

# **JACKING UP BUILDINGS BY GROUTING**

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## Jacking Up Buildings by Grouting

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**ABSTRACT:** During the construction of the Taipei Rapid Transit Systems, trials were out for evaluating the effectiveness of several grouting techniques in jacking up structures and there were also cases in which tilts of buildings were indeed corrected by grouting. This paper discusses the procedures adopted and the results obtained. Also discussed are the heave mechanisms involved.

### 1 INTRODUCTION

Compensation grouting has been widely adopted to correct building settlements and/or tilts in underground constructions, being tunnelling or deep excavations. For the construction of the Taipei Rapid Transit Systems, compensation grouting using the compaction grouting technique has been opted by several contractors as a provisional measure for protecting buildings adjacent to the works and trials were carried out to verify its effectiveness. The conventional procedures were adopted and the results were disappointing. The technique was later modified to suit the local ground conditions. The modified technique was adopted to jack up a row of 8 columns, which suffered excessive ground settlements, of a 4-storey shop houses successfully.

### 2 GROUTING IN SOFT GROUND

#### 2.1 COMPACTION GROUTING

Among the various techniques for compensating for ground loss, compaction grouting is probably most known to engineers. Compaction grouting is a process in which low slump paste is injected into the ground at high pressures for the purpose of reducing the compressibility of soil and/or increasing soil strength. It was adopted by several contractors as a provisional building protection measure and, in accordance with specifications, trials had to be conducted beforehand to verify its effectiveness. Take Contract CH221 of the Hsintien Line for example, trials were carried in two holes, namely, GH-1 and GH-2. Grouting started at a depth of 18m below surface and proceeded upward till a depth of 2m. In each hole, 32 bulbs were formed at spacings of 0.5m. The volume of grout in each bulb was 134 liters, giving a total of 4.3 cubic meters of grout injected in each hole. If the grout indeed expanded uniformly in all the directions in horizontal planes, the two grout columns would be 0.6m in diameter.

The test site is located in the T2 Zone of the Taipei Basin and the subsoils belong to the so-called Sungshan formation. The typical properties of the Sublayers VI, V and IV, in which grouting was carried out, of the Sungshan formation are given in Table 1.

In each cubic meter of the grout injected, there were: 320 kg of gravel (upto 10mm in size), 1040 kg of sand and silt, 160 kg of cement, and 426 kg of water. The slump of the grout was about 25mm. The grout was injected at a maximum line pressure of 4 MPa. Figure 1 shows the accumulative surface heaves measured at distances of 0.5m, 1m and 1.5m away from

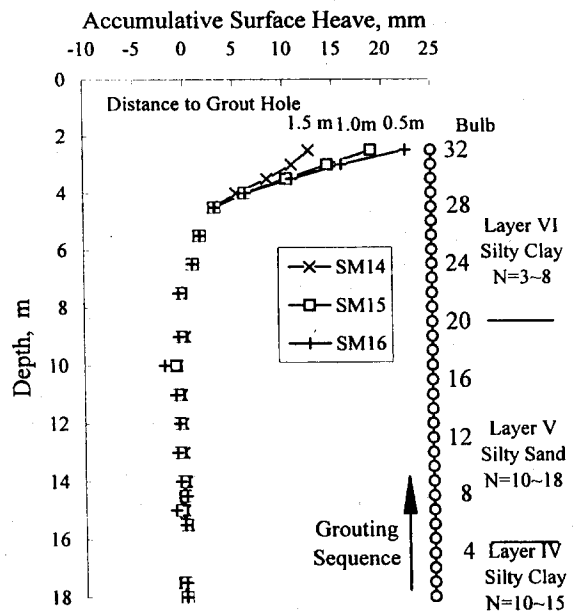


Figure 1. Ground heaves due to grouting in Hole GH-1 (CH221)

Table 1 Properties of Subsoils

Soil Layer	Soil Type	Total Unit Weight kN/m <sup>3</sup>	Dry Weight kN/m <sup>3</sup>	Water Content %	Void Ratio	PI	LI	Cc	m <sub>v</sub> (kPa) <sup>-1</sup>	Gradation			Coef. of Permeability m/sec
										sand %	silty %	clay %	
VI	CL	19	14.5	31	0.87	36	13	0.29	2.5 x 10 <sup>-4</sup>	10	58	32	1 x 10 <sup>-8</sup>
V	SM	19.5	15.4	26						76	20	4	4 x 10 <sup>-6</sup>
IV	CL	19	14.3	32	0.94	34	12	0.39	1.6 x 10 <sup>-4</sup>	8	61	31	4 x 10 <sup>-8</sup>

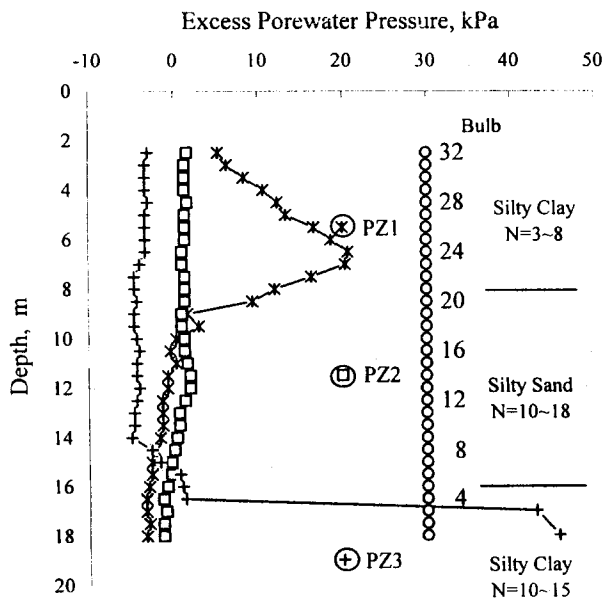


Figure 2. Porewater pressure response to grouting in Hole GH-2 (at a distance of 1.6m)

grouting Hole GH-1 as the grouting proceeded, bulb by bulb, from the bottom. As can be noted that heaves were practically nil when injection was carried out below a depth of 8m. As soon as the nozzle entered the upper silty clay layer at the depth of 8m, surface heaves became apparent. The final heave at a distance of 0.5m away from the grouting hole was 22mm. However, in three days, half of this heave was gone. Unfortunately subsequent settlements were not monitored.

Figure 2 shows the excess porewater pressures obtained by three piezometers, i.e., PZ1, PZ2 and PZ3, installed at a distance of 1.6 m away from the grouting hole GH-2, when grouting was carried out in the said hole. They were installed at depths of 5.5m, 11.5m and 19m, respectively. As can be noted that PZ3, which was buried in the lower silty clay layer, showed a drastic excess pore pressure of 50 kPa when injection was carried out in this clay layer. This excess pressure dissipated rather quickly as the nozzle left this layer and little response was measured afterward. On the other hand, PZ1, which was located in the upper silty clay layer did not show any response till the nozzle entered the upper silty clay layer. Piezometer PZ2 showed little response all the times because of the rapid dissipation of excess pore pressures in sands.

It took 3 to 7 minutes to complete grouting for each bulb. Subsequently, it took 25 minutes to take readings from all the instruments including piezometers, settlement plates, inclinometers, rod extensometers, etc. Therefore, each cycle was roughly 30 minutes. Piezometