CONTROL OF GROUND MOVEMENTS CAUSED BY JET GROUTING

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ABSTRACT

Three ground treatment areas were formed by jet grouting in stratified sandy and clayey subsoils. The grouted piles had the diameter of 1.2 m and were formed by a double-tube technique. The maximum settlements occurred along the front row of the grouted piles were as high as 40 mm. The cumulative lateral displacements observed at an inclinometer casing distance 2.7 m to the front row of the grouted piles were about 15 mm. Inward lateral movements in the sandy layer and lateral expansion in the clayey layer were observed. It can be concluded that settlements is mainly attributed to the ground loosening effects caused by the drilling operations in the sandy layer. It was back-calculated that the amount of settlements induced by each row of the grouted piles was about 8 mm, diminishing as the distance from the piles increases. The influence zone ranges from 1 to 2 times the depth of the piles. Three settlement mitigations having various sequence of grouting were attempted. The philosophy is that the ground shall be improved before the subsequent drilling operations. The most effective mitigation was conducting grouting in stages with sufficient quiet periods between stages.

1.0 INTRODUCTION

Jet grouting is a process in which high speed water jet is utilized to cut the ground and meanwhile mix the disturbed soil in-situ with cement grout to form improved soil columns (grout piles, as commonly referred to). It can be applied in both sandy and clayey soils for improving soil strength, reducing soil permeability and for settlement mitigation around underground works such as bored tunnelling and deep excavations. While it did work successfully in numerous cases, however, it should be noted that jet grouting itself may induce a considerable amount of ground movements. Wong et al. (1994) reported that the installation of 23 piles in clay led to settlement of, up to, 58mm of an adjacent structure. Such an undesirable consequence cannot be overlooked.

This paper presents a case history in which jet grouting was conducted in stratified sandy and clayey subsoils with different construction sequences attempting reducing ground movements. Ground settlements and lateral displacements induced were closely monitored. A critical study on the performance provides valuable information on how ground settlements can be minimized.

2.0 CASE STUDIED

Jet grouting was conducted in a 200m section of the route on the Nankang Line of the Taipei Rapid Transit Systems for minimizing potential ground settlements due to boring of twin tunnels which are extremely close to adjacent buildings, of which one is a preserved historical monument. At places, the tunnels are even directly underneath some of these buildings. Figures 1 to 3 show the plans of the three areas in which the problem was the most serious. Also shown in these figures are the sequence of grouting and typical layouts of grout piles.

