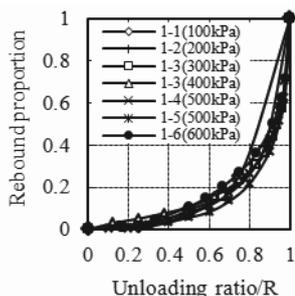


Figure 2. The relation curves of unloading ratio-rebound proportion of clay soil sample

(2) The relation curves of unloading ratio-modulus of resilience
The modulus of resilience is not a constant, see Figure 3. It varies with the unloading ratio and exhibits three-phase characteristics. For the soil of the same depth, the modulus of resilience is varied according to the excavation depth. The relation curves of $R-E_c$ can be divided into two line segments, see figure 3(a), and the unloading ratio of intersection of the two line segments can be defined as critical unloading ratio R_{cr} . When $R < R_{cr}$, E_c increases sharply and rebound deformation could be negligible. The relation curves of $R- \lg E_c$ also can be divided into two line segments approximately, see figure 3(b), and the intersection point of the two line segments can be defined as limit unloading ratio R_{li} . When $R > R_{li}$, E_c decreases sharply and the most rebound deformation occurs.

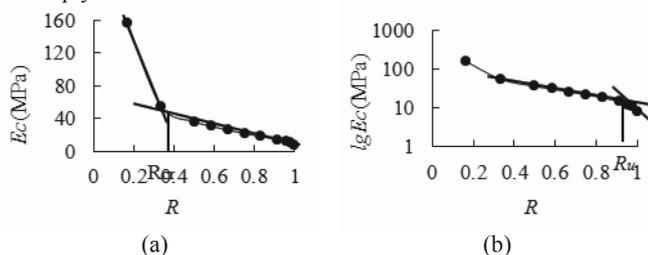


Figure 3. The relation curves of $R-E_c$ and $R-\lg E_c$ of clay soil sample

The relation curves of unloading ratio-modulus of resilience can be used to determine the calculation depth of rebound deformation. In calculation, the depth of R_{cr} can be calculated. The rebound deformation beneath the depth is negligible, and rebound deformation of this depth can be calculated. The rebound deformation result meets the requirements of engineering.

2.2 The Law of Recompression Deformation

(1) The relation curves of reloading ratio-recompression ratio^[3]
In the process of recompression, the curves of reloading ratio-recompression ratio of clay soil, see figure 4, shows that: i) as the reloading ratio R' is 0.2, the recompression deformation is about 40% ~60% of rebound deformation; ii) as the reloading ratio increases to 0.4, the recompression deformation is about 70% of rebound deformation; iii) as the reloading ratio increases to 0.6, the recompression deformation is about 90% of rebound deformation; iv) as the reloading ratio reaches 0.8, the

recompression is roughly equal to the rebound deformation; v) for this kind of soil, as the reloading pressure is equal to the unloading pressure, the recompression deformation is 1.2 times to the rebound deformation. A large amount of testing data show that, the recompression deformation is not equal to the rebound deformation in value as the reloading ratio is equal to 1.0. Generally the recompression deformation is larger, and the increase proportion of deformation varies with different kind of soil^[4].

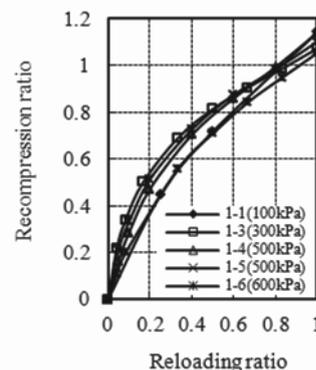


Figure 4. The curves of reloading ratio-recompression ratio of clay soil

2.3 Verification by Model experiment

In order to verify the law of rebound and recompression, the model experiment was carried out in the laboratory of Institute of Foundation Engineering, China Academy of Building Research. In the model experiment, soil deformation was monitored during excavating and backfilling. The dimension of the test pit is 13.0m×5.3m, the excavation depth is 3.5m, and the backfilling depth is about 3.5m. Rigid measure points were installed into the soil in different depth to measure the deformation during the model experiment^[1, 5, 6].

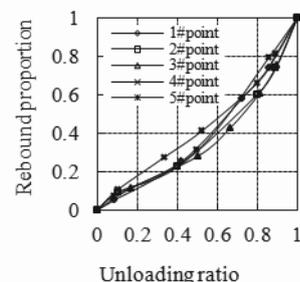


Figure 5. The curves of unloading ratio-rebound proportion of soil at the bottom of excavation

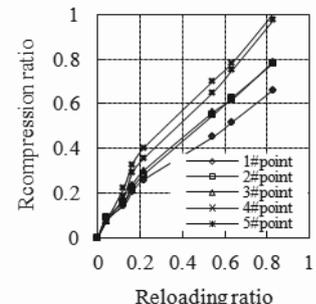


Figure 6. The curves of reloading ratio-recompression ratio of soil at the bottom of excavation

The curves of unloading ratio-rebound proportion of soil at the bottom of excavation, see figure 5, reflect the similar law of rebound deformation with curves of soil tests, but the curves are relatively flat, compared with the curves of soil tests. In the process of backfilling, the curves of reloading ratio-recompression ratio of soil show as figure 6. The recompression deformation of soil can be divided into two line segments, and the reloading ratio of the intersection point of the two line

segments is about 0.2, similar as the law of soil tests. As the reloading ratio is still low, the recompression deformation is obvious. As the reloading ratio of soil at the bottom of excavation increases to 0.8, the recompression deformation is roughly equal to the rebound deformation.

3 THE CALCULATION METHOD OF REBOUND AND RECOMPRESSION DEFORMATION

3.1 The Calculation Method of Rebound Deformation

The systematic analyzing method of rebound deformation is as follow^[1]:

- i) get no less than 6 samples for each solum by investigation, and then obtain the basic data of soil by consolidation-rebound-recompression test;
- ii) analyz the data by graphing curves of unloading ratio-rebound proportion and curves of unloading ratio- modulus of resilience, determine the value of R_{cr} ;
- iii) determine the calculation depth of rebound deformation according to R_{cr} , divide the calculation depth to several layers, and calculate both unloading ratio R and modulus of resilience E_c of every layer;
- iv) calculate rebound deformation of every layer and add them together to get the total rebound deformation.

The rebound deformation can be calculated as formula 1:

$$s_c = \sum_{i=1}^n \frac{p_c}{E_{ci}} (z_i \bar{\alpha}_i - z_{i-1} \bar{\alpha}_{i-1}) \quad (1)$$

Where :

- s_c - rebound deformation of foundation soil, mm ;
- p_c - gravity of soil upon foundation base, kPa , buoyancy should be deducted underneath ground water;
- E_{ci} - modulus of resilience, it can be determined from soil test directly or calculated from the relation curves of $R-E_c$ and $R-lgE_c$;
- n - number of layers which the calculation depth is divided;
- z_i, z_{i-1} - distance between foundation base and the bottom of No. i , No. $i-1$ layer ;
- $\bar{\alpha}_i, \bar{\alpha}_{i-1}$ - additional stress coefficient of No. i , No. $i-1$ layer.

In this method, both E_c and R_{cr} must be determined by corresponding stress state of soil and stress history. This method is not only simplifying the process of calculation but also improving accuracy.

3.2 The Calculation Method of Recompression Deformation

According to the law of recompression deformation, the recompression deformation can be calculated as formula 2^[7]:

$$s'_c = \begin{cases} r'_0 s_c \frac{p}{p_c R'_0} & p < R'_0 p_c \\ s_c [r'_0 + \frac{r'_{R=1.0} - r'_0}{1 - R'_0} (\frac{p}{p_c} - R'_0)] & R'_0 p_c \leq p \leq p_c \end{cases} \quad (2)$$

Where:

- s'_c - recompression deformation of foundation soil, mm ;
- s_c - rebound deformation of foundation soil, mm ;
- r'_0 - the critical recompression ratio. The curves of reloading ratio-recompression ratio of soil can be divided into two line segments. The recompression ratio of intersection of the two line segments is critical recompression ratio, and its value can be determined in the curves of reloading ratio-recompression ratio from soil test;
- R' - the critical reloading ratio. Similar to r'_0 , the reloading ratio of intersection of the two line segments is critical reloading ratio, and its value also can be determined in the curves;

$r'_{R=1.0}$ - The value of recompression ratio, when $R'=1.0$. it is equal with the increase proportion of recompression deformation.

4 ENGINEERING APPLICATION

In Beijing there is a 20-storeyed building with 4-storeyed basement. The foundation area is about 6000 m^2 , and the excavation depth is 19.1m. In the process of the building's construction, research on rebound and recompression deformation was carried out by Institute of Foundation Engineering China Academy of Building Research. Rebound deformation was monitored during the excavation, and settlement was also observed in the process of construction.

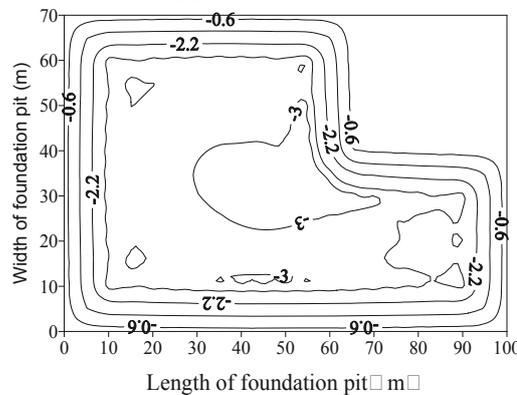
4.1 Calculation of Rebound Deformation

According to the data of soil tests, the expression of $R-E_c$ and $R-lgE_c$, and the value of R_{cr}, R_u of soil can be determined. For example, for sample 1-3: $R_{cr}=0.33, R_u=0.92$, and the expression of $R-E_c$ is listed in table.1.

