Experimental and Theoretical Static Analysis of High-Speed Railway Bridge Settlement for Deep Soft Soil

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Abstract: This paper is a study of Beijing-Shanghai high-speed railway and measuring the settlement values of the Bridge with the time and load. The structure is safe to carry the applied loads. The settlement is measured using the single point of settlement account meter and calculated using the norm codes. The results showed a new field measurement method to calculate the compressed layer thickness which is considered as a difficult task to monitor in the field. The final results calculated for the settlement of the pile foundation needed correction of factors to be conservative for the measurement of the project. The correction factors are proposed to modify the codes calculation within the permissible ranges.

Keywords: Bridge engineering, compressed layer thickness, correction factor, designed codes, high-speed railways.

1. INTRODUCTION

Observational data of Beijing-Shanghai high speed railway line project are obtained under the settlement monitoring [1, 2]. Accurate calculations of the settlement of soft ground in the modern soil mechanics and foundation engineering need to solve the major problem of settlement. Therefore, the current specifications of various settlement formulas require correction factor to adjust through experience, and will limit its application within a certain range. Such as “Building Foundation Design Code” (GB50007-2002), the empirical coefficient value is 0.2~1.4 [3]. Whereas, the TB10002.5-2005 code is between 0.4~1.2 [4].

The determination of the thickness of the deep compression under deep pile foundation based on domestic and commercial level according to the experience of the authors is still not beneficial. By the different control criteria to determine the deep pile foundation having soft deep compression layer, the thickness is different. This leads to the settlement difference between calculated and measured values. Specifications of various formulas mentioned the settlement is modified by empirical coefficients to calculate the value of settlement, and limited to a certain range of applications, and the correction factor used varies with a great experience [3, 4]. It can be seen only by the empirical formula that the settlement check meets the design and construction requirements.

Current practice for pile design varies and codes differ between countries as well as within countries, indeed, even between individual engineering disciplines. The references do not become apparent until the designer includes the effect of settlement [5]. In the United States, Bridge Engineers use the code of AASHTO, namely, “American Association of State Highway and Transportation Officials”, and this code can be adopted for designing the high speed railway bridges with special requirements [6]. China has formed a set of sophisticated theory, technology and standard for high-speed railway subgrade foundation reinforcement and settlement control [7]. It is necessary to perform an analysis of comparison of the results with different codes. In this study, four codes will be adopted for the analysis, i.e.:

1. AASHTO-LRFD Bridge Design Specifications (2007) [6].
2. The Chinese National Standard (CNS, 2002) (GB50007-2002) [3].
3. TB 10002.5-2005/J 464-2005, Code for Design on Subsoil and Foundation of Railway Bridge and Culvert, Chinese code [4].
4. Technical Code for Building Pile Foundation JGJ 94–2008 [8].

The four codes will be used to perform analysis for the settlement of bridge foundation, and the similarities, differences will be investigated. The settlement is a very important part of the bridge analysis; therefore, the choice of the correction factor and appropriate code will provide conservative way for design, in addition to be the successful analysis of this part means success for the other related requirements [9].

2. MATERIAL AND METHODS

2.1. DK124 Worksite Euipment Layout

Test program in the construction site is done according to the actual situation at the worksite in DK124, piers D18, D19. The soil settlement at the pile end is measured by a single-point settlement gauge and liquid level settlement gauge. Field tests in the worksite started at beginning of June 2009. The installation location of single point of settlement account is shown in Tables **1** and **2** Figs. (**1** and **2**) respectively.

2.2. DK152 Worksite Equipment Layout

Synopsis work is practiced according to the test point in the DK152’s F371, F372 and F373 piers using a single-point

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settlement gauge and liquid level settlement gauge at the project site. Field test of the worksite started at the beginning of March 2009. Single point of settlement account level is shown in Tables **3** and **4**; Figs. (**3** to **5)** respectively.

Table 1. A Single Point of Settlement Account Meter of DK124 Worksite

Single Point of Settlement Position	Depth of Buried Point (m)	Installation Location
D18-4	– 60.5	4.5m under the pile bottom
D18-6	– 65.5	9.5m under the pile bottom
D18-7	– 56.5	0.5m under the pile bottom
D18-9	– 74.5	18.5m under the pile bottom
D19-5	– 58.3	2.3m under the pile bottom
D19-6	– 83.5	27.5m under the pile bottom
D19-7	– 69.6	13.6m under the pile bottom
D19-9	– 78.5	22.5m under the pile bottom
D19-12	– 60.6	4.6m under the pile bottom

Table 2. The Installation Location of DK124 Worksite

Settlement Level Meter	Installation Location
D18	Caps Department, Between piles D18-6 and D18-7
D19	Caps Department, Between piles D19-6 and D19-7

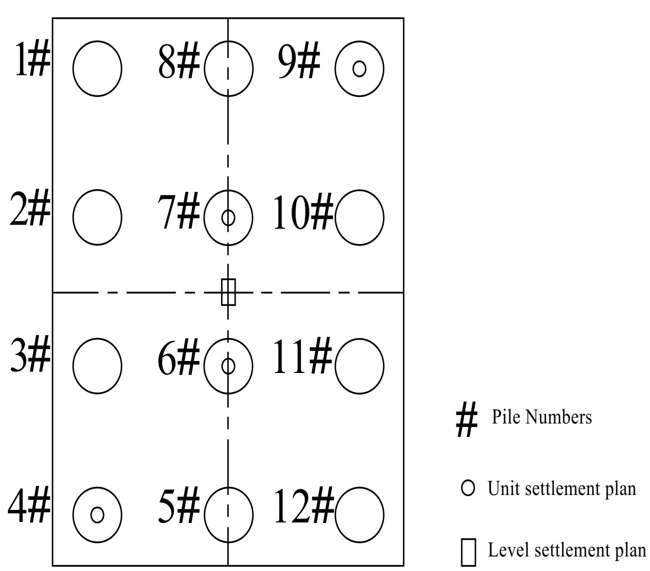

Fig. (1). Layout of D18 cap level of single point of settlement account meter.

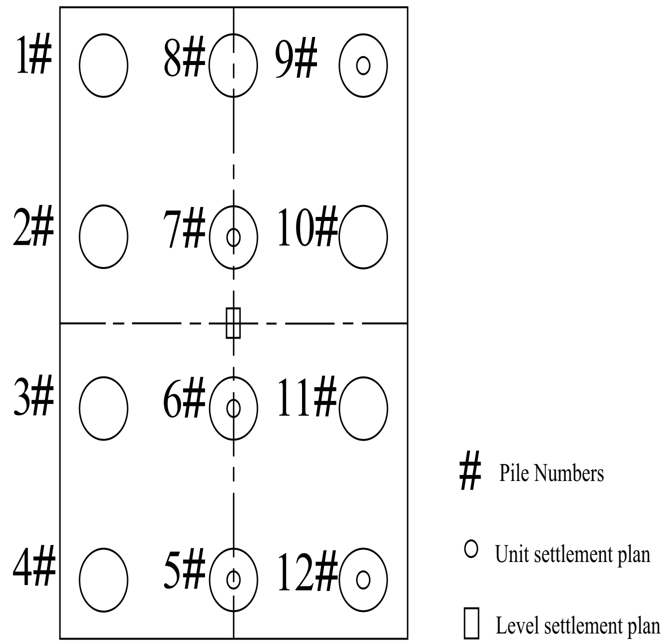

Fig. (2). Layout of D19 cap level single point of settlement account meter.

Table 3. A Single point of Settlement Account Meter of DK152 Worksite

Single Point of Settlement Position	Depth of Buried Point (m)	Installation Location
F371-1	– 55.00	5m under the pile bottom
F371-6	– 60.00	10m under the pile at the bottom
F371-8	– 50.00	Pile bottom position
F372-3	– 70.30	20.3m under the pile bottom
F372-6	– 66.00	16m under the pile bottom
F372 Pile cap center	– 75.35	25.35m under the pile bottom
F373-5	– 52.00	3m under the pile bottom
F373-6	– 76.90	27.9m under the pile bottom
F375-8	– 70.00	21m under the pile bottom

Table 4. The Installation Location of DK152 Worksite

Settlement level Meter	Installation Location
F371	Caps Department
F372	Caps Department
F373	Caps Department

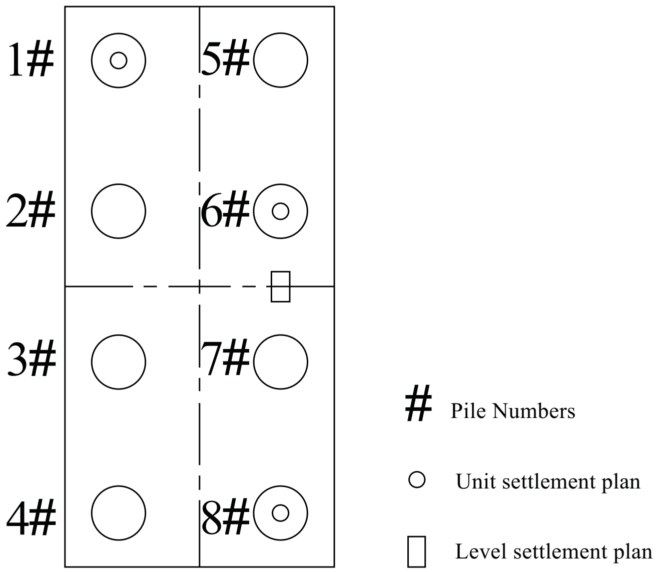

Fig. (3). Layout of F371 cap of single point of settlement account level meter.

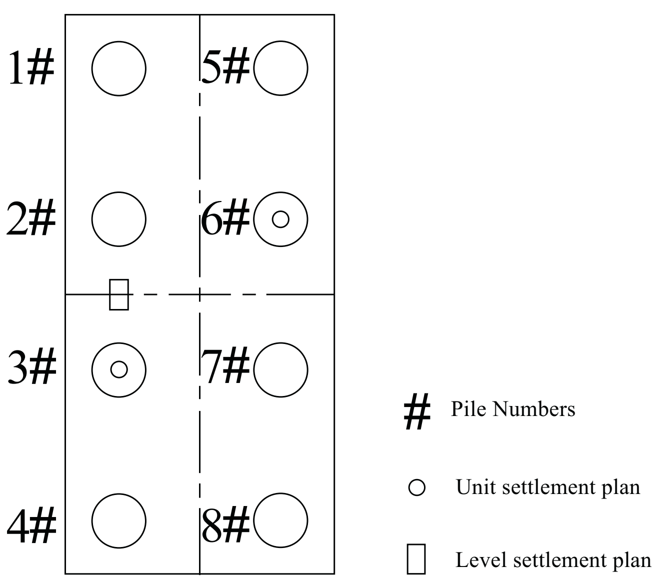

Fig. (4). Layout of F372 cap of single point of settlement account level meter.

3. PROBLEM STATEMENT

Foundation design like other structural design requires a good sound basic approach in order to achieve a genuinely successful result [10]. The stability of the structure depends upon the stability of the supporting soil, the foundation must not settle beyond a tolerable limit to avoid damage of the structure [11]. Structures built on deep soft soils are prone to excessive settlement. A large portion of this settlement is attributed to the consolidation process, which may continue for an extended period depending on the soil's ability to dissipate the excess pore water pressure imposed by the construction loads. The relationship between settlement and time is not linear because a large percentage of settlement usually takes place early in the timeline [12]. The consolidation characteristics of the soil are influenced by numerous factors including the size and shape of the soil particles, the moisture content, permeability, initial density and physical and chemical properties of the soil. Predicting the amount of settlement is possible after the soil characteristics have been determined, and the pressure distribution below the loaded area due to the estimated structural loading [13]. The determination of the compressed layer thickness is considered as a difficult task in the deep soft soils, this problem has been solved for this project using the single-point settlement gauge and liquid level settlement gauge in the field. The other difficulty is to find the suitable way to calculate the settlement using the norms depending on different codes to predict the long term of settlement. The next sections show the analysis results of the settlement obtained from the norms and the need for the correction of factors to match the field measurements. The results of the theoretical calculations are high compared with the field measurement; therefore, the correction factors are needed to modify the results and match the field results, likewise to meet the requirements of the codes according to their specifications.

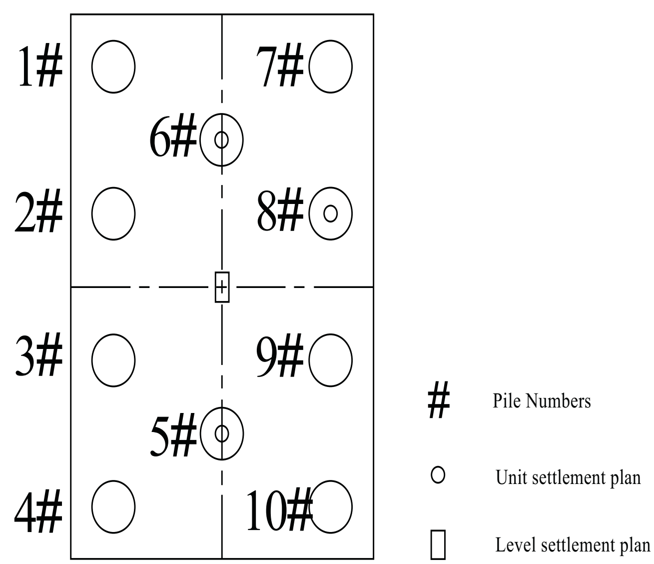

Fig. (5). Layout of F373 cap of single point of settlement account level meter.

4. RESULTS AND DISCUSSION

4.1 Field Test Data Analysis

Tables **5** and **6** summarise the results of the compression readings in the field within the compressed soil layers. The standard of adjacent measurement based points on each meter of soil compression is between 0.1mm and less. Therefore, from Tables **5** and **6**, it can be estimated that the thicknesses of the compressed layers equal to 9.5m and 10m for DK124 and DK152 worksites respectively. The monitoring is done using the single-point settlement gauge and liquid level settlement gauge to find the compressed layer thickness which is considered a difficult task in the deep soft soils.

Table 5. DK124 Worksite Compression Results for Compressed layer (Piers D18 and D19)

Location (m) (under the pile tip)	Compression (mm)			Average compression (mm)	Compression per meter between adjacent measurement points (mm)
	2010-10-24	2010-11-21	2010-12-6		
0.5	2.72	2.72	2.71	2.72	5.43
2.3	3.12	3.14	3.13	3.13	0.23
4.5	4.28	4.28	4.28	4.28	0.52
4.6	4.41	4.42	4.42	4.42	1.37
9.5	4.86	4.86	4.87	4.86	0.09
13.6	5.15	5.16	5.18	5.16	0.07
18.5	5.10	5.11	5.12	5.11	~0.0
27.5	5.56	5.58	5.58	5.57	0.05

Table 6. DK152 Worksite Compression Results for Compressed Layer (Piers F371 and F372)

Location (m) (under the pile tip)	Compression (mm)			Average compression (mm)	Compression per meter between adjacent measurement points (mm)
	2010-10-24	2010-11-21	2010-12-6		
0.5	4.12	4.13	4.13	4.13	8.25
5	5.94	5.95	5.93	5.94	0.40
10	6.38	6.39	6.39	6.39	0.09
20.3	6.49	6.51	6.51	6.50	0.01
25.35	6.55	6.56	6.58	6.56	0.01

The compression readings during the bridge construction are measured at the pile tip with different level gauges, as shown in Fig. (**6**) for pier No. 18 at worksite DK124. The negative sign indicates the direction of the settlement. The readings showed that the compression increases but sometimes decreases overtime after the completion of girder construction. This may be attributed to the fact that the foundations are backfilled during the monitoring of points on the piers. Unfortunately, at various times during construction, the survey reference points are either obstructed or filled over before reference elevations could be obtained by surveying multiple points [14].

