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LONG-TERM SETTLEMENT BEHAVIOR OF MULTI-STORY BUILDINGS ON SOFT SUBSOIL IN SHANGHAI

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ABSTRACT: The soft deposit in Shanghai is a multilayered formation due to different sedimentary environments and eras. This soft deposit has high compressibility, and the buildings on it undergo long-term settlement. Most of the multi-story buildings in Shanghai are built on natural soft subsoil with a shallow foundation. This paper presents the settlement behavior of 50 multi-story buildings based on long-term observed data. According to the characteristics of the soil profile in various areas, the subsoil condition is categorized into four zones: "hard" Zone, "normal" Zone, "soft" Zone, and "very-soft" Zone. The results of observations of settlement on these four types of subsoil over a long term are presented and compared. Statistical analysis is employed to analyze the observed settlement of various subsoils, including final settlement and the developing process of settlement. In order to investigate the effect on settlement behavior of the thickness of very soft clay layers in the four zones, the relationship between the thickness ratio of soft clay layer R_s and the long-term settlement of buildings is obtained through an analysis of all records. With the increase of R_s, the final settlement and settlement duration increase; however, the settlement during construction decreases. These results can be applied in research on the settlement mechanism and can be used to judge the possible settlement range and provide a design scheme for multi-story buildings in the soft clay region.

Keywords: Long-term settlement, multi-story building, soft clay, final settlement, settlement duration.

INTRODUCTION

Most of the highly populated metropolitan areas of the world are located in lowland areas in coastal regions on soft deposit. Shanghai is located on deltaic deposit near the estuary of the Yangtze River. The soft deposit in Shanghai is a multilayered soft formation, composed of Quaternary alluvial and marine sediments. The thickness of the deposit varies from 150 to 400m. The soft deposit in Shanghai is well known for its high water content, high compressibility, high plasticity, low permeability, low strength, and long-term settlement. Long-term settlement of foundations on soft soil is a significant consideration in geotechnical engineering.

There are more published methods for predicting the settlement of foundations on sands and gravels than on soft clay in the literature. Since it is extremely difficult to obtain undisturbed samples of noncohesive soil, much of the literature has been devoted to interpretation of field data. Burland and Burbidge (1985) presented a method for predicting long-term settlement based on field observations of 200 buildings, tanks, and embankments on sand and gravel. The predicted long-term settlement using Burland and Burbidge's method for foundations on sand may be too large for the settlement at the end of construction, but is remarkably accurate for the time- dependent phase (Lopes et al, 1994). Enormous progress has been made over the past few decades in the understanding of soft clay behavior. The final settlement of a building can be computed within an error range of about 20%, but it is still difficult to predict the relationship between settlement and time. Balasubramaniam and Brenner (1981) discussed the consolidation and settlement of soft clay, and compared different methods to determine the parameters in different places. In recent years, many cases have been reported to describe the settlement behaviors of buildings on different soft clay subsoils in the world (Landva et al, 1994; Wong et al, 1996; Silvestri, 2000; and so on), most of which have involved the long-term settlement of foundations. However, these reports only discussed the long-term settlement behavior for special cases. The general characteristics of and prediction method for settlement on clay subsoil are not

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Note: Discussion on this paper is open until December 2005.

given. Meyerhof (2002) reviewed the design and performance of spread footings and rafts in relation to the prediction and control of settlement, and analyzed the relation between the variation of settlement and the allowable bearing pressures of shallow foundations by considering the influence of consolidation settlements. This method could not be directly applied for predicting the settlement of Shanghai's soft deposit.

Most of the multi-story buildings (less than seven stories) in Shanghai are built on shallow foundations on natural soft subsoil. Settlement prediction becomes the most significant aspect in the foundation design for multi-story buildings. The foundation design code of Shanghai (Committee of Civil Engineering in Shanghai (CCES), 1999) recommended a computing method for final settlement; however, it did not discuss the settlement-time relationship. This paper discusses the long-term settlement behavior of the multi-story buildings on Shanghai soft subsoil. The subsoil condition for the shallow foundation in Shanghai is divided into four types of subsoil zones based on the characteristics of the soil profile in different areas. Then, a prediction method of the settlement behavior based on long-term observed data is presented. The proposed method can predict not only the final settlement but also the settlement-time relation. Finally, the long-term settlement behavior of these buildings in different areas is compared.

Table 1 Geological description of soil layers in Shanghai according to the design code (CCES, 1999)

Geological era	Layer No.	Soil description	Color	H (m)	Z (m)	Geological description
Q_4^3	1	Fill	Brownish yellow or gray clay	0.5-3	0	Building debris in urban areas; cultivated landfill in the suburbs; and reclaimed land on old river way; loose and with very high plasticity.
	2	Silty clay or silty sand	Brownish yellow or Gray	2-3	0.5-3	Silty clay: low to medium compressibility; saturated; high to very high plasticity. Silty sand: medium compressibility; saturated; slightly dense; nonuniform. Surface crust layer; Bearing layer for shallow foundation.
Q_4^2	3	Very soft silty clay	Gray	5-12	3-5	High compressibility; saturated; Medium to high plasticity.
	4	Very soft clay	Gray	3-10	7-12	High compressibility; saturated; very high plasticity. Seat of settlement of buildings.
Q_4^1	5	Clay	Gray	5-15	15-20	Medium to slightly high compressibility; very wet; low to medium plasticity; sometimes within thin layers of very fine sand or silt. Bearing layer for pile foundation when No.6 layer missing.
Q_3^2	6	Silty clay	Blackish green	1-4	20-30	Low compressibility; very wet; medium to low plasticity; over-consolidated. Missing in some places. Bearing layer for pile foundation.
	7	Silty sand or very fine sand	Greenish yellow or Greenish gray	4-14	28-35	Low compressibility; saturated; medium dense; over - consolidated. Bearing layer for piles under heavy structure.
	8	Clay	Gray	10-20	40-60	Medium compressibility; saturated; medium to low plasticity. Sometimes within thin layers of very fine sand. Seat of settlement under pile foundation.
Q_3^1	9	Fine sand	Greenish gray	5-10	65-77	Low compressibility; saturated; medium to high dense; overconsolidated. Bearing layer for long-pile foundation of very heavy structure.
Q_2^2	10	Clay	Brownish gray	4-10	86-101	Low compressibility; overconsolidated; low plasticity.
	11	Very fine sand	Greenish gray	10-30	88-101	Low compressibility; saturated; high density.
	12	Clay	Greenish gray	8-12	110-120	Low compressibility; medium to low plasticity; layers with very fine sand lenses.

Z—Depth of layer top; H—Thickness

SUBSOIL CONDITIONS IN SHANGHAI

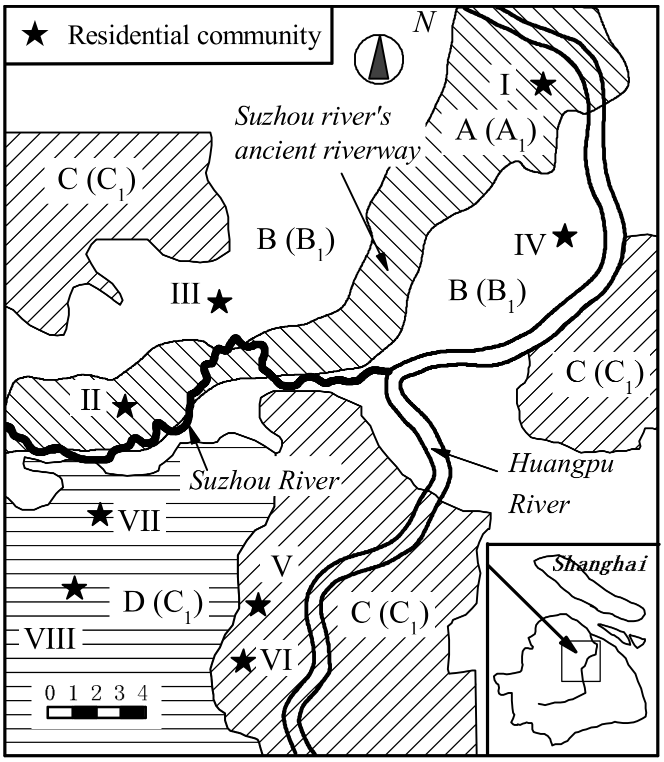
The soil layers of the soft deposits in Shanghai from the ground surface to a depth of about 100m, so-called "shallow soils", are related to the engineering activity. In the geotechnical investigation code (Committee of Civil Engineering and Management in Shanghai (CCEMS), 2002) and the foundation design code of Shanghai (CCES, 1999), these shallow soils are divided into 12 layers according to sediment era, soil color, and soil type. Moreover, some soil layers can be divided into several sub-layers. The soil profile and basic geological description of soil layers are given in Table 1.

LOCALIZATION CHARACTERISTICS OF SUBSOIL IN SHANGHAI

The uppermost soil layers from the ground surface to about 20m deep are most significantly related to the foundations of multi-story buildings. Geological investigation shows that the subsoil underneath the foundation is composed of very soft clay, soft silty clay, sandy soil, and sand layers. The thickness and engineering properties of soil layers vary among locations in Shanghai because of their different sedimentary era and environment. The long-term settlement behavior of multi-story buildings in different areas is not consistent.

Based on the soil properties of different layers, subsoil condition, and the settlement observation data of more than 250 buildings, subsoil in Shanghai was divided into three types in the Shanghai geotechnical investigation code (CCEMS, 2002). As shown in Fig. 1, the three types are shallow sand layer area (Zone A_1), normal profile area (Zone B_1), and soft subsoil area (Zone C_1). Many observation results show that the settlement of buildings in some parts of Zone C_1 is much larger than in other parts of Zone C_1. Thus, Zone C_1 can be divided into two parts according to the long-term deformation behavior of foundations. The subsoil condition is divided into four zones in this paper. The distribution of the four zones of subsoil in Shanghai is plotted in Fig. 1.

Zone-A is the so-called "hard" subsoil with a shallow sand layer. In this zone a thick layer of sandy silt or silty sand, which is the alluvial deposit of the Suzhou river's ancient riverway crossing the very soft silty clay, is embedded. The thickness of this layer ranges from 4 to 15m. This layer is helpful for dispersing the vertical stress increase in the subsoil and reducing the settlement of the building.



Note:

- Zones A, B, C, D: four types of subsoil zones as defined in this paper
- Zones A1, B1, C1: three types of subsoil zones according to the Code for Investigation of Geotechnical Engineering
- I, II, …, VIII: Residential communities

Fig. 1 Distribution of four types of subsoil zones (Based on CCEMS, 2002)

Table 2 Geotechnical profile and soil properties in different zones of Shanghai

Zone	Layer No.	Soil description	Thickness (m)	Density ρ(kN/m^3)	Void ratio e	water content w (%)	Compress module $E_{0.1\text{-}0.2}$ (MPa)	p_s * (MPa)
A	2-1	Silty clay	1.4-2.3	18.4-19.2	0.83-1.02	29.6-38.2	6.0-11.50	1.10
	2-2 or 2-3	Silt or silty sand	4.7-10.7	17.7-18.9	0.89-1.09	30.0-38.0	6.5-11.57	3.95
	4	Very soft clay	2.4-6.1	17.0-17.9	1.17-1.43	41.2-50.1	2.30-3.70	0.65
	5	Clay	1.7-6.6	18.0-18.5	0.95-1.14	32.3-40.6	3.30-5.26	1.05
B	2	Silty clay	1.7-2.6	18.0-19.0	0.88-1.16	30.6-42.5	3.00-5.44	0.90
	3	Very soft silty clay	2.8-5.0	17.6-18.3	0.98-1.23	34.3-43.4	2.90-7.00	0.65
	4	Very soft clay	8.2-9.9	16.8-17.5	1.30-1.52	46.9-54.4	2.00-2.70	0.55
	5	Clay	8.4-8.6	18.0-18.7	0.94-1.08	32.6-37.3	4.04-5.25	0.95
C	2	Silty clay	1.5-2.0	18.0-19.5	0.80-1.11	28.5-38.5	3.15-5.81	0.95
	3	Very soft silty clay	3.3-5.6	17.5-18.3	1.04-1.26	37.7-45.2	1.95-5.18	0.70
	4	Very soft clay	7.5-8.6	16.7-17.2	1.38-1.51	29.0-54.1	1.27-2.31	0.45
	5-1	Clay	7.5-9.3	17.5-18.5	0.97-1.20	32.7-43.8	2.60-5.32	0.85
D	2	Silty clay	1.6-2.3	17.8-19.0	0.88-1.16	31.3-40.2	3.00-8.09	0.75
	3	Very soft silty clay	2.3-5.4	17.3-18.2	1.05-1.35	37.5-48.7	2.03-8.74	0.55
	4	Very soft clay	9.3-11.5	16.6-17.2	1.34-1.52	47.5-53.7	1.71-2.33	0.40
	5-1	Clay	5.8-12.4	17.2-18.3	1.00-1.31	34.4-45.7	2.64-5.40	0.75

* CPT Tip resistance

Zone-B is the so-called "normal" subsoil. It has the typical soil profile in Shanghai and is mainly composed of clay. The surface crust layer (silty clay) is the bearing layer for shallow foundations. The settlement of foundations in this zone is mainly due to the deformation of the very soft silty clay layer and the very soft clay layer underneath the top crust.

Zone-C is the so-called "soft" subsoil. There exist thick soft soils (very soft silty clay and very soft clay, which is the seat of settlement for buildings). In some parts this subsoil has the same properties as that in zone-B. However, the thickness of the soft layer is greater than that in zone-B.

Zone-D is the so-called "very-soft" subsoil. In this zone, there exists a very soft layer with a high level of thickness and at a shallow depth. Most of the soil is very soft clay, which is often in an under-consolidated state. Compression of the thick soft substratum under additional foundation pressure causes a high degree of settlement in foundations.

Table 2 gives the geotechnical profile of the soils in the aforementioned zones in Shanghai. Most of the total settlement of the foundations is due to the deformation of very soft silty clay and very soft clay (Layer No.3 and Layer No.4) because of the high compressibility and creep characteristics of these two soil layers. The thickness of these two very soft clay layers in subsoil is the most significant factor influencing the long-term settlement of foundations. In order to investigate the effect of the thickness of soft clay layers on the settlement behavior, the thickness ratio (R_s) of the very soft clay layer in subsoil is defined as: $R_s=H_s/H_I$, where H_s is the total thickness of very soft silty clay and very soft clay; H_I is the influential depth of over loads. Regarding the influential depth, Burland (1985) suggested that it is about twice the breadth of the building foundation. However, this does not consider the value of overburden pressure. In one-dimensional settlement analysis based on elastic theory, the influential depth is considered to be the depth where the vertical stress increase is about 10% of the effective overburden stress (Das, 1983; Shanghai foundation design code, 1999). The influential depth (H_I) is defined as such a computed depth in this paper. For seven-story buildings, H_I is about 22m; for six-story buildings, H_I is about 20m; and H_I is 16m for four-story buildings. From Table 2, the value of R_s can be obtained in different zones: R_s in zone A is less than 30%, in zone B it ranges from 30 to 55%, in zone C it ranges from 50 to 75%, and in zone D it is greater than 75%.

Table 3 Details of the long-term settlement of buildings

Zone	Building No.	Foundation Length m	Foundation Breadth m	Number of floors	Construction Time (days)	S_c mm	Observation Time (years)	Settlement at the end of observation	State of settlement at the end of observation	Predicted results S_∞	Predicted results S_∞-S_0	Predicted results a	R^2	S_f (mm)	t_d (years)	R_s %
A	I-1	76.8	12.5	7	333	93.9	3.52	126.2	Converged	126.07	134.2	294.84	0.975	126.2	3.52	22.50
	I-2	94.2	13.1	7	328	118.5	3.51	146.7	Converged	144.94	153.6	224.95	0.948	146.7	3.51	18.50
	I-3	43.2	10.9	7	366	61.1	3.61	80.0	Converged	80.33	86.1	307.74	0.968	80.0	3.61	22.50
	II-1	68	12.8	7	278	27.7	3.68	79.0	Tended to Convergence	122.89	120.4	1328.6	0.980	83.02	4.02	25.50
	II-2	68	12.8	7	274	35.5	3.67	81.7	Tended to Convergence	148.63	144.8	1744.6	0.980	96.28	4.86	25.50
	II-3	68	12.8	7	274	33.3	3.67	100.1	Tended to Convergence	122.64	205.2	612.36	0.980	110.39	4.73	25.50
B	III-1	57.24	11.5	6	175	38.1	2.48	93.7	Not Converged	98.82	91.54	332.36	0.981	95.5	3.02	47.34
	III-2	32.34	11.5	6	230	21.4	2.65	73.6	Not Converged	87.38	107.8	468.42	1.000	82.7	4.02	42.02
	III-3	32.34	11.5	6	239	44	2.71	100.0	Not Converged	117.36	116.3	510.66	0.996	112.2	4.37	42.02
	III-4	32.34	11.5	6	206	33.6	2.62	85.8	Not Converged	115.01	116.7	661.75	0.996	108.4	5.20	42.02
	III-5	82.2	11.5	6	233	34.1	2.69	84.4	Not Converged	105.51	107.5	587.78	0.994	99.6	4.68	47.62
	IV-1	55.2	11.7	7	346	41.1	3.78	104.3	Not Converged	134.17	136.4	911.54	0.997	125.0	6.76	49.50
	IV-2	69	11.7	7	256	153.3	3.71	336.3	Not Converged	344.79	371.8	456.67	0.991	340.2	5.50	49.50
	IV-3	55.2	11.7	7	322	50.9	3.77	123.0	Not Converged	153.66	154.6	880.34	0.998	144.9	6.91	49.50
	IV-4	55.2	11.7	7	320	106.9	3.85	273.7	Not Converged	289.17	300.7	561.92	0.988	283.5	6.13	49.50
	IV-5	55.2	11.7	7	361	125	3.82	273.6	Not Converged	308.48	334.5	636.32	0.992	302.1	6.91	49.50
	IV-6	41.4	11.7	7	353	63.2	3.43	144.7	Not Converged	156.06	151.0	550.47	0.987	150.6	4.99	49.50
	IV-7	55.2	11.7	7	314	144.5	3.88	251.8	Not Converged	284.62	297.3	721.85	0.988	277.4	7.35	49.50
C	V-1	75.9	11.7	6	310	136.9	4.55	304.8	Not Converged	336.06	468.0	580.69	0.977	330.3	6.98	57.14
	V-2	55.2	11.7	6	310	104	4.55	276.7	Not Converged	283.69	718.8	378.47	0.971	279.9	5.44	57.14
	V-3	55.2	11.7	6	310	135.3	3.95	271.6	Not Converged	316.91	410.2	657.55	0.992	310.3	7.44	57.14
	V-4	41.4	11.7	6	249	82	3.71	235.1	Not Converged	258.43	258.0	505.86	0.992	253.4	5.45	55.00
	V-5	27.6	11.7	6	346	60.5	3.18	192.8	Not Converged	235.70	236.3	680.47	0.997	228.9	6.61	52.63
	V-6	41.4	11.7	6	249	89.1	3.11	259.9	Not Converged	300.13	298.1	558.92	0.991	294.5	6.09	55.00
	V-7	48.3	11.7	6	272	104.8	3.83	241.0	Not Converged	274.62	283.2	642.14	0.991	268.2	6.66	55.00

To be continued

Table 3 Details of the long-term settlement of buildings

Continued

Zone	Building No.	Foundation		Number of floors	Construction Time (days)	Sc mm	Observation Time (years)	Settlement at the end of observation	State of settlement at the end of observation	Predicted results				S_f (mm)	t_d (years)	R_s %
		Length m	Breadth m							S_∞	S_∞-S_0	a	R^2			
C	V-8	27.6	11.7	6	282	89.3	3.26	203.5	Not Converged	228.75	239.0	506.22	0.999	223.7	5.34	52.63
	V-9	55.2	11.7	4	275	106	3.84	236.4	Not Converged	252.31	258.6	491.71	0.997	247.4	5.34	44.12
	V-10	41.4	11.7	4	278	102.1	3.80	244.9	Not Converged	280.83	285.4	637.86	0.997	274.5	6.64	46.88
	V-11	41.4	11.7	4	265	132.7	3.76	283.7	Not Converged	306.21	298.2	538.01	0.996	300.8	5.92	46.88
	V-12	55.2	11.7	6	273	117	3.79	250.3	Not Converged	269.96	270.2	532.5	0.998	264.6	5.73	57.14
	VI-1	51	12	7	366	102.4	2.90	194.7	Not Converged	268.34	267.4	780.16	0.997	260.5	7.55	62.50
	VI-2	42	12	7	366	111.1	2.63	212.2	Not Converged	284.80	309.0	637.11	0.993	278.4	6.77	62.50
	VI-3	51	12	7	362	51.7	2.62	100.3	Not Converged	141.34	150.7	761.12	0.979	133.7	6.22	62.50
	VI-4	51	12	7	346	66.7	2.58	176.8	Not Converged	260.57	340.6	609.27	0.992	254.5	6.71	62.79
	VI-5	42	12	7	342	80.5	2.56	186.7	Not Converged	286.22	315.8	791.13	0.997	278.3	7.99	62.79
	VI-6	51	12	7	322	90.1	2.51	201.8	Not Converged	305.82	318.3	800.97	0.998	297.8	8.08	62.79
	VI-7	43.2	12	6	366	170.2	2.90	264.4	Not Converged	277.95	356.5	314.37	0.999	274.8	4.07	57.50
	VI-8	43.2	12	6	366	160.8	2.63	251.8	Not Converged	276.51	280.0	425.94	0.998	272.2	4.88	62.50
	VI-9	43.2	12	6	361	162.3	2.90	293.0	Not Converged	351.87	359.6	570.01	0.999	346.2	6.47	62.50
	VI-10	57	12	6	358	81.9	2.88	151.6	Not Converged	216.83	217.6	803.97	0.986	208.8	7.26	57.50
	VI-11	51	12	6	370	74.8	2.64	234.9	Not Converged	281.11	288.9	467.1	0.983	276.4	5.28	57.50
D	VII-1	61.54	13.8	6	210	72.3	5.67	441.2	Tended to Convergence	442.07	448.7	471.16	0.994	437.4	5.88	88.75
	VII-2	61.54	13.8	6	210	51.6	5.67	356.5	Tended to Convergence	372.04	372.5	693.95	0.993	365.1	7.57	88.75
	VII-3	61.54	13.8	6	210	38.8	5.67	302.3	Tended to Convergence	309.16	317.8	569.11	0.990	303.5	6.27	88.75
	VII-4	61.54	13.8	6	210	79.9	5.67	467.4	Tended to Convergence	458.63	459.3	477.49	0.987	453.9	5.97	83.25
	VII-5	43.2	11.8	6	210	73.1	5.67	459.9	Tended to Convergence	446.89	452.7	451.5	0.984	442.4	5.70	82.37
	VII-6	61.54	13.8	6	210	39.5	5.67	306.8	Tended to Convergence	314.67	319.4	620.76	0.994	308.5	6.70	83.25
	VIII-1	33.84	14.04	6	268	107.7	6.19	468.2	Tended to Convergence	552.80	552.2	998.03	0.995	532.8	9.08	90.00
	VIII-2	33.84	14.04	6	246	88.2	6.12	485.1	Tended to Convergence	569.90	587.2	946.2	0.996	551.0	8.90	90.00
	VIII-3	33.84	14.04	6	260	115	6.25	378.0	Tended to Convergence	410.00	408.9	710.17	0.997	402.9	7.88	90.00

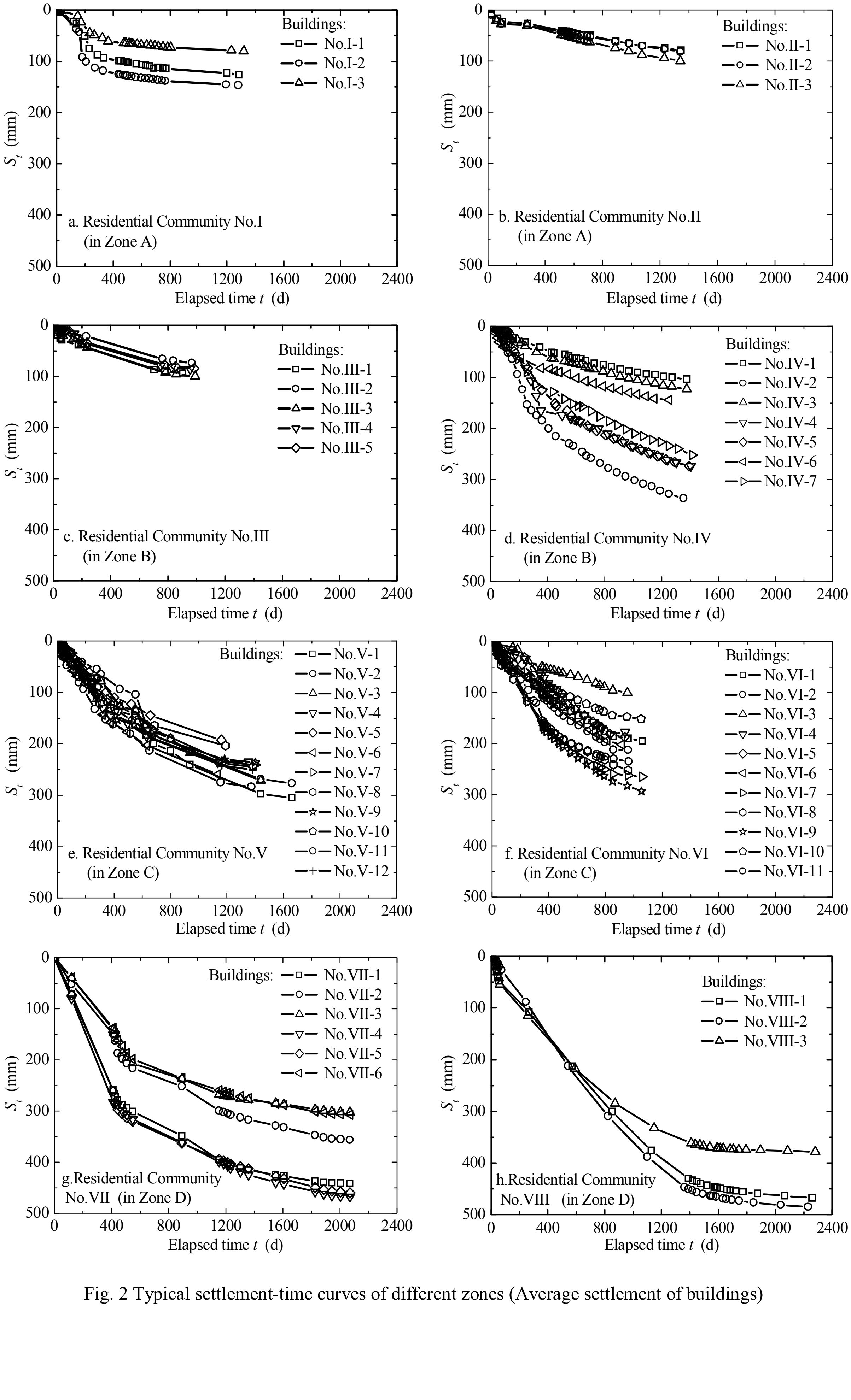


Fig. 2 Typical settlement-time curves of different zones (Average settlement of buildings)

ANALYSIS OF THE FIELD DATA

In order to research the long-term settlement behavior of multi-story buildings in Shanghai, 50 cases are investigated and analyzed, most of which are six-story buildings, with ten cases being seven-story buildings and four cases being four-story buildings. These 50 buildings are located in 8 different residential communities. The locations of the communities are marked I to VIII, as illustrated in Fig. 1. Details of the buildings with settlement in the communities are described in Table 3.

Settlement-time Relations

The observed settlement-time curves of buildings in different zones are illustrated in Fig. 2. The settlement was determined by level surveying. Land subsidence occurred in a large area in Shanghai due to excessive pumping of groundwater (Zhang and Wei, 2002; Chai et al., 2004; Chai et al., 2005), and in order to eliminate the effect of land subsidence, bench marks were set in the same area as the buildings. However, the bench marks were set far enough from the buildings to avoid building-load-induced settlement. Therefore, the settlement of the bench marks due to land subsidence would be the same as that of the building. The settlement of the buildings is defined as the differential settlement between the bench marks and buildings in this paper. As shown in Fig. 2, the long-term settlement curves of multi-story buildings in the four zones are much different. The figure shows that settlement-time relations are different in the four zones. The settlement of buildings in zone-A is the smallest, and is only about 1/5 of that in zone-D. Settlement in zone-A begins to converge at about 400 days, while the settlement in zones-C and D has not finished after 2000 days.

Analysis of Long-term Settlement

Because observation is stopped before the settlement has converged, the future settlement should be predicted in order to analyze the whole procedure of settlement and to determine the final settlement and the evolution of settlement with time.

Regression analysis is employed to fit the measured value of the settlement. The following mathematical functions are generally used in regression analysis (Sun and Zheng, 1984; Zai and Mei, 2000): the hyperbola model, the exponential curve model, and the growth curve model. The detailed expressions of these three models are as follows:

1. Hyperbola model：

$$S_t = S_0 + \frac{t}{a+bt} \tag{1}$$

where, S_t = settlement at time t; S_0 = initial settlement; a and b = regression parameters.

2. Exponential model:

$$S_t = S_0 + (S_\infty - S_0)(1 - e^{-\frac{t}{a}}) \quad = S_\infty - (S_\infty - S_0)e^{-\frac{t}{a}} \tag{2}$$

where, S_t = settlement at time t; S_0 = initial settlement; S_∞ =calculated value of settlement when time is equal to an infinite value; a = parameter of time.

3. Growth curve model:

$$S_t = \frac{k}{1 + ae^{-bt}} \tag{3}$$

where, S_t = settlement at time t; a, b, and k = regression parameters.

The long-term settlement analyses for a typical value using the three models are compared in Fig. 3. Analyses show that the mean square deviations of empirical equations obtained by the above three methods are small and are close to one another. All of these models can satisfy the precision requirement in calculation. For final settlement, the value obtained by the exponential model is closest to the practical situation when the measured settlement curve lasts a long time. Thus, settlement evolution is analyzed by the exponential model in this study. The analyzed results for the four typical settlement curves are shown in Fig. 4. It is shown that the correlation coefficient of the settlement calculated by using the exponential model is greater than 0.95 and in most cases reaches 0.99. The method is confirmed to be effective. According to the aforementioned analysis, the later-stage settlement can be predicted and the final settlement and settlement duration can be estimated.

Final Settlement

In design, the final settlement, S_f, should be less than the allowable settlement. Based on the above results, the final settlement of a foundation can be calculated by the settlement evolution curve. In this study, the final settlement, S_f, is defined as the settlement occurring within the settlement duration, at which the settlement rate is less than 0.01mm/day.