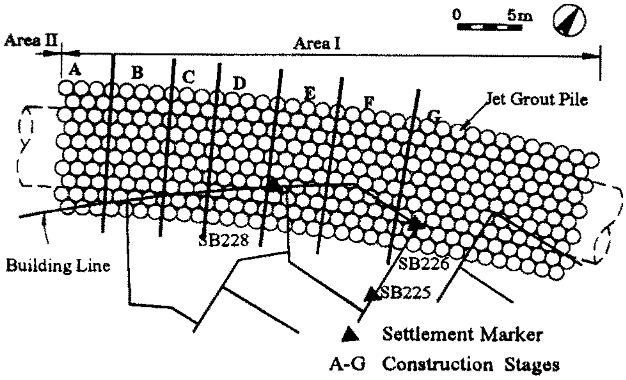

Fig. 1 : Extent of jet grouting in Area I

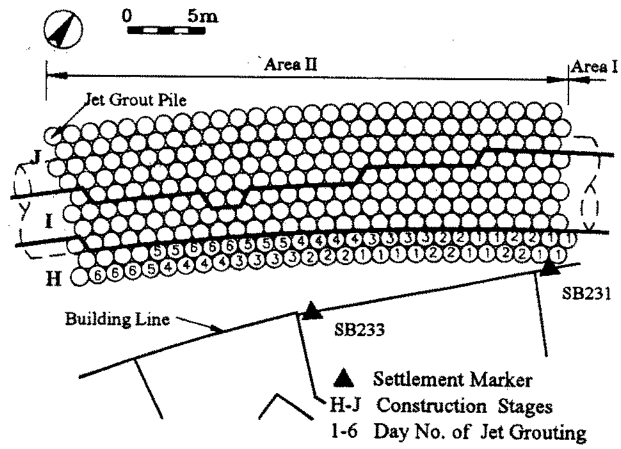

Fig. 2 : Extent of jet grouting in Area II

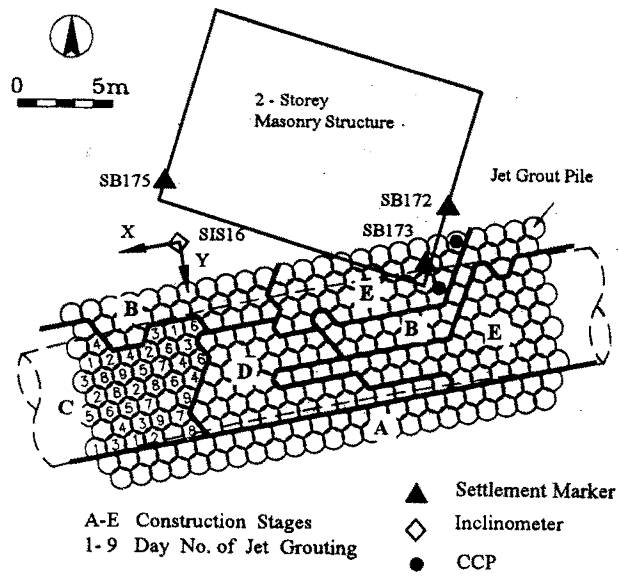

Fig. 3 : Extent of jet grouting in Area III

The two stacked tunnels are 6.1m in diameter and are at depths of 9.1m and 18.7m below surface. Figures 4 and 5 show two typical cross sections. In Areas I and II grouting was conducted to form a frame in the shape of flattened capital "A". In Area III in which the 2-storey historical monument is located, grouting was conducted in a conservative way that a solid rectangular block was formed. The details of the operation, including the quantities, spacings and the lengths of the piles, etc., in the three areas are listed in Table 1.

Table 1: Summary of layout and progress of jet grouting

Area	Extent of Grouting Area			No. of Rows Along Longitudinal Direction	Total No. of Grout Piles	Total No. of Inclined Piles	Spacing of Jet Grout Piles		No. of Piles Formed Per day		Max. Ground Settlement mm
	Width m	Length m	Depth m				Longitudinal m	Transverse m	Range	Average	
I	10.6	42.0	13.7	4	350	86	1.20	1.04	6-11	7	40
			19.8	6							
II	10.6	34.0	13.7	4	279	0	1.20	1.04	6-20	11	40
			19.8	6							
III	11.1	26.2	21.8	11	268	12	1.04	0.90	2-8	4	35

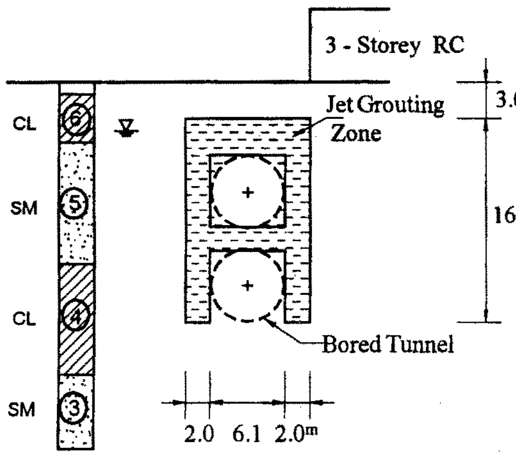

Fig. 4 : Typical cross-section for jet grouting Areas I and II

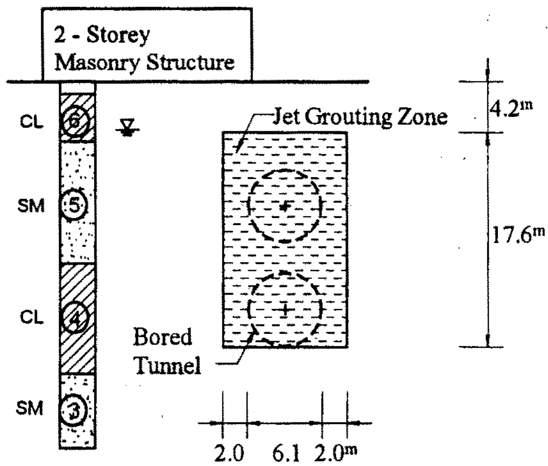

Fig. 5 : Typical cross-section for jet grouting Area III

3.0 SUBSOIL CONDITIONS

The site is located in the city central of Taipei. As can be noted from Figs. 4 and 5, the subsoils at the site comprise the typical 6 sublayers in the Sungshan formation. Sublayers 1, 3 and 5 contain silty sands (SM/ML) and sublayers 2, 4 and 6 contain silty clays (CL/ML). The properties of these sublayers are available in Woo and Moh (1990). The ground water table was at a depth of about 4m below surface.

