

COMPACTION GROUTING FOR CORRECTING BUILDING SETTLEMENT

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Compaction Grouting for Correcting Building Settlement

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ABSTRACT: Compaction grouting was applied for raising the subsided foundations of two buildings in sandy soils. The performance of the case history could be interpreted by the conical soil failure mechanism. The critical injection pressure and volume which would induce uplift vary with the depth of the injection and the foundation load. For loosened ground a reloading stage will be inevitable before the conical failure mode could be mobilised.

1 INTRODUCTION

Compaction grouting is one of the methods which could rectify foundation settlement. During the 40 years of application this grouting technique has lots of successful experience on uplifting foundations. However, it has still been regarded as experimental as there are cases without significant uplifting effects despite a large quantity of grout materials was injected. This paper presents a case history of using compaction grouting to reduce foundation settlement. The mechanism causing ground heave has been reviewed and the factors for unsuccessful applications are investigated. Finally, tentative guides for improving the grouting technique are proposed.

2 A CASE STUDY

2.1 Background

The subsoils at the site for contract CP263 of the Taipei Rapid Transit Systems consist 50m thick Sungshan formation, which is composed of alternately deposited silty sand and silty clay layers. The uppermost sandy layer is 10m thick with the standard penetration blow counts between 2 to 16. The groundwater table is about 4.0m below ground. During the construction of the underground works two adjacent 4-storey buildings A and B, which were founded on spread footings at a depth of 1m, suffered from settlements of 20mm to 44mm. Figure 1 shows the position of building A and the outline of the underground station. As shown in Figure 2 the

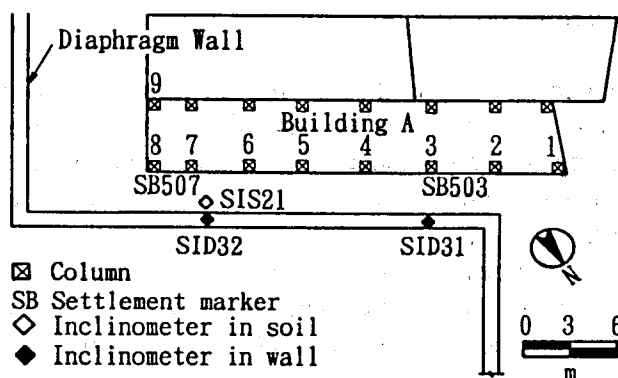


Figure 1. Plan of building A

settlements of building A were attributed to various construction activities which include the followings:

1. Construction of guide wall of 1.5m deep.
2. Installation and extraction of sheet piles of 12m deep which were aligned at 1m northeast from the building.
3. Jet grouting up to a depth of 11m along the alignment of the previously extracted sheet piles.
4. Diaphragm wall trenching along the northeast and the southeast sides of the building. The depths of the trenches were 23m and 30m, respectively.
5. Construction of 34 number 1.5m diameter bored piles with a minimum spacing of 3.75m on the northeast side of building A.
6. Excavating to a depth of 16m on the southeast side of building A.
7. Excavating to a depth of 2m on the northeast side of building A.

For building B the settlements were mainly attributed to trenching of 3 rows of diaphragm walls and excavation. Compaction grouting was then carried out at both buildings to reduce the settlements

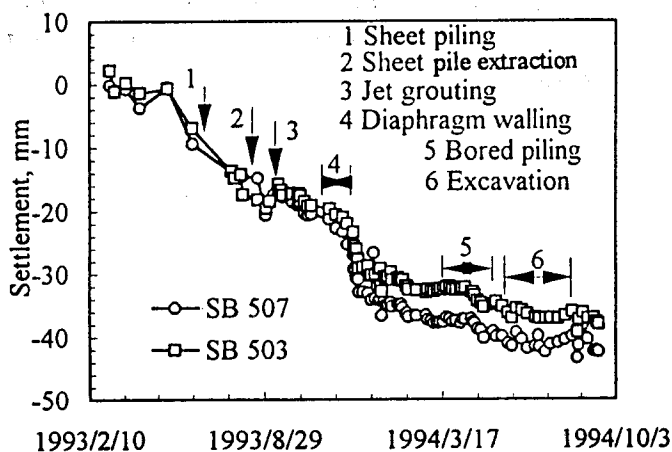


Figure 2. Settlement of building A prior to compaction grouting

which would otherwise cause detrimental effects to the building structures.

2.2 Grouting procedures

At each column 4 groutholes, with series number of i, a, b and c, were installed and injected sequentially. According to the sequence of grouting, grouthole i is the primary, a and b are the secondaries and c is the tertiary.

The grout pipes were formed by drilling and reaming 100mm outer diameter steel casings to depths of 5m to 8m. Groutholes i were inclined at 12° and groutholes a, b and c were at 15° from the vertical. Figure 3 shows the positions of the groutholes.

Grout injection was conducted at 0.5m intervals between depths of 8m and 3m, working progressively upward from the maximum depth of the grouthole. Injection quantity was measured by counting the number of the piston strokes. One stroke is equivalent to 7.08 litre. The rate of injection was about 42.5 litre/min. Between each 0.5m step there was a 5 to 10 min pause for grout pipe lifting and settlement monitoring. The peak pressures were recorded at the end of each piston stroke by observing the pressure gauge installed at the top of the groutholes.

For every cubic meter of grout material the mixture was composed of 320 kg pea gravels, 1040 kg silty sand, 160 kg cement and 425 to 526 kg water. The slump ranged between 30mm to 40mm.

2.3 Results of grouting

Initially the criteria for grouting were that the grout should be injected continuously until the refusal pressure of 4MPa was reached. However, after injection through groutholes i were complete none of

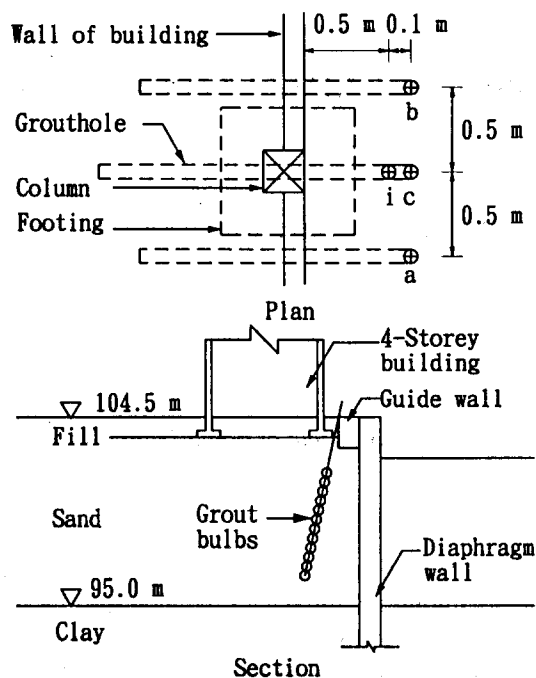


Figure 3. Layout of groutholes

the columns achieved the uplifting effects except ground heave of 26mm and 30mm was recorded at two settlement points which were both at distance of 2m from grouthole 5i. As the ground heave caused minor damage to the floor slabs of building A, criteria for injection for groutholes a, b and c were revised to limit the peak pressure to 3.5 MPa. Since then ground heave was not induced.

Totally 268 and 90 bulbs were injected beneath 9 columns and 3 columns at buildings A and B, respectively. Table 1 shows the average grout intake and the average peak injection pressure for each bulb. Figures 4 to 6 are the records for a typical set of groutholes which were located in the vicinity of column 7.