Fig. (**7**) shows the relationship between settlement and the reading times for different depths during the application of construction loads of piers No. 18 and 19 at worksite DK124. Fig. (**8**) shows the same relationships for piers F371, F372 and F373 at worksite DK152. The results of the field tests at worksite DK124 show a maximum settlement of 7.0mm at pier D18 and 7.1mm at pier D19, while at worksite DK152, the maximum settlements at piers F371, F372 and F373 are 9.0mm, 8.7mm and 8.1mm, respectively.

From Figs. (**7** and **8**), it can be seen that the settlement-load-time curve can be divided into three segments. When the load is less than 5MN, the settlement of the pile cap increases to the amount of about 4mm for piers at DK124 and 7mm for piers at DK152. When the load increases from 5MN to 17MN at DK124 and from 5MN to 10MN at DK152, the settlement of the pile cap reaches 6.5mm and 8mm respectively, with an increase of 100%. When the load increases from 17MN to 20MN for DK124 and from 10MN to 15MN for DK152, the increase of the settlement of the pile cap is small; the settlement becomes stabilized and the total settlement is approximately 7mm for piers at DK124 and 9mm for piers at DK152.

The above results show that the maximum settlement values measured by field testing are within the limits allowed by the standard specifications. The code for "200 kilometre per hour passenger railway interim design provisions" specifies an allowable settlement of 50 mm [15]. The foundations for simply supported deck bridges are frequently designed for differential settlement relative rotations of up to 1/800 (40mm in a 32m span). In reasonably homogeneous soils, differential settlements between adjacent foundations are often assumed to make up half of the total settlement [16]. Thus, the total measured settlements of the bridge are less than the allowable settlement under these criterions.

4.2 Theoretical Analysis of Settlement by Using Different Codes

The results can be obtained through the application of the settlement equations shown in Appendices A, B, C and D.

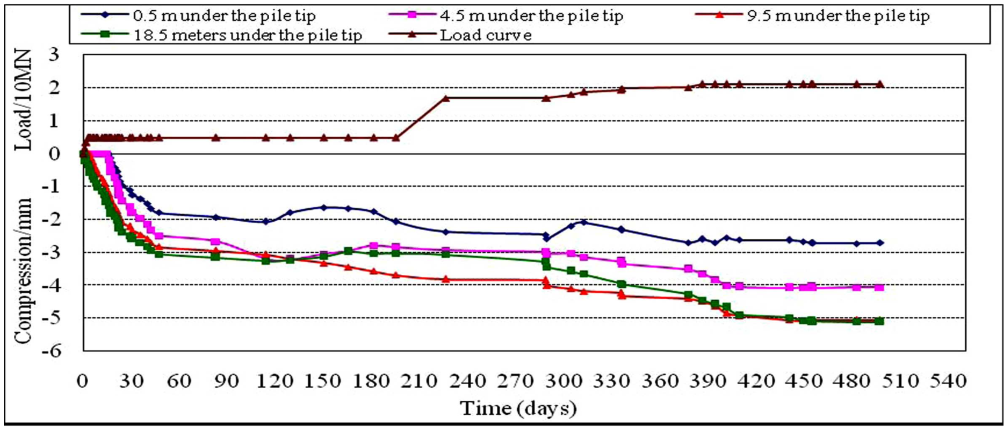

Fig. (6). Compression settlement of pier D18 at DK124.

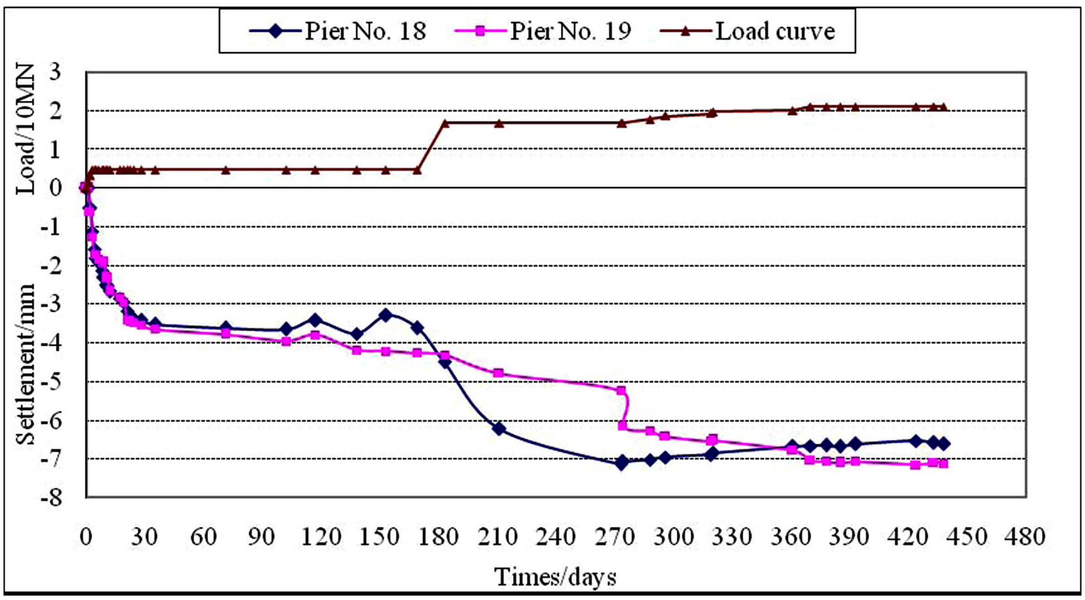

Fig. (7). Compression settlement of piers D18 and D19 at DK124.

The required calculations depended on the available data of the soil and the information from design. Therefore, the results have been included in the following sections:

4.2.1 Calculation of Settlement Using the Chinese Code (CNS, 2002) (GB50007-2002)

By applying equation A–1 in Appendix A [3], it can be found that the settlement values due to the total construction load equal to 33.603mm for the piers in DK124 worksite, whereas, it is equal to 18.198mm for the piers in DK152 worksite. These values are within the permissible limits of the settlement mentioned previously.

4.2.2 Calculation of Settlement Using the AASHTO Code

The estimation of the settlement by the AASHTO code is calculated using equations B–1 and B–2 shown in Appendix B [6]. By applying the standard procedure and the calculations, the results of the settlement due to the total construction load can be found. The value of settlement is equal to 48.126mm for DK124 worksite, whereas it is 32.766mm for DK152 worksite, piers F371 and F372.

Results of the settlement using the above code are higher than that calculated using the Chinese Code (CNS, 2002). This may be attributed to the AASHTO code that started the calculations from the two-third of the pile foundation depth reaching to a depth by which the settlement and additional stress values become very small. The settlement values calculated by AASHTO code are high compared with the maximum allowable settlement for AASHTO code (C10.6.2.6.1) for bridge foundations which limit it to be not more than 25mm.