4.0 JET GROUTING

The JSG jet grouting method, a double-tube technique, was adopted. The design diameter of the jet grout piles was 1.2 m. The piles were arranged in a staggered pattern. The jet grouting procedures were similar to shose reported by Kauchinger and Welsh (1989). The parameters for jet grouting in Areas I to III are summarised in Table 2.

Table 2: Summary of jet grouting parameters

Area	Grouting Method	Design Diameter of Grout Piles m	Stage	C/W Weight Ratio	Injection - Pressure, MPa		Rate of Injection ℓ/min	Withdrawal Rate min/m	Rotation Speed rpm
					Cement Grout	Air			
I & II	JSG	1.2	-	0.39	20.5-22.5	0.7	60-65	22	5-10
III	JSG	1.2	A	0.67	21	0.7	60	25	5-10
			B-E	0.53					
III	CCP	0.4	-	0.38	18-20	-	25-50	3-5	-

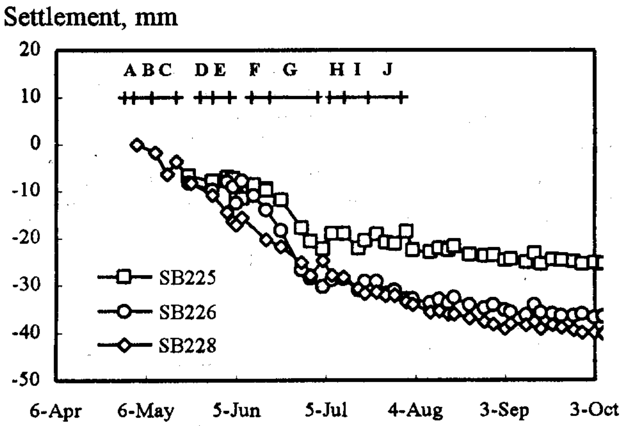

Fig. 6 : Settlement due to jet grouting in Area I

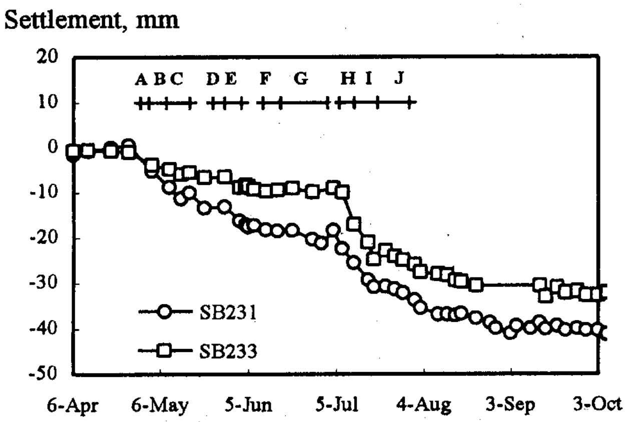

Fig. 7 : Settlement due to jet grouting in Area II

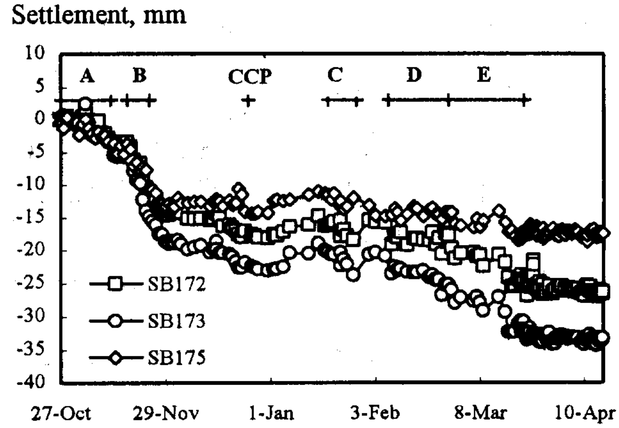

Fig. 8 : Settlement due to jet grouting in Area III

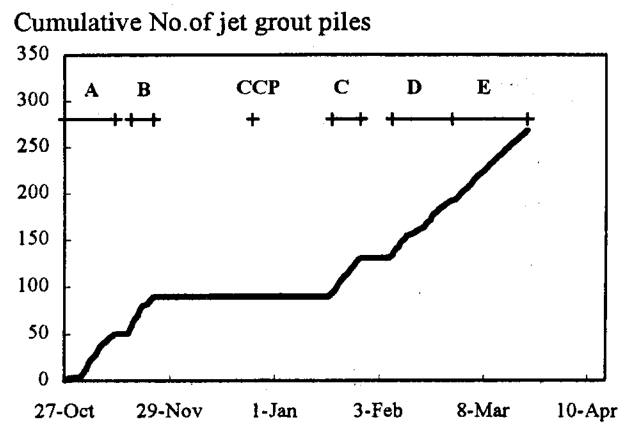

Fig. 9 : The progress of jet grouting in Area III

Areas I and II are next to each other while Area III is 40m to the east of Area I. In Area I, as depicted in Fig. 1, grouting was carried out in 7 stages, i.e., Stages A to G, progressing along the longitudinal direction of the tunnels. After the completion of grouting in Area I, grouting continued in Area II.

As depicted in Fig. 2, grouting in Area II was carried out in 3 stages, i.e., H to J, progressing from the side of the tunnels near to the buildings towards the other. Three to four machines were working at the same time and each machine was able to form 4 piles in a day. The pattern of grouting is similar in both areas and is illustrated in Fig. 2. In short, each machine was responsible for completing a cluster of four piles in each day. Clusters completed in different days were staggered and no adjoining clusters were completed in the same day.

In Area III, grouting was carried out in 5 stages, i.e., A to E, without a well-defined sequence, nor a clear pattern in each stage, except that adjoining piles were never grouted on the same day. As can be noted, grouting was suspended for 50 days after Stage B was completed.