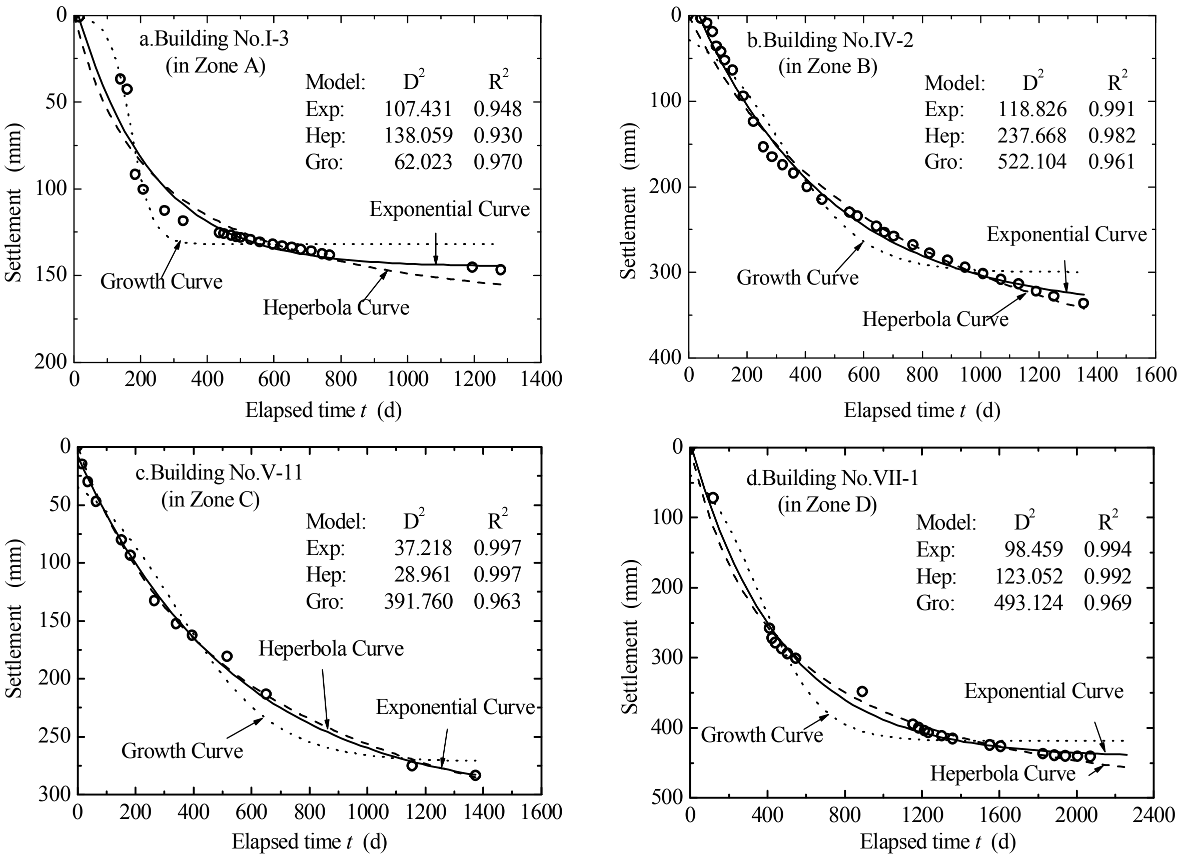


Fig. 3 Comparison of the long-term settlement analysis using the three models

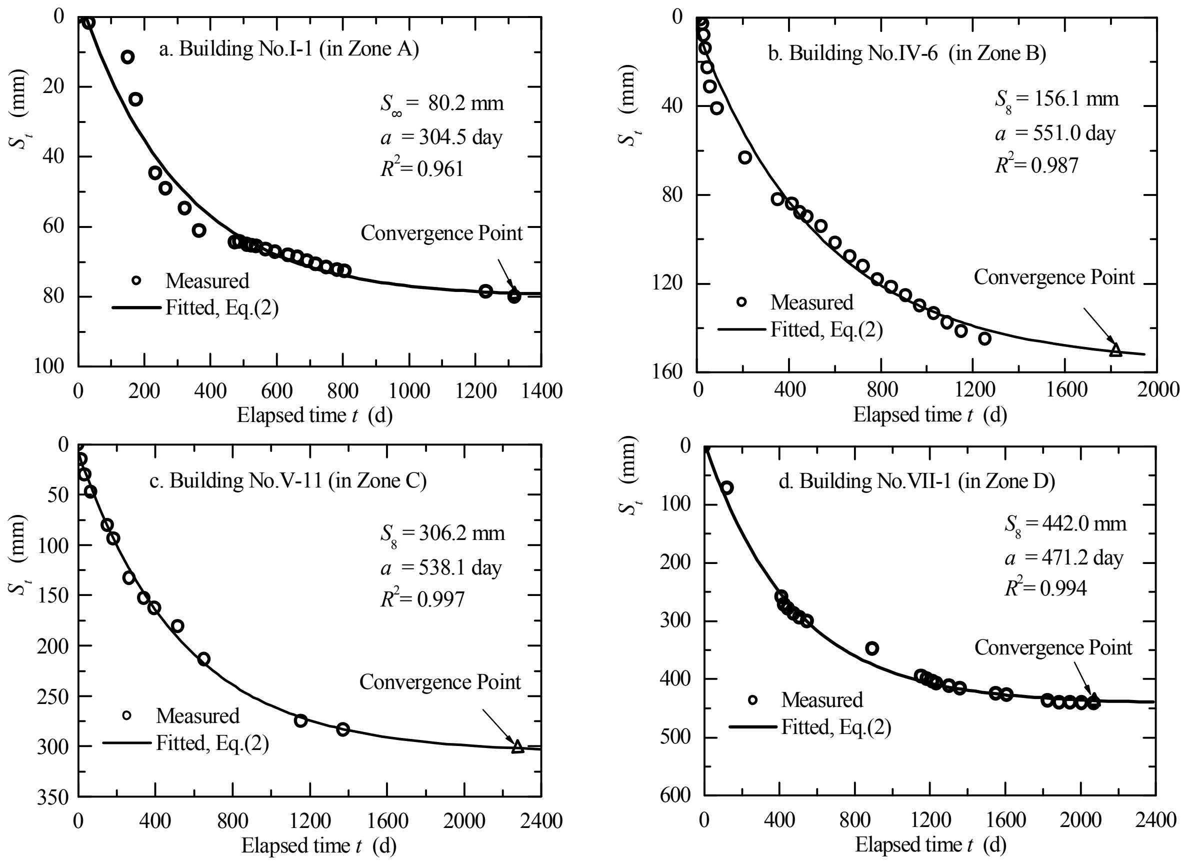


Fig. 4 Fitted curves for the settlement-time relation of different zones

Table 4 Final settlement of different zones (mm)

Zone	Maximum	Minimum	Average
A	146.7	80.0	107.1
B	340.2	82.7	176.8
C	346.2	133.7	267.7
D	551.0	303.5	421.9

Table 4 lists the predicted final settlement in different zones. As shown in the table, settlement in zone-A ranges from 80 to 150 mm within the limit of allowable settlement as established in the Shanghai code (<200mm for multi-story buildings). Settlement in zone-B is within the range of 80 to 340 mm. At some areas in this zone, ground treatment should be carried out to control settlement within the allowable range. Settlement in zone-C ranges from 130 to 350 mm. In most areas, ground treatment should be carried out to control settlement within the allowable range. If the settlement is too large and cannot satisfy this requirement, pile foundation may be applied. Settlement in zone-D ranges from 300 to 550 mm, which is much larger than the allowable settlement as established in the code. Ground treatment should be carried out, or pile foundation should be adopted to decrease the settlement of the buildings.

Settlement Duration

Settlement duration is used to judge whether a building is safe and if the settlement has converged or not. According to the previous results, settlement duration is predicted by the settlement evolution curve (Eq.2). Settlement convergence is reached when the settlement rate is less than 0.01 mm/day. The calculated settlement durations of the four zones are tabulated in Table 5.

Foundations in zone-A are on sand. In most cases, settlement will be convergent within 3 to 4 years. Foundations in zone-C and zone-D are on soft clay where creep deformation occurs. It takes longer for settlement to be convergent in these zones, and the stabilization time of settlement may be 9 years or more. The settlement times of foundations in zone-B fall between the above two cases, as settlement can be convergent within 3 to 7 years.

Table 5 Predicted settlement duration (years)

Zone	Maximum	Minimum	Average
A	4.86	3.51	4.04
B	7.35	3.02	5.49
C	8.08	4.07	6.30
D	9.08	5.70	7.11

Influence of R_s on Long-term Settlement

Long-term settlement behavior (final settlement and settlement duration) is related to the thickness ratio (R_s) of very soft clay in subsoil. The influence of R_s on the final settlement and settlement duration is obtained from the settlement prediction by using Eq.(2). The relation between R_s and S_f is plotted in Fig. 5. The settlement increases with the increase of R_s. The solid line in Fig. 5 is the regression line of all settlement. Final settlement is about 476mm when R_s is 100% on the regressed line. The dashed lines are the upper and lower limit lines with a computed difference range of ±20%. Fig. 5 shows that most of the points are within the limit range. The settlement duration varied with R_s in a way similar to that of the final settlement. The relationship between the settlement duration and thickness ratio of very soft clay is shown in Fig. 6.