4.2.3 Calculation of Settlement Using TB10002.5-2005 Code

The settlement calculated by the TB10002.5-2005 code using the equations from C–1 to C–4 is shown in Appendix C [4]. The results are 56.500mm for DK124 worksite and 44.119mm for DK152 worksite due to the applied construction loads. The values of σ_{z0} according to the properties of soil layer of DK124 worksite are 45.73kPa for DK124 and 63.6kPa for DK152. The settlement equation used in this code can be found as a similar one in the CNS 2002, 5.3.5,

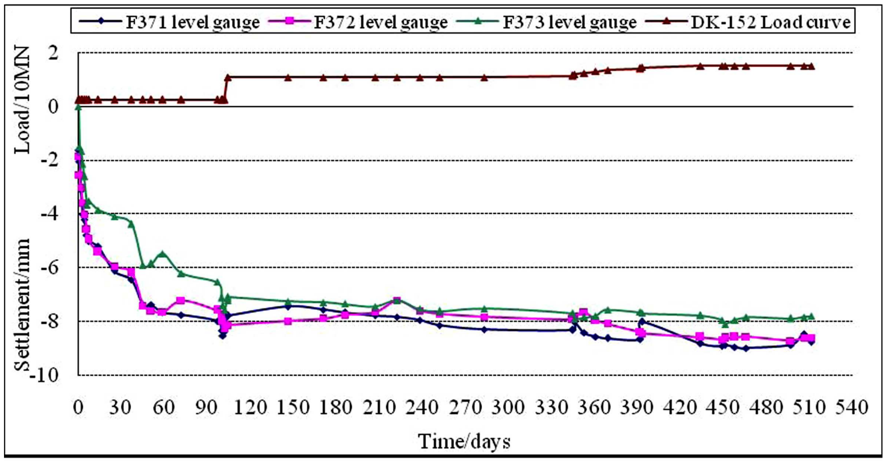

Fig. (8). Compression settlement of piers F371, F372 and F373 at DK152.

where the factor m_s is expressed as ψ_s in the second code. The TB10002.5-2005 code (3.2.1) specifies an allowable settlement of Ballast railways with two requirements: the allowable settlement of a single foundation must not be more than 80mm, while two adjacent foundations may have settlement of not more than 40 mm. Therefore, the settlements calculated due to the constructed loads are within the allowable limits.

4.2.4 Settlement Estimation Using JGJ 94 – 2008 Code

For piled foundation, the pile center distance is no larger than 6 times pile diameter, its final settlement calculated value may adopt equivalent acting layer wise summation methods [8]. Equivalent acting surface is lying on pile tip plane, equivalent active area is projected area of pile cap, and equivalent acting additional pressure is approximately taking average additional pressure of pile cap bottom. Stress distribution under equivalent acting surface adopts isotropy beeline deformable body theory. Computation schema sees Fig. D–1, ultimate settlement calculated value of any point of the pile foundation may be calculated according to the following formulate with angular point method.

The stress control method calculates the compression layer thickness using "Technical Code for Building Pile Foundations" JGJ 94-2008 provisions basement subsidence. Calculation of the compression depth reached to additional stress is less than or equal to the of soil pressure of 20% according to this Code, which is also used to calculate the depth from the substrate surface reaching to additional stress equal to or less than 10% of soil pressure.

5. DISCUSSION OF RESULTS

The final settlement calculated by the equation of (CNS, 2000, R.0.4-8) code is a one way compressive stratified summation method. In addition to, it depends on two factors, first the ratio of pile end resistance α of additional load under the quasi-permanent combination of vertical load effects; second the coefficient of experience ψ_p which should be determined on the basis of the surveying and measuring data of engineering projects in the locality through statistical analysis. By these factors, the calculation of settlement will become close for the reality.

In the AASHTO code, section 10.6.2.4.3., if the footing width, B, is small relative to the thickness of the compressible soil, the effect of three-dimensional loading shall be considered and shall be taken as:

$$S_{c(3\text{-}D)} = \mu_c \, S_{c(1\text{-}D)} \ldots \quad (1)$$

Where:

μ_c = reduction factor taken as specified in Fig. (**B–1**) (Appendix B) (dim.).

$S_{c(1\text{-}D)}$ = single dimensional consolidation settlement (mm).

The settlement readings for the Beijing-Shanghai Bridge show reasonable values and explain the processing of the consolidation with the time of construction. As shown from the above results of the methods applied in this paper, it can be concluded that the values of settlement calculated with different codes will give different results. The higher value of the settlement in the AASHTO and TB10002.5-2005 codes compared with that in the CNS, 2002 code. The CNS, 2002 code gives close results from the field measurements compared with the other two codes. This is maybe attributed that the CNS, 2002 code has many parameters and requirements to be more suitable for the nature of the deep soft soil area. As observed that the values of settlement calculated using norm codes have a high gap from that measured in the field. For the four codes used in this study, it should find a correction of factors according to the filed measurements to modify the calculations of these codes.

6. CONCLUSION

(1) For this experiment, the measured settlements of bridge foundation work points and bottom compression layer thickness measured values are shown in Table 7. Field tests showed that the deep pile support layer compression thickness is closely related to soil properties:

- For the silty sand stratum (σ_0 = 200kPa, Table 7), the value of compressed layer thickness is about 1.2 times the length of the short side;
- For the silty clay stratum (σ_0 = 250kPa, Table 7), the value of compressed layer thickness is about 2.5 times the length of the short side;

Table 7. Summary of the Working Point Thickness Compression Measured Values

Worksite	Bridge Name	Pier No.	Maximum Measured Settlement (mm)	Compressed Layer Thickness Measured, h_s (m)	Pile Outer Contour Length a′× Width b′ (m×m)	h_s/b'
DK124	Tianjin Bridge	D18	7.0	9.5	11.45×8.05	1.18
		D19	7.1			
DK152	Tianjin Bridge	F371	9.0	10	9.4×4	2.5
		F372	8.7			
		F373	8.1	10	9.4×6.1	1.64

Table 8. Summary of the Measured and Calculated of Compressed Thickness of the Working Points.

Compressed Layer Thickness Measured (m)		"Stress Control Method," the Calculated Value (m) Compared with the Measured		"Strain Control Method" the Calculated Value (m) Compared with the Measured
		Stress Ratio ≤20% (JGJ 94-2008)	Stress ratio ≤10% (JGJ 94-2008)	
DK124 worksite D19	9.5	6.59	11.59	15.48
		69.37%	122%	162.9%
DK152 worksite F373	10	7.3	9.64	16.39
		73%	96.4%	163.9%

Table 9. Summary of the Worksite of Measured Settlement and the Calculated Settlement Values

Worksite	Pier No.	Maximum Measured Settlement (mm)	Norms Calculated Settlement (mm)	(Measured/Calculated) Empirical Correction Factor ψ
DK124	D18	7.0	33.603 (CNS, 2002)	0.208
			48.126 (AASHTO, 2007)	0.145
	D19	7.1	56.500 (TB10002.5-2005)	0.123
			44.24 (JGJ 94-2008)	0.158
DK152	F371	9.0	18.198 (CNS, 2002)	0.494
	F372	8.7	32.766 (AASHTO, 2007)	0.274
	F373	8.1	44.119 (TB10002.5-2005)	0.204

(2) Bridge pile compression measured thickness compared with the norms calculated as follows:

In Table **8**, from the points of the bridge pile settlement workers measured compared with the norms calculated can be discussed in the following points:

- Compared with the measured value to 10% of the stress ratio conditions of the "Stress control method", the calculated value come closest to the compression layer thickness, the average is greater than the actual of about 9.2%;
- Compared with the measured value to 20% of the stress ratio conditions of the "Stress control method", compression calculated thickness is too small, the average is smaller than the measured value of about 28.8%;
- Compared with the measured value, "Strain control method", the compressed layer thickness calculated generally too large, the average is greater than the actual of about 63%;
- Stress ratio of 10% is recommended for the formation of experimental work points, bridge foundation, and ap-

propriate for the conditions of the "Stress control method" compression layer thickness.