Table 1 The expression of $R-E_c$ of sample 1-3

Condition of R	expression
$0 < R \leq 0.33$	$E_c = 257533.3 - 386300R$
$0.33 < R \leq 0.92$	$E_c = 181009.2 - 165111.8R$
$0.92 < R \leq 1.0$	$E_c = 219419.9 - 203110.2R$

The rebound deformation can be calculated as formula 1. The calculated deformation contour of the foundation pit shows as figure 7. The rebound deformation of the foundation pit is not the same, the maximum of rebound deformation is 35 mm in the center of foundation base, and it reduces gradually to 6 mm at the edge of foundation base. The measured rebound deformation is about 32 mm.



4.2 Calculation of Recompression Deformation

For this foundation pit, the estimating unloading stress is about 353.35kPa. For the main buildings, since the pressure under the foundation is larger than unloading pressure, the settlement of foundation soil includes both recompression deformation and consolidation settlement. Recompression deformation can be calculated as formula 2. Firstly the curves of reloading ratio-recompression ratio of soil can be obtained by soil tests. By analyzing the curves, the expression of reloading ratio-recompression ratio can be determined and listed in table 2.

Table 2 The expression of reloading ratio and recompression ratio

NO.	Pressure (kPa)	Condition of R'	expression
1-3	300	$0 < R' \leq 0.125$	$r' = a_1 + b_1 R'$ $a_1 = 0.0541 \quad b_1 = 2.8726$
		$0.125 < R' \leq 1.0$	$r' = a_2 + b_2 R'$ $a_1 = 0.5173 \quad b_1 = 0.5643$
1-4	400	$0 < R' \leq 0.125$	$r' = a_1 + b_1 R'$ $a_1 = 0.0264 \quad b_1 = 3.551$
		$0.125 < R' \leq 1.0$	$r' = a_2 + b_2 R'$ $a_1 = 0.4206 \quad b_1 = 0.6625$

Estimate the reloading stress of each construction stage according to the construction progress to get the recompression ratio of each stage. Then recompression deformation of each stage can be calculated as table.3. When the reloading pressure is equal to the unloading pressure, the compression deformation is about 36.7mm.

Table 3 The calculating table of recompression deformation under main building in each conditions

NO.	Reloading kPa	Unloading kPa	R'	r'	S _c mm	S' _c mm
(1)	80.3	353.35	0.2272	0.5711	35.0	19.99
(2)	103.4		0.2926	0.6144		21.50
(3)	134.9		0.3818	0.6735		23.57
(4)	145.4		0.4115	0.6932		24.26
(5)	176.9		0.5006	0.7522		26.33
(6)	218.9		0.6195	0.8310		29.08
(7)	250.4		0.7086	0.8900		31.15
(8)	302.9		0.8572	0.9885		34.60
(9)	318.9		0.9025	1.0185		35.65
(10)	334.9		0.9478	1.0485		36.70

The consolidation settlement caused by additional stress is calculated by the layer-wise summation method recommended by Code for Design of Building Foundation^[7]. By calculating, the consolidation settlement is 10.24mm. So the final settlement of the main building is 46.94 mm.

Usually the settlement of foundation is observed after raft foundation construction, and observation points are set on the raft foundation, so the recompression caused by gravity of raft foundation can't be monitored. According to the basic law of recompression deformation, the recompression deformation cannot be ignored, when reloading stress is low. The recompression deformation caused by gravity of raft foundation can be calculated as No. (1) in table 3. In this stage of construction, since the concrete strength of foundation had not formed completely and the superstructure had not constructed generally, there is no additional stress caused by the recompression deformation.

The settlement curves of calculation and observation of the main building are shown as Figure 9, and the line of dashes shows the calculated final settlement. Both the calculated settlement and monitored settlement have the same development tendency, but the calculated settlement is little higher than the corresponding one monitored.

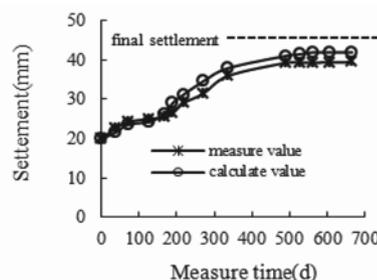


Figure. 9 the developing curves of settlement from calculating and measuring of main building

5 CONCLUSIONS

Through the soil test, model experiment and engineering application, the conclusion of rebound and recompression deformation can be summarized by the following clauses:

- (1) The dimensionless parameters such as rebound proportion, reloading ratio, recompression ratio are proposed and used in research, and the basic law of rebound deformation and recompression deformation can be got, and then the calculation methods of rebound deformation and recompression deformation are put forward. Mathematical relation between rebound and recompression deformation is established;
- (2) R_{cr} can be determined by the curves of $R-E_c$, and the calculation depth of rebound deformation can be calculated according to R_{cr} . E_c must be determined by corresponding stress state of soil and stress history. This method is not only simplifying the process of calculation but also improving accuracy.
- (3) The calculation method of recompression deformation proposed by this paper can compute deformation of each construction stage.
- (4) In initial stage of construction, the reloading stress is low, but the deformation is obvious. Meanwhile, the concrete strength of foundation had not formed completely and the superstructure had not constructed generally, so there is no additional stress caused by the recompression deformation. It is beneficial for the deformation control.

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