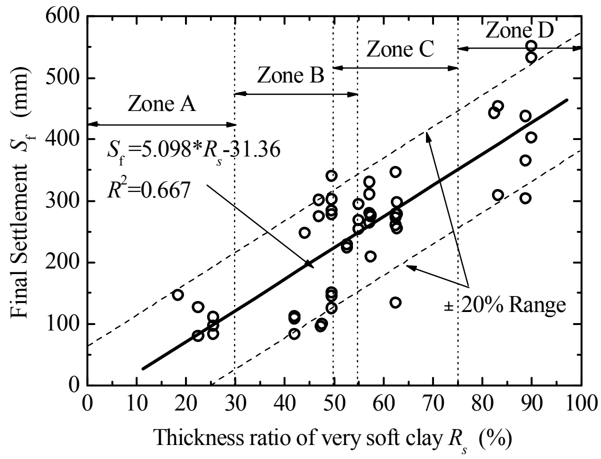


Fig. 5 Relationship between the final settlement and thickness ratio of very soft clay in subsoil

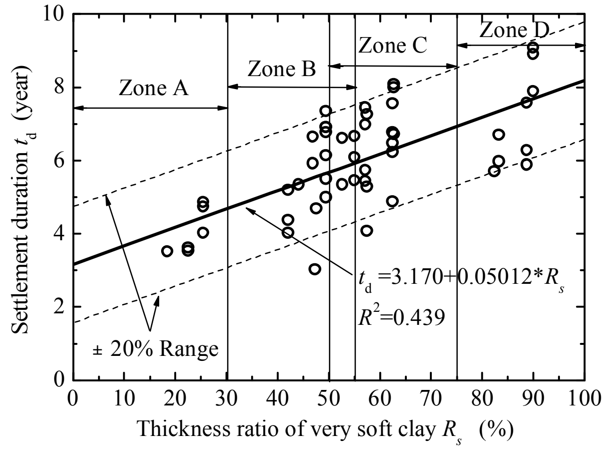


Fig. 6 Relationship between the settlement duration and thickness ratio of very soft clay in subsoil

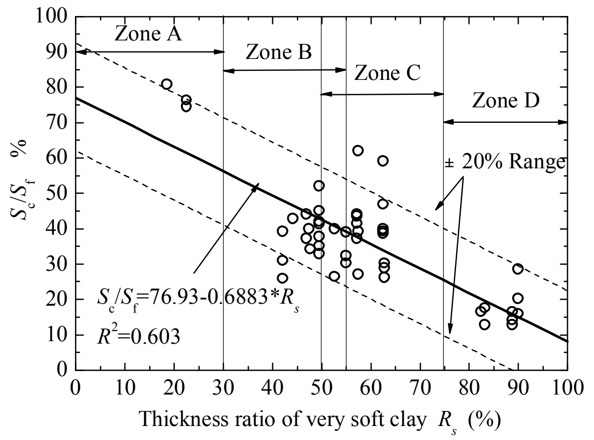


Fig. 7 Relationship between S_c/S_f and thickness ratio of very soft clay in subsoil

Settlement that occurs after construction is strongly related to R_s because the consolidation settlement and creep deformation of very soft clay are much larger than those of sand and hard clay. Table 4 shows the predicted results for the settlement of different buildings. The settlement ratio between settlement during construction and final settlement is defined as S_c/S_f, where S_c is settlement at the end of building construction, and S_f is the predicted final settlement. S_c/S_f decreases with an increase of R_s in subsoil as shown in Fig. 7. S_c/S_f is 8.1% when R_s is 100%. Most of the settlement will occur after construction when R_s is high. From Figs. 6 and 7, S_c/S_f is about 77% and the settlement duration is about 3.17 years when R_s is zero, which means that the subsoil is completely composed of sand and hard clay. This result is similar to that for the time-dependent settlement of the foundation on sand and gravel, as summarized by Burland and Burbidge (1985). In Burland's conclusions, when t is 3 years, S_t is $1.3S_c$.

CONCLUSIONS

This paper presented the settlement behavior of multi-story buildings on Shanghai soft deposit based on the long-term observed data of 50 multi-story buildings. According to the observed long-term settlement of multi-story buildings and analytical results, the following conclusions were obtained:

1. Long-term settlement evolution processes of the multi-story building in different zones of Shanghai are different because of the variation of the subsoil composition. The subsoil condition can be divided into four zones by considering the variation of long-term deformation behavior.

2. The exponential model is effective for analyzing the settlement and predicting the future settlement of buildings. The process of settlement, final settlement, and duration of settlement can be analyzed by using this method.

3. Final settlements are different in the four zones. Final settlement in zone-A is the smallest and can satisfy the requirement for allowable settlement. In some parts of zone-B, foundation treatment should be applied to control the settlement. Settlement in zone-C and zone-D, which may reach 600mm, is much bigger than the allowable settlement as established in the design code. Ground improvement must be conducted and/or pile foundation should be adopted to decrease the settlement of buildings in these zones.

4. Settlement in zone-A tends to be convergent within 4 years and settlement in zone-B will reach convergence within 5 to 7 years, while the settlement duration in zone-C and zone-D may reach 10 years due to the creep deformation of soft subsoil.

5. The final settlement and settlement duration is influenced by the thickness of the very soft clay in the subsoil. The settlement linearly increases with the soft clay ratio, and the settlement duration varies with the thickness ratio of very soft clay as does the final settlement.

6. The settlement that occurs due to consolidation after construction is much larger when the thickness ratio of very soft clay in subsoil is higher because of the large consolidation settlement and creep deformation of very soft clay.

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NOTATION

a, b, and k = regression parameters.

H_s = total thickness of very soft silty clay and very soft clay;

H_l = influential depth of additional foundation pressure;

R_s=H_s/H_l, thickness ratio of very soft clay layer in subsoil;

S_0 = initial settlement;

S_c = settlement at the end of building construction;

S_f = predicted final settlement, at which the settlement rate <0.01mm/day;

S_t = settlement at time t;

S_∞ =calculated value of settlement when time is equal to infinity;

S_c/S_f = settlement ratio between settlement during construction and final settlement;

t_d = settlement duration.

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