Table 1. Statistics of grouting for buildings A and B

Building	Grouthole	Number of grout bulbs	Total injected	Average injected	Average peak
			volume	volume	pressure
			m ³	m ³	MPa
A	i	100	52.55	0.52	3.45
	a	61	23.66	0.39	2.48
	b	61	19.55	0.32	2.30
	c	46	14.31	0.31	2.87
B	i	33	17.14	0.52	1.99
	a	21	5.27	0.25	2.52
	b	21	7.92	0.38	2.21
	c	15	4.27	0.28	2.40
Total		358	144.7	-	-

2.4 Ground response

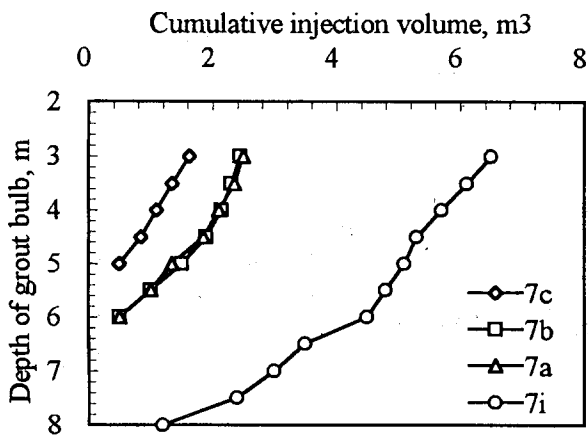


Figure 4. Injected amount for each grout hole at column 7

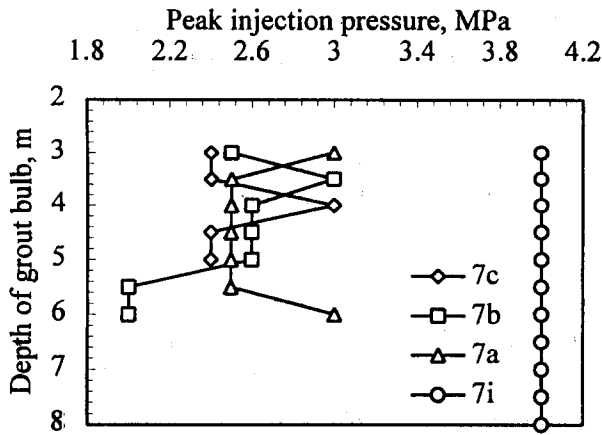


Figure 5. Peak injection pressure for each grout hole at column 7

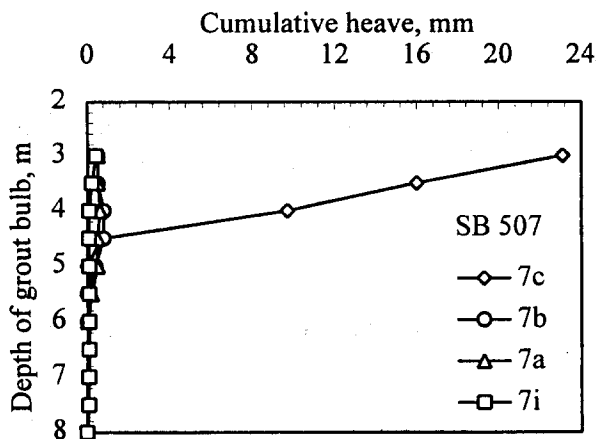


Figure 6. Heave induced by grouting at each grout hole

Settlement readings as shown in Figure 6 indicate that uplifting of the columns were induced when the grout bulbs at or above 4.5m depth of the nearest tertiary grout holes c were being injected. Although the injection quantities and pressures are similar between each grout holes at depths between 5m and 3m and the injection pressures of grout holes i were the highest, column heave did not occur during injection of grout holes i, a and b. The reasons are to be studied in this paper. The maximum heave induced at column 7 was 24mm.