As shown in Figs. 6 and 7, grouting in Area I took about two months to complete and grouting in Area II took only one month. Grouting in Area III, refer to Fig. 8, lasted for about 5 months with a 50-day intermission between Stage B and Stage C. As shown in Table 1, piles were formed at a daily rate of 7 piles in Area I, 11 piles in Area II and only 4 piles in Area III. The slower rate in Area III was because of the presence of the vulnerable 2-storey masonry structure on surface calling for a more cautious operation.

During the intermission between stages B and C in Area III, a trial with the CCP (Chemical Churning Pile), a single tube jet grouting technique, was conducted on 15 December, around the southeast corner of the 2-storey structure. The purpose of this trial was to

Table 3: Mix proportion for the CCP trial grouting

Type of Grout	Cement Grout		Chemical Grout	
	Cement	Water	Sudium Silicate	Water
Quantity	380kg	380ℓ	100ℓ	400ℓ
Total	500ℓ		500ℓ	
Volume	1000ℓ			
Gel Time	60sec			

observe any effects on minimising the consolidation settlement. Two grout piles of CCP were formed up to a depth of 22 m. The operating parameters for the CCP are presented in Table 2. The mix proportion of the chemical and cement grout are summarised in Table 3. As shown in Fig. 8, the maximum settlements of 3 mm occurred on 15 December. In view of the ground disturbance effects the trial was terminated. This cement/chemical grouting measure was no longer adopted in Area III.

5.0 GROUND MOVEMENTS

All the buildings adjacent to the tunnels are founded on shallow footings. The settlements induced are shown in Figs. 6 to 8. The maximum settlements were 40mm in both Areas I and II and 35mm in Area III. The different sequences of grouting in the three areas apparently did not lead to different results as far as the total settlements are concerned. The settlements subsequent to the completion of grouting were about 5mm to 10mm in Areas I and II, and nil in Area III.

Although the total settlements in the three areas were more or less the same, the settlement trends were somewhat different. Of particular interest is the trend shown in Fig. 8 for the settlements observed in Area III. The settlements were induced at a much faster rate in the first two stages of grouting, in comparison with the subsequent 3 stages, notwithstanding the fact that more piles were formed at closer distances in the latter stages.

The progress of grouting in Area III is shown in Fig. 9. A total of 90 piles were formed in Stages A and B, accounting for one third of the total, while the settlements induced in these two stages, refer to Fig. 8, were about two thirds of the total.

An inclinometer, SIS16, was installed at a distance of about 2.7m away from the last row of piles in Area III. The tip of the inclinometer was at a depth of 30m while grouting was carried out to a depth of 21.8m. Figure 10 shows the lateral displacement profiles induced by

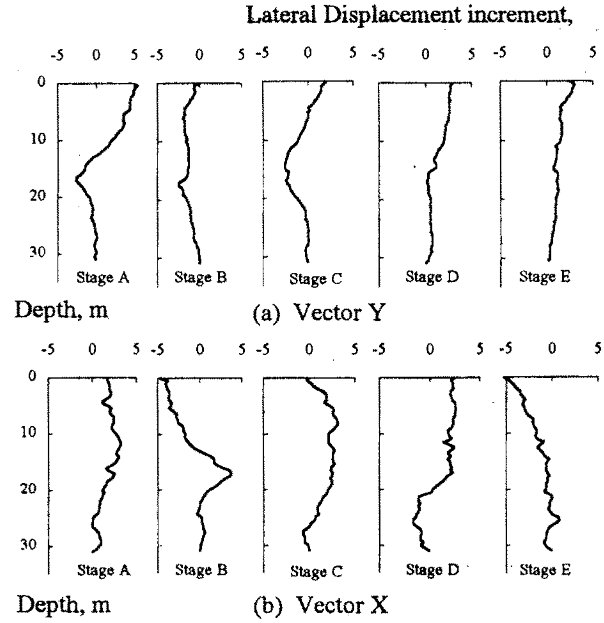

Fig. 10 : Lateral displacement increment at SIS16 between each stage of grouting in Area III

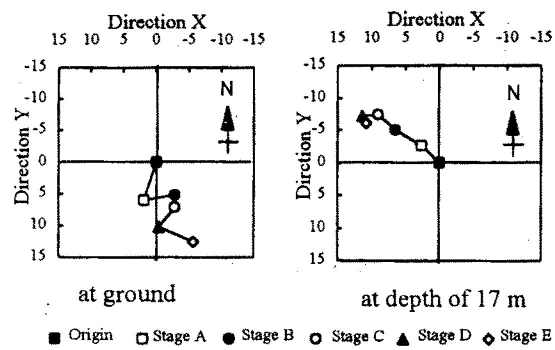

Fig. 11 : Direction of displacement of SIS 16 in Area III

each stage of grouting. At the depth between 13 m and 22 m where the sub-layer 4 clay is dominant, the ground moved toward the northwest and was away from the grouting zone. Above the depth of 13 m where the sub-layer 5 sand is dominant, the ground moved toward the southeast and was approaching to the grouting zone.

Figure 11 shows the steady northwest and southeast movements observed at the surface and at the depth of 17 m, respectively.

Table 4 summarizes the lateral and vertical ground movements observed at the inclinometer SIS16 and at the settlement marker SB175. A total of 90 piles were

Table 4: Summary of ground displacements caused by grouting in Area III

Stage of Grouting	No. of Grout Piles	Distance of Instrument to Nearest Jet Grout Pile, m		Displacements at Ground Surface Caused By Each Stage, mm			$\frac{\delta}{\Sigma\delta}$ %
		SIS16	SB175	Lateral $\vec{\delta}_h$	Vertical $\vec{\delta}_v$	Vector Sum $\vec{\delta} = \vec{\delta}_h + \vec{\delta}_v$	
A	49	11.4	13.4	6	5	8	28
B	41	2.6	5.0	5	9	10	34
C	41	4.6	7.0	2	1	2	7
D	87	5.8	8.2	4	1	4	14
E	50	5.4	7.7	5	2	5	17
Total	268			22	18	29	100

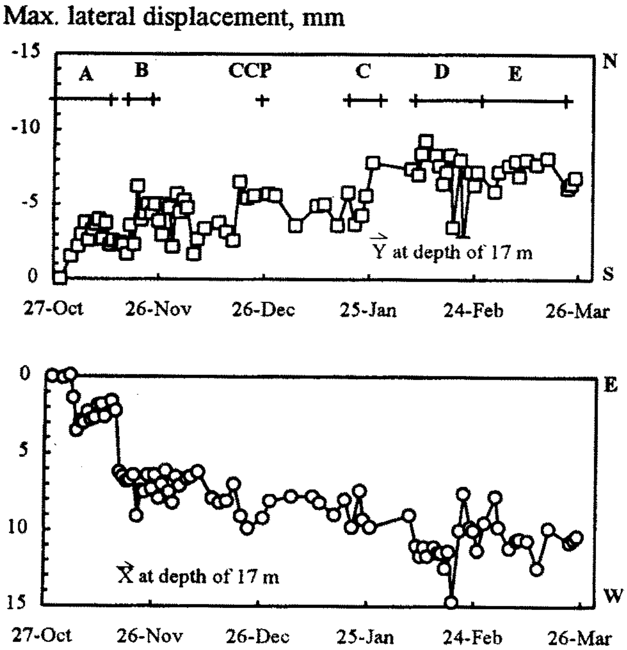

Fig. 12 : Lateral displacement of SIS16 versus progress of jet grouting

formed in Stages A and B, accounting for one third of the total, while the settlements and lateral movements induced in these two stages were about two third of the total, despite the distances from the grout piles to the two instruments were the longest among the other stages.

Figure 12 shows the lateral displacements of inclinometer SIS16 against the progress of grouting, indicating the ground response to the jet grouting activities. Since the lateral movement toward the grouting zone has been observed, there is evidence that the settlement is associated with the ground loosening effects caused by the drilling operations, in the sandy layer.

6.0 SETTLEMENT PROFILES

Figure 13 shows the settlements observed at various distances away from the boundaries of the treated zones in Areas I and II. They were normalized to the depth of grout piles. The data can be represented by a regression equation as follows:

$$\frac{\delta_x}{H} = 1.8 \times 10^{-3}\left(1 - \frac{x}{2H}\right)^3, |x| \le 2H, \quad (1)$$

where:

δ_x = the total ground settlement occurred at the distance x.
x= the absolute horizontal distance from the point of interest to the centre-line of the front row of the grout piles.
H= the depth of the grout pile.

In these two areas, as shown in Table 1, piles were in two different lengths, i.e., 13.7m and 19.8m. However, for simplicity, H=19.8m has been assumed in the regression analysis for deriving Eq. 1.

The settlement profile for Area III is shown in Fig. 14. The representative expression is:

$$\frac{\delta_x}{H} = 1.6 \times 10^{-3}\left(1 - \frac{x}{H}\right)^2, |x| \le H, \quad (2)$$

In this area, all the piles were of the same length of 21.8m.

As can be noted from these two figures that the zone of

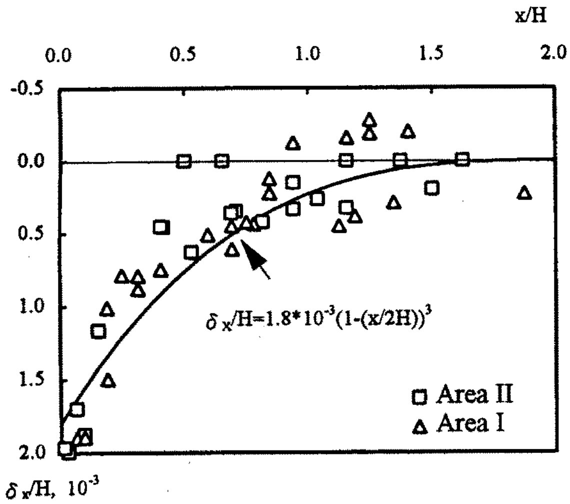

Fig. 13 : Settlement profile in Areas I and II

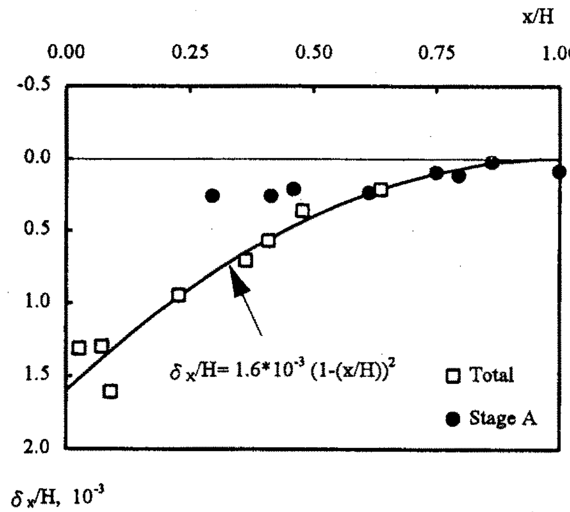

Fig. 14 : Settlement profile in Area III

influence extended to a distance of 2H from the boundary of the treatment in Areas I and II, while in Area III, the zone of influence was limited to H. This might be due to the less number of piles in each row in the latter case.