(3) The measured value of the bridge pile settlement and the calculated values by "strain-controlled method" comparison can be seen in Table 9 as follows:

(4) It can be seen from Table 9, the bridge pile settlement of the experimental worksite is far less than the value of the standardized calculation. The "empirical correction factor" is less than the minimum of the given relevant specification $\psi = 0.2$, but it is a little more from this value and stay within the range of (0.2–1.4) in the other specification codes at DK152 worksite. Therefore, the specifications of correction factors in the code can be modified to start from a value of 0.1 according the results in Table **9**.

(5) In this experiment, a single point settlement account with the level joint monitoring method can meet the deep soil observation points of the settlement and monitoring the amount of compression. A single settlement account with a single point measurement is used to overcome the difficulties, when the base bottom layer cannot be stable anchorage in the soft soil or rock layer be difficult to monitor.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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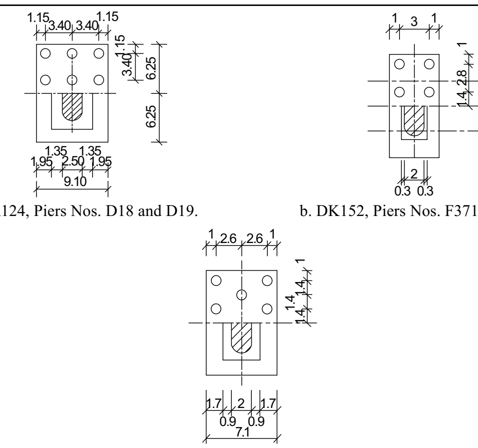
APPENDIX A: SETTLEMENT ESTIMATION USING CHINESE CODE (GB 50007-2002)

The settlement of the pile foundation can be calculated from the following formula (Chinese Code, CNS 2002-R.0.4-8):

$$s = \emptyset_p \frac{Q}{l^2} \sum_{j=1}^{m} \sum_{i=1}^{n_j} \frac{\Delta h_{j,i}}{E_{s,j,i}} \sum_{k=1}^{n} \left[\alpha I_{p,k} + (1-\alpha) I_{s2,k}\right] \qquad \text{(A–1)}$$

Where:

Fig. (**A–1a**) shows that the bridge foundation is a pile foundation located at DK124 worksite for piers D18 and D19 with cap dimensions of 13×9.1m and stepped capping thicknesses of 2.5m and 1.5m. The number of piles is 12 bored piles with a diameter of 1.25m; the spacing between the piles is 3.4m in both directions, length of pile is 52m. The bridge at DK152 worksite as shown in Figs. (**A–1b** and **A–1c**) is supported on reinforced concrete pile groups, which consist of 8 bored piles for F371 and F372 piers and 10 bored piles for F373 pier with a pile diameter of 1.0m for F371, F372 and F373, the pile length is 50m for F371 and F372 and 47m for F373. The caps are rectangular with a length of 10.4m and a width of 5m for F371 and F372 piers, and a length of 10.4m and a width of 7.1m for F373 pier. The caps thickness is 0.55m for the upper cap and 2.2m for the lower cap for F371 and F372, while for F373 is 1.1m for the upper cap and 2.2m for the lower cap. The groundwater levels below the ground surface are 1.4m for D18, 2.3m for D19, 1.6m for F371 and 1.2m for both of F372 and F373. Figs. (**A–2** and **A–3**) are showing the soil layers classification sketches of the Beijing-Shanghai high-speed railway bridges at locations DK124 and DK152 respectively. The span length for the bridge at both worksites is 32m. Tables (**A–1** and **A–2**) show the soil characteristics and strength parameters at the DK124 and DK152 working points.



a. DK124, Piers Nos. D18 and D19.

b. DK152, Piers Nos. F371 and F372.

c. DK152, Pier No. F373.

Fig. (A–1). Sketches of the Beijing-Shanghai high-speed railway bridge piers at locations DK124 and DK152 (All dimensions are in meter).

S	is the final calculated amount of settlement for pile foundation (mm).
ψ_p	is the coefficient of experience of settlement of pile foundation, in the different districts, it shall be determined on the basis of the local measured data through statistical contrast.
Q	is the additional load of single pile under the quasi permanent combination of the vertical load effects.
l	is the length of the pile.
m	is the total amount of soil stratum within the range of compressive stratum under the plane of pile end.
$\Delta h_{j,i}$	is the depth of the i^{th} stratification (m) of the j^{th} stratum soil under the plane of the pile end.
$Es_{j,i}$	is the modulus of compression (MPa) of the i^{th} stratification of the j^{th} stratum soil in the applied segment of the self-weight stress to the self-weight plus additional stress under the plane of the pile end.
n_j	is the stratification number of the j^{th} stratum soil under the plane of pile end.
α	is $\varphi/4$
φ	is the angle of internal friction.