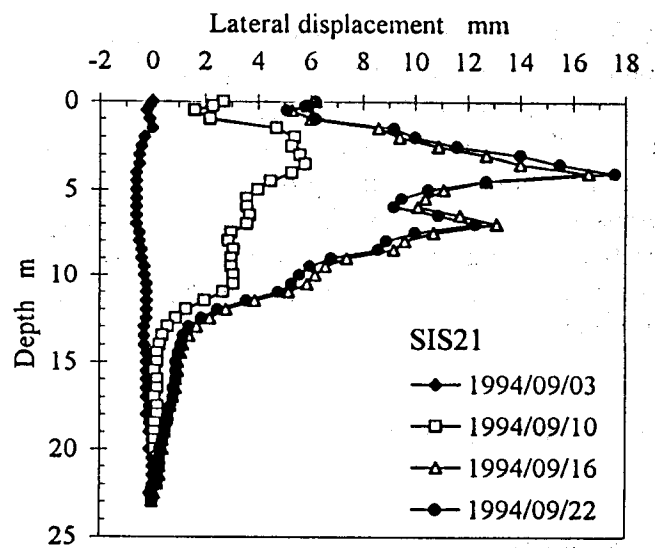


Figure 7. Lateral ground displacement induced by compaction grouting

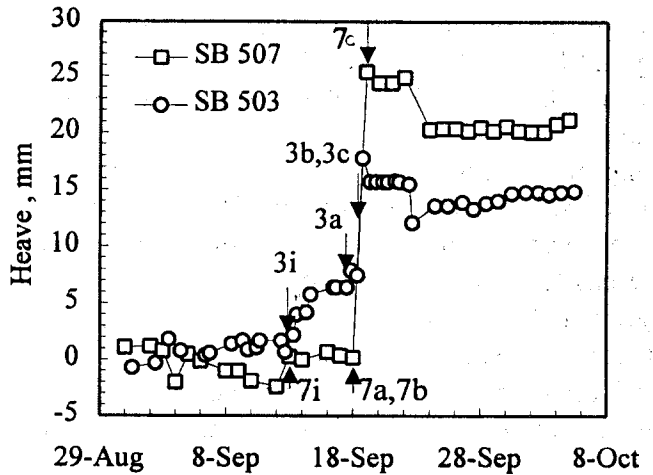


Figure 8. Response of column heave against progress of grouting

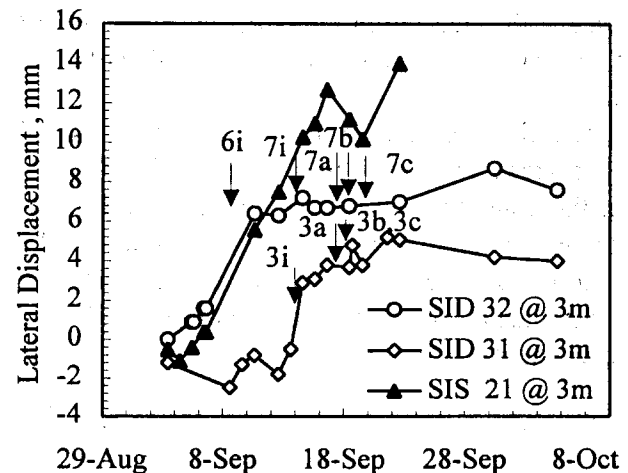


Figure 9. Response of lateral displacement against progress of grouting

As shown in Figure 7 the inclinometer profiles for SIS21 indicate that the maximum lateral displacement of 17mm was mainly attributed to the injection of grout holes 6i and 7i, which were distanced 3.0m and

1.8m from the inclinometer casing, respectively.

Compaction grouting at building A was carried out from 3 September to 21 September, 1994. Figure 8 indicates that up to 2mm and 4mm settlements occurred within 1 day after grouting at the relevant columns and within 3 days after grouting at building A, respectively. Figure 9 shows that not much reduction of lateral displacement occurred after the completion of grouting.

3 HEAVE MECHANISM

3.1 Recent studies

The mechanism of ground heave induced by compaction grouting has recently been established. Based on the results of 4 trial grouting cases, Moh, Yang and Hwang (1994) established the basic factors which would affect the performance of compaction grouting.

Compaction grouting would cause two different modes of soil deformation as shown in Figure 10. The occurrence of each mode depends upon the magnitude of the cavity pressure acting at the interface between the grout bulb and the surrounding soil. When the uplift force exceeds the weight of the overlying soil, a conical failure mode would occur and the associated ground heave becomes significant. When the uplifting force is less than the soil weight, the surrounding soil would only expand elastically or plastically and the ground heave is very minimal. It should be noted that when the failure mode is mobilised the grout could easily escape through the failure surface to the ground surface, giving the apparent phenomena of hydraulic fracture.

At failure the mechanism for causing the conical shearing surface is quite complicated. The friction between the cone and the surrounding soil is difficult to assess. However, assuming at critical conditions the friction could be neglected, Moh, Yang and Hwang (1994) established that the conical failure conditions will occur when:

$$U - W > 0 \quad (1)$$

$$U = \pi r^2 P_c \quad (2)$$

$$W = \frac{\pi \gamma}{3k^2} [(D + kr)^3 - k^3 r^3] \quad (3)$$

in which:

U : uplifting force,

W : weight of the conical soil mass,

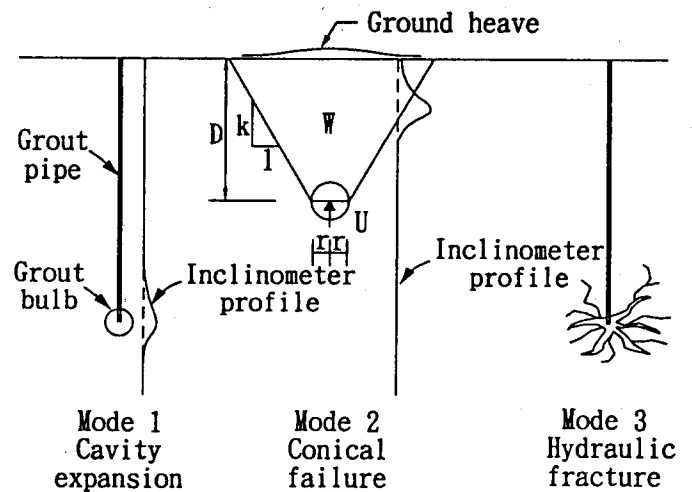


Figure 10. Modes of deformation of the soil mass (Modified from Moh, Yang & Hwang 1994)

r : radius of the grout bulb,

D : depth to the centre of the grout bulb,

P_c : cavity pressure,

γ : unit weight of the soil,

k : gradient of the conical surface.

It can be inferred from the inclinometer readings that in sandy materials the inclination of the shearing surface is around 30° from the vertical. These observations agree with that reported by Graf (1969). The equivalent k value is about 1.7.

3.2 Effects of foundation load

In order to interpret the results of compaction grouting to control foundation settlements, column load L shall be included in Equation (1) such that:

$$U - (W + L) > 0 \quad (4)$$

Re-arranging equations (2) to (4) gives critical depth:

$$D < r k \left[\frac{3}{r k \gamma} \left(P_c - \frac{L}{\pi r^2} \right) + 1 \right]^{\frac{1}{3}} - 1 \quad (5)$$

Family of curves using cavity pressures of 2 to 4 MPa are indicated in Figure 11. A column load of 320 kN and k value of 1.7 have been adopted. These curves represent the critical pressure and the critical radius of the grout bulb which would induce foundation heave for various depths.

4 DISCUSSIONS

4.1 Field performance

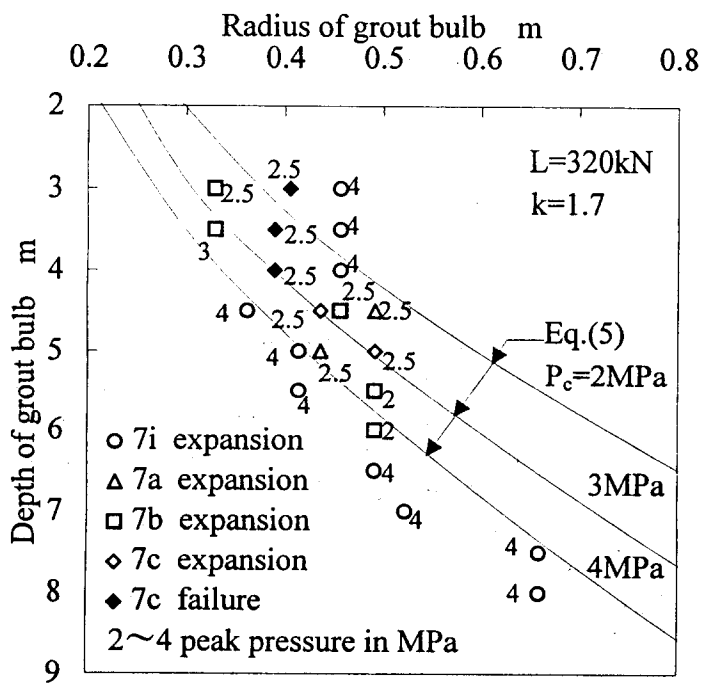


Figure 11. Critical grouting pressure to induce heave

The response to compaction grouting of this case history can be interpreted by the modes of deformation as proposed by Moh et al. (1994). As indicated in Figure 6, the 3 uppermost grout bulbs at grouthole 7c induced the failure mode where column heave of 6 to 8mm were observed. The remaining 27 grout bulbs, which were injected through groutholes 7i, 7a, 7b and the lower portion of grouthole 7c, were essentially in the cavity expansion mode where column heave of less than 1mm were induced.

The validity of the conical failure mechanism expressed by equation (5) is supported by the actual performance of this case history. The field records of the 30 grout bulbs which are presented in Figures 4 to 6 are plotted on Figure 11. The solid and the hollow symbols denote those grout bulbs which exhibited the failure mode and the cavity expansion mode, respectively. As shown in Figure 11, when the grout bulbs were injected with peak pressures greater than the critical cavity pressures as computed by equation (5), the conical failure mode occurred. For those grout bulbs which were injected with peak pressures lower than the corresponding theoretical critical pressures, the surrounding soil mass remained in the expansion mode.

4.2 Reloading stage

There are cases, for instance, at grouthole i the bulbs locating between depths of 4m and 3m, the injection pressures exceeded the critical values but failure modes were not induced. Heave should have been occurred according to equation (5).

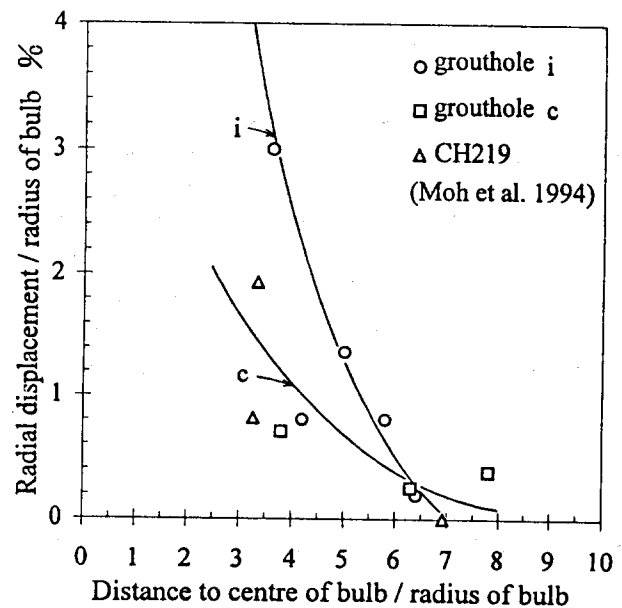


Figure 12. Distribution of radial displacement against radial distance to grout bulbs

Review of the settlement history of buildings A and B could explain the discrepancies. Settlements of the buildings were mainly attributed to diaphragm walling and excavations. These construction activities induced loosening effects to the adjacent soil mass. Much grout was used to fill the voids before pressure could build up.

4.3 Soil densification

There are evidences of densification of the subsoils. Table 1 shows that in the course of grouting the grout intake became less. Meanwhile the average peak pressure for the tertiary groutholes c were 20% higher than those for the secondary groutholes a and b. These comparisons indicate that stiffer soil conditions had been achieved by compaction grouting.

The soil densification effects are further supported by the results of inclinometer observations. Normalised with the radius of the grout bulbs, the distributions of the radial displacements against the radial distance to the grout bulbs are presented in Figure 12. The ratio between radial displacement to bulb radius represents the radial strain caused by compaction grouting. While the subsoil was unloaded under the plane strain conditions and was reloaded under the spherical cavity expansion conditions, exact solution for the stress-strain relationship would be difficult to obtain. Nevertheless, the relative soil stiffness could be inferred from Figure 12. The radial strain response to groutholes i were about 2 time of those response to groutholes c, implying that the shear modulus for the unloaded soil was about one half of the reloaded soil.

4.4 Zone of influence

Figure 12 indicates that the zone of influence of compaction grouting is about 6 times the radius of the grout bulb. The vertical extent is also about 6 times the radius as indicating in Figure 7. These observations are generally consistent with the findings of Meyerhof (1960) who measured the amount of densification caused by driving piles into cohesionless soils. The extent of the compacted zone along the pile shaft and beneath the tip extends to a distance of about 6 pile radius.

5 TENTATIVE OPERATION GUIDES

Statistics of the injected volume for various modes of deformation are given in Table 2, revealing the expansion mode consumed 75% of the total injected volume. Strictly speaking the expansion mode does not fulfill the prime purpose of raising foundations although these groutings have densified the soil mass. From the economical point of view, it will be a potential saving if these quantity could induce heave in the first instance.

Table 2. Injected volume for various modes of deformation

Building Number	Injected volume			Total injected volume m ³	
	of Re-loading columns m ³	Expansion mode m ³	Failure mode m ³		
A	9	21.2	79.1	9.8	110.1
B	3	3.1	29.7	1.8	34.6
Total	12	24.3	108.8	11.6	144.7
%	-	16.8	75.2	8.0	100

In order to further improve compaction grouting as a technique for raising subsided foundations, and to promote the status of this technique from 'experimental' to more 'rational', tentative guides based on this case history and according to equation (5) are proposed as follows:

1. When the maximum injection pressure is restrained by the capacity of the grouting equipment, compaction grouting shall be carried out as shallowest as possible in order to achieve ground heave.

2. When the maximum injection pressure is limited and shallow depth of grouting is restricted by foundations or by unfavourable soil conditions, for instance, where clayey layer is encountered, ground heave could be induced by increasing the radius of the grout bulb. Grout materials shall keep on pumping into the sandy subsoil until heaving is detected.

3. For foundations which have experienced

settlements, additional amount of grout to compensate the volume loss would be inevitable.

6 CONCLUSIONS

1. The conical soil mass failure mechanism is applicable for compaction grouting in sandy soils.

2. The critical pressure for inducing foundation heave depends on 3 basic factors, the depth of injection, the radius or the injected volume of the grout bulbs and the magnitude of the column load.

3. When the grouting pressure and the volume of each bulb are restrained, there is a critical depth beyond which the conical failure mode could not be mobilised.

4. For soil mass which has been unloaded due to various construction activities a reloading state will be inevitable before the conical failure mode could be mobilised.

5. In sandy soils the zone of influence of the densification effects induced by compaction grouting is about 6 times the radius of the grout bulb.

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