As mentioned previously, notwithstanding the sequences of grouting in the three areas were all different, the total settlements at the end were apparently similar. On the other hand, Fig. 8 and Table 4 indicate that two thirds of the ground movements occurred in the first two stages of grouting in Area III while only one third of piles were formed in these two stages. The intermission between Stage B and Stage C appears to have improved the soil strength.

To quantify the difference between the ground settlement in the early stages and the latter stages of grouting, it is necessary to study the settlements induced due to grouting in individual rows. Assuming the distribution of settlement due to each row of pile can be represented by a 2nd order equation and the zone of influence for a row is H, the regression equation can be generalized as follows:

$$\frac{\delta_{x1}}{H} = b \times 10^{-4} \left(1 - \frac{x}{H}\right)^2 \qquad (3)$$

where δ_{x1} is the settlement due to one row of grout pile. Analysis indicates that the coefficient b varies from 4 for Stages A and B and 0.6 for Stages C to E. The settlement due to the later stages were about 1/6 of that caused by the early stages.

7.0 SETTLEMENT MITIGATION MEASURES

According to Wong et el. (1994), and based on the lateral displacements observed in the sandy layer at SIS16, ground settlement due to jet grouting can be attributed to the loosening effects as a result of drilling. In this case history, the sequence of grouting adopted in Area I is the one commonly adopted. Four mitigation measures were attempted in Areas II and III:

(1)As was the case in Area II, grouting started from the side near the buildings and proceeded away from the buildings, hoping that the completed piles would become a barrier reducing the building settlements to be induced in the subsequent stages of grouting.

(2)As was the case in Area III, piles were formed sparsely so that no two adjoining piles were formed in the same day. The philosophy is that the piles formed on the previous days would strengthen the surrounding ground, hoping that disturbance due to the drilling operation could be less.

(3)Also as was the case in Area III, sufficient curing time was provided between Stage B and Stage C of grouting, hoping that the ground could be improved before the subsequent operation.

(4)Chemical grouting by the CCP method was tried in Area III. This method was soon abandoned when 2 grouted piles caused considerable amounts of ground disturbance.

The first measure did not really make much difference as can be noted by comparing the settlements induced in

Areas I and II. The 50-day intermission between Stage B and Stage C in Area III appears to have helped in reducing the settlements in the subsequent grouting. The improvement in soil strength apparently reduced the loosening effects.

According to Wong and Hwang (1997) , the 1-day strength of the grouted ground is about 15% of the 21-day strength. While the gaining of strength and stiffness are the major contributing factors on minimising ground settlements, it would be preferably that the time interval for forming the adjacent grout piles be further extended for mitigation measures 1 and 2 to be effective.

The settlement effects due to the inclined grout piles was not obvious in this case history. Table 1 indicates that the settlements for Cases I and II were identical, whether or not the inclined jet grout piles were installed.

8.0 CONCLUSIONS

Based on the results obtained, the following is concluded:

(1)In the case studied, the maximum settlement induced by each row of piles was about 8mm (typical), diminishing as the distance from the piles increases.

(2)The influence zone ranges from H to 2H.

(3)Evidences of inclinometer monitoring indicate that ground settlements are mainly attributed to loosening and disturbance in the sandy layers caused by the drilling operations.

(4)In clayey layers, small amounts of lateral expansion caused by jet grouting were observed.

(5)Settlements can be reduced by carrying out grouting in stages with sufficient quiet periods between stages.

9.0 ACKNOWLEDGMENTS

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10.0 REFERENCES

Kauchinger, J L and Welsh, J P - Jet Grouting for Urban Construction; *Proceedings of the 1989 Seminar, Design, Construction and Performance of Deep Excavations in Urban Areas*, MIT, 1989, pp1-58.

Wong, L W and Hwang, R N - Evaluation of Jet Grouting by In-situ Tests, *Proceedings of the International Conference on Ground Improvement Techniques*, May, 1997, Macau.

Wong, L W, Shirlaw, J N and Kao, H S - Application of Jet Grouting in Geotechnical Engineering, *Proceedings of the International Symposium on Structures and Foundations in Civil Engineering*, October, 1994, Hanzhou, China. (in Chinese)

Woo, S M and Moh, Z C - Geotechnical Characteristics of Soils in the Taipei Basin, *Proceeding of the Tenth Southeast Asian Geotechnical Conference*, April, 1990, Taipei, Taiwan.