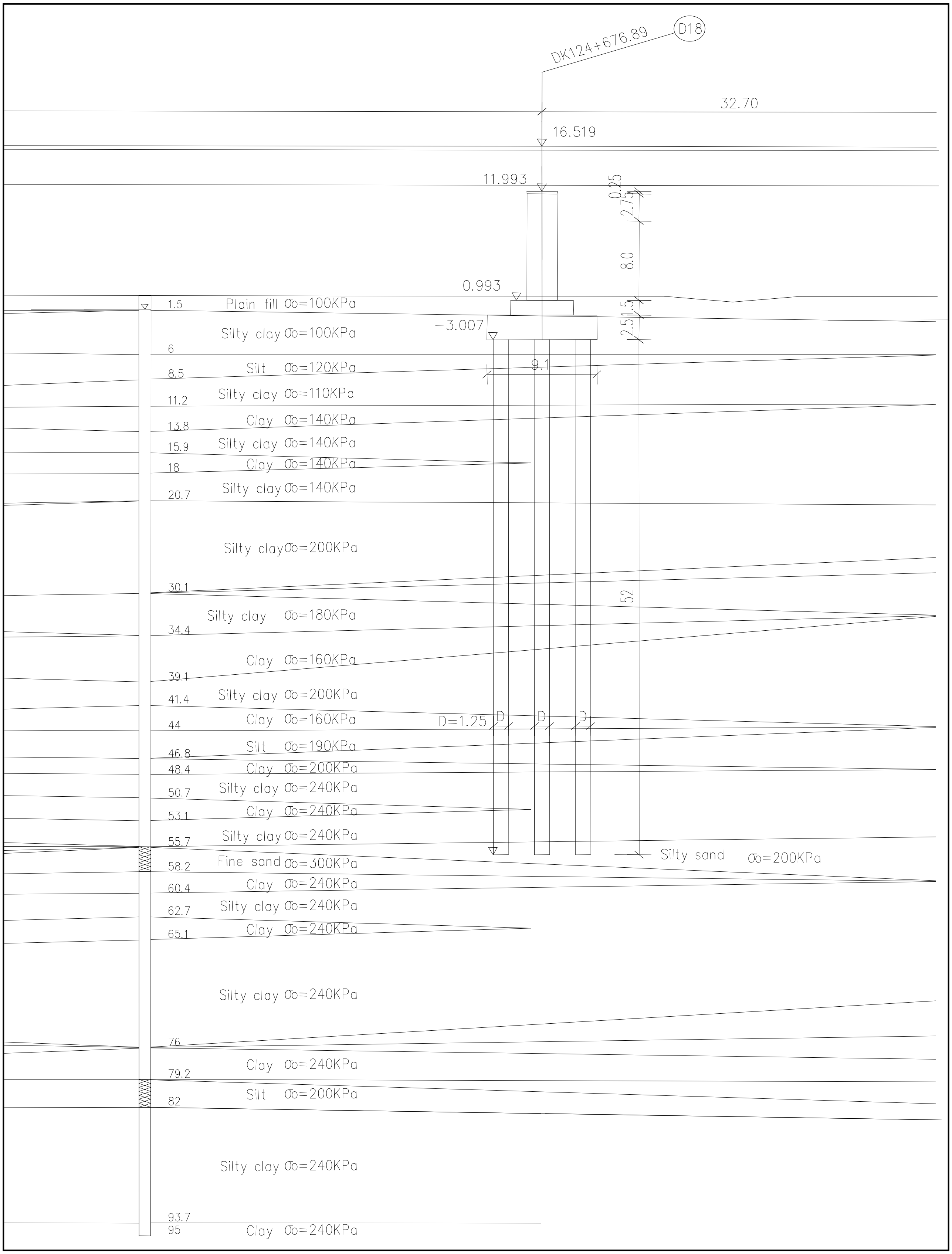


Fig. (A–2). Sketch of the soil layers of Beijing-Shanghai high-speed railway bridge at location DK124, D18 (All dimensions are in meter).

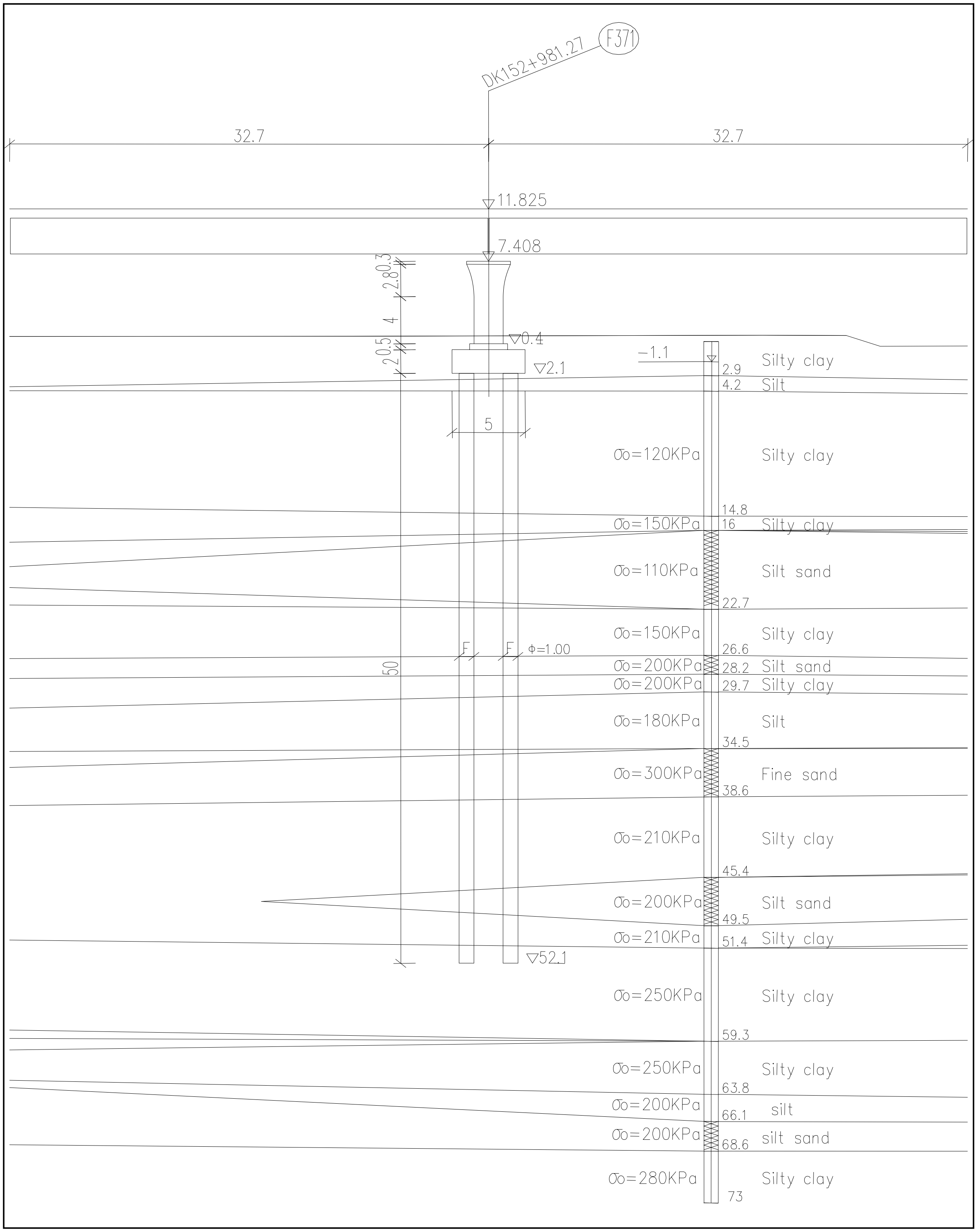


Fig. (A–3). Sketch of the soil layers of Beijing-Shanghai high-speed railway bridge at location DK152, F371 (All dimensions are in meter).

Table A–1. Soil Characteristics and Strength Parameters at the DK124 Working Points

Sampling depth (m)	ω %	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	e	k (m/day)	ν	a_v (MPa^{-1})	E_s (MPa)	c (kPa)	φ (degree)	ψ (degree)
1.07	30.7	17.7	18.0	0.849	0.086	0.32	0.51	3.6	14	8.5	0.0
4.37	27.4	18.3	18.6	0.813	0.086	0.31	0.17	4.8	15.9	9.2	0.0
9.37	31.1	18.2	18.5	0.852	0.432	0.32	0.47	3.8	11.0	10.6	0.0
19.57	26.7	19.4	19.5	0.756	0.432	0.30	0.41	7.8	25.6	13.5	0.0
24.82	22.9	19.3	19.5	0.651	0.432	0.30	0.25	6.1	20.9	16.7	0.0
26.37	24.2	20.4	20.6	0.658	0.864	0.29	0.32	5.6	21.4	30.8	0.8
30.72	26.0	18.7	18.9	0.737	0.086	0.29	0.23	7.0	96.8	14.6	0.0
41.97	28.2	18.9	19.2	0.804	0.432	0.28	0.31	8.8	35.6	15.5	0.0
46.27	24.7	19.2	19.4	0.677	0.432	0.28	0.13	9.4	42.0	21.3	0.0
53.07	30.6	19.4	19.7	0.887	0.043	0.27	0.20	9.8	43.8	17.1	0.0
57.57	27.4	20.0	20.2	0.772	8.64	0.28	0.29	10.2	8.9	32.7	2.7
69.57	18.9	19.4	19.7	0.587	0.043	0.27	0.18	6.4	43.8	17.1	0.0
73.17	28.2	20	20.2	0.820	8.64	0.28	0.34	13.2	8.9	32.7	2.7
80.67	23.9	19.2	19.5	0.685	0.043	0.27	0.23	9.1	44.7	15.5	0.0
83.57	23.2	20.2	20.4	0.673	8.64	0.28	0.24	19.9	13.7	36.2	6.2

Table A–2. Soil Characteristics and Strength Parameters at the DK152 Working Points

Sampling depth (m)	ω %	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	e	k (m/day)	ν	a_v (MPa^{-1})	E_s (MPa)	c (kPa)	φ (degree)	ψ (degree)
3.3	30.7	17.7	18.9	0.849	0.086	0.30	0.51	6.5	52.5	14.8	0.0
13.7	27.4	18.6	18.9	0.813	0.432	0.30	0.17	4.3	16.6	11.2	0.0
16.2	31.1	19.4	19.6	0.852	0.432	0.30	0.47	6.7	17.0	13.2	0.0
21.4	26.7	19.7	20.0	0.756	8.64	0.28	0.41	5.8	6.8	37.7	7.7
25.5	22.9	19.4	19.6	0.651	0.432	0.30	0.25	6.1	17.0	13.2	0.0
28.1	24.2	19.9	20.6	0.658	0.864	0.29	0.32	31.8	14.8	29.1	0.0
30.3	26.0	19.1	19.3	0.737	0.432	0.28	0.23	8.2	35.8	20.1	0.0
34.2	28.2	18.9	19.2	0.804	0.864	0.29	0.31	18.5	31.4	24.5	0.0
38.7	24.7	19.8	20.0	0.677	8.640	0.28	0.13	7.1	6.8	37.7	7.7
41.7	30.6	18.3	18.4	0.887	0.086	0.31	0.20	6.6	30.0	11.2	0.0
43.4	27.4	19.3	20.2	0.772	0.086	0.29	0.29	10.6	18.0	11.5	0.0
51.3	18.9	19.5	19.6	0.587	0.043	0.27	0.18	7.0	29.0	18.0	0.0
55.1	28.2	19.0	20.2	0.820	0.086	0.29	0.34	9.1	38.5	10.9	0.0
64.7	23.9	19.2	19.4	0.685	0.086	0.29	0.23	26.9	42.3	21.8	0.0
73.0	23.2	19.9	20.4	0.673	8.64	0.28	0.24	7.0	11.6	39.0	9.0

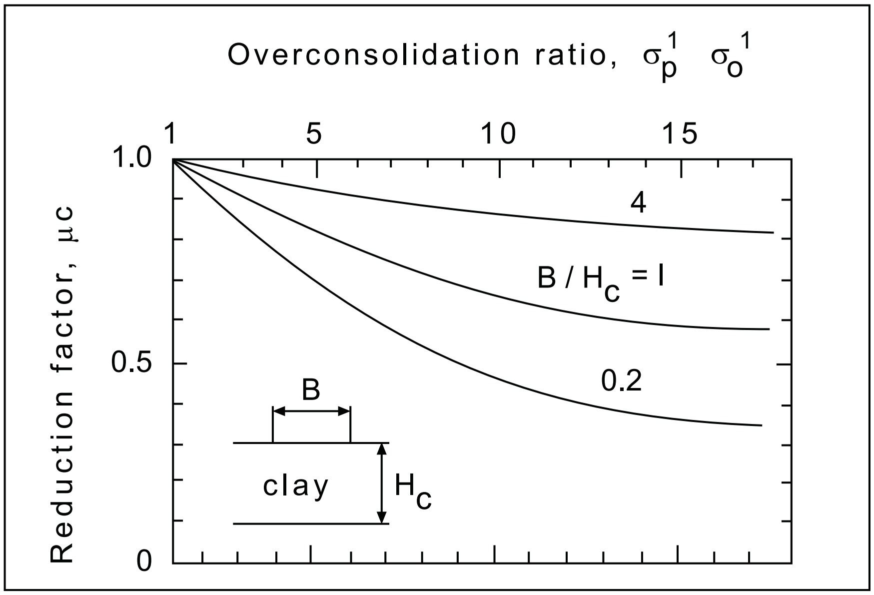


Fig. (B–1). Reduction factor to account for effect of three-dimensional consolidation settlement [2].

Where: ω: Water content; γ_{unsat} : The unsaturated unit weight of soil; γ_{sat} : The saturated unit weight of soil; *e*: Void ratio; *k*: Permeability; ν: Poisson's ratio; a_v: Compressibility; E_s: Compression modulus; *c*: Cohesion; φ: Internal friction angle; ψ: Dilatancy angle.

APPENDIX B: SETTLEMENT ESTIMATION USING AASHTO CODE

Effective depths for piles are equal to two-third of the pile length (the depth of the effective stresses). This depth is regarded the reference depth to the values of stresses generated in the soil layers as a result of applied pressures. The stress increase at the middle of each soil layer by the load Q_g is calculated in the following formula (AASHTO, 2007, C10.7.2.3.1):

$$\Delta\sigma_i' = \frac{Q_g}{(L+z_i)(B+z_i)} \quad ...(B-1)$$

Where:

$\Delta\sigma$	is the effective stress increase at the middle of i^{th} layer.
Q_g	is the total applied load.
L, B	are the length and width of the plan of pile cap, respectively.
z_i	is the vertical distance from z = 0 to the middle of the i^{th} soil layer.

Then calculate of settlement of each layer ΔS_{ci} by the following formula, (AASHTO (10.6.2.4.3-2)):

$$\Delta S_{ci} = \left[\frac{C_{ci}H_i}{1+e_{0i}}\right]\log\left[\frac{\sigma_{0i}'+\Delta\sigma_i'}{\sigma_{0i}'}\right] \quad ...(B-2)$$

Where:

ΔS_c	is the calculated settlement at the middle of each layer of the soil.
C_{ci}	is the compression index of the i^{th} layer.
e_{0i}	is the initial void ratio of the i^{th} layer.
H_i	is the thickness of the i^{th} layer.
σ_{0i}'	is the initial stress at middle of the i^{th} layer.

For purposes of calculating the settlements of pile groups, loads should be assumed to act on an equivalent footing based on the depth of embedment of the piles into the layer that provides support as shown in Fig. 10.7.2.3.1-1 of this specification [1].

Pile group settlement shall be evaluated for pile foundations in cohesive soils, soils that include cohesive layers, and piles in loose granular soils. The load used in calculating settlement shall be the permanently applied load on the foundation. The reduction factor for this code can be calculated using Fig. (B–1).

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APPENDIX C: SETTLEMENT ESTIMATION USING TB 10002.5-2005 CODE

The total settlement of the foundation generated by its bottom layer z_n's compression can be calculated by layer-wise summation method as the following equation in TB10002.5-2005 Code, section (3.2.2):

$$S = m_s\sum_{i=1}^{n}\Delta S_i = m_s\sum_{i=1}^{n}\frac{\sigma_{z(0)}}{E_{si}}(z_iC_i - z_{i-1}C_{i-1}) \quad (C–1)$$

Where:

S is the total settlement of the foundation (m).

n is the total number of soil layers divided by the compression modulus not more than the calculated depth of compression.

$\sigma_{z(0)}$ is the additional stress at the bottom of the foundation (kPa).

$\sigma_{z(0)}$ is $\sigma_h - \gamma h$
…(C–2)

σ_h is the substrate stress at the bottom of the foundation.

When *z/b* >1: σ_h should be taken as the average stress at the bottom of the foundation.

When *z/b* ≤ 1: σ_h should be taken as the stress in the point of maximum stress between *b/3* and *b/4* in the foundation stress graph.

b is the width of the foundation (m).

γ is the soil bulk density (kN/m^3).

h is the embedded depth of the foundation. When, the base erosion by water, it will be counted from the general erosion line. While, if not erosion by water, it will be counted from the natural ground. Such as in the excavation, it is counting from the ground after excavation.

z is the distance between the base of the foundation to the top surface of the soil layer (m).

z_i, z_{i-1} is the distance from the base of foundation to the bottom of *i* and *i-1* layers respectively (m).

Determination of the total calculating depth of foundation settlement z_n should meet the following requirements:

$$\Delta s_n \leq 0.025 \sum_{i=1}^{n} \Delta s_i \qquad \text{(C–3)}$$

Where:

Δs_i is the soil settlement calculated within the depth of the *i* layer.

Δs_n is the settlement value at depth z_n of a thickness Δz of soil (see the Table **C–1**).

Table C–1. Δz values according to the width of foundation.

b (m)	*b*≤2	2<*b*≤4	4<*b*≤8	8<*b*≤15	15<*b*≤30	>30
Δz	0.3	0.6	0.8	1.0	1.2	1.5

E_{si} is the compression modulus of the *i* thin-layer within the soil pressure of the following base bottom, the values range to the actual stress is according to the compression curve (kPa);

C_i, C_{i-1} is the average additional stress factors from the base of the foundation ground to the *i* and *i-1* soil layers (see in the Fig. (**C–1**).

m_s is the experienced settlement correction factor, determined according to regional settlement observations and experience, or use Table **C–2**, if no regional experience, m_s cannot less than 1.3 for soft soil.

The total settlement of the friction pile can be calculated by Article 3.2.2 of this specification as 2.2 by taking the pile as physical infrastructure.

A – *A* Ground level; *i* – *i* Bottom of layer *i*

B – *B* Foundation bottom; *n* – *n* Bottom of layer *n*;

i – 1 – *i* – 1 Bottom of layer *i* – 1; *C*– curve of average additional stress factor *C*.

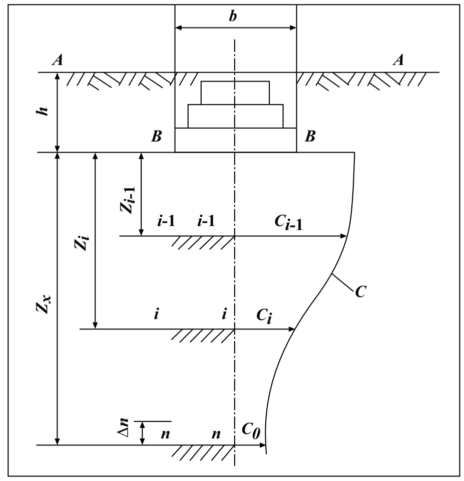

Fig. (C–1). Settlement calculations of the foundation.

Table C–2. Experienced correction factor m_s of settlement.

$\overline{E_s}$ / (kPa) $\sigma_{z(0)}$	2500	4000	7000	15000	20000
$\sigma_{z(0)} \geq \sigma_0$	1.4	1.3	1.0	0.4	20
$\sigma_{z(0)} \leq 0.75\ \sigma_0$	1.1	1.0	0.7	0.4	20

Where: $\sigma_{z(0)} = \sigma_h - \gamma h$, σ_h is the substrate stress of the foundations ground, similar to the stress which is taken as the stress in the point of maximum stress between *b/3* and *b/4* in the foundation stress graph. σ_0 is the basic soil stress at the bottom of foundation. $\overline{E_s}$ is the equivalent value of compression modulus of foundation in the total depth z_n of settlement calculation, it can be determined as follows:

$$\overline{E_s} = \frac{\sum A_i}{\sum \frac{A_i}{E_{si}}} \qquad \text{(C–4)}$$

Where A_i is the integral value along the thickness of the soil of the average additional stress factor, which is the area of the average additional stress factor of the *i*-layer soil.

APPENDIX D: SETTLEMENT ESTIMATION USING JGJ 94 – 2008 CODE

The equation used to calculate the settlement is:

$$s = \psi \cdot \psi_e \cdot s' = \psi \cdot \psi_e \cdot \sum_{j=1}^{m} p_{oj} \sum_{i=1}^{n} \frac{z_{ij}\overline{\alpha}_{ij} - z_{(i-1)j}\overline{\alpha}_{(i-1)j}}{E_{si}} \qquad \text{(D–1)}$$

Where:

S — Ultimate settlement volume of piled foundation (mm);

S' — Settlement volume of piled foundation calculated according to entity deep foundation layer wise summation method by adopting Boussinesq's solution (mm);

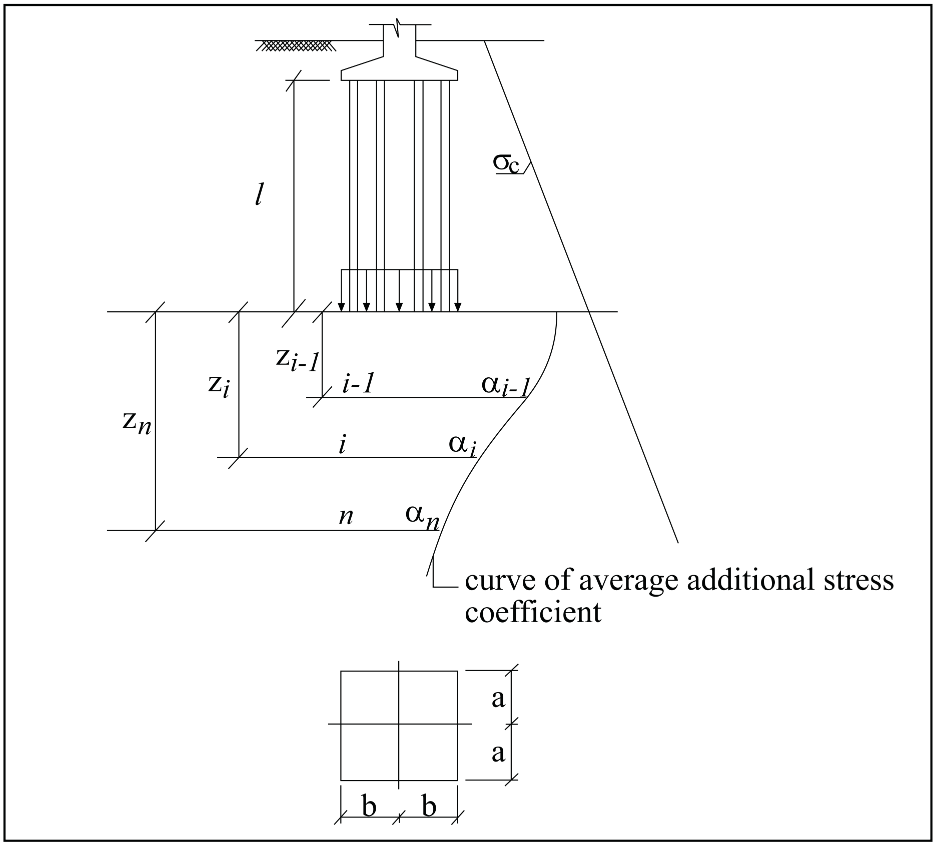

Fig. (D–1). Pile settlement calculation schematic.

ψ — Calculated empirical coefficient for applied foundation settlement may be determined according to article 5.5.11 of this code when it hasn't reliable local experience;

ψ_e — Equivalent settling ratio of piled foundation may be determined according to article 5.5.9 of this code;

m — Blocking numbers with angular point method calculating load with point correspondence;

p_{0j} —Additional pressure of the j^{th} rectangular bottom surface under would-be permanent combination of load effect (kPa);

n—Dividing soil layers within calculated depth range of piled foundation settlement;

E_{si}—Compressive modulus of the i^{th} soil layer under equivalent acting surface (MPa), it adopts compressive modulus of foundation soil under acting of sole weight pressure to sole weight pressure to sole weight pressure plus additional pressure;

Z_{ij} , $Z_{(i-1)j}$ —Distance from the j^{th} piece of load acting surface on pile tip plane to the i^{th} soil layer and i-1th soil layer bottom surface (m);

$\overline{\alpha}_{ij}$, $\overline{\alpha}_{(i-1)j}$ —Average additional stress coefficient of depth range from the jth piece of load calculated point on pile tip plane to the i^{th} soil layer and i-1th soil layer bottom surface may be adopted according to Appendix D of this code.

Fig. (**D–1**) shows the Pile settlement calculation schematic as shown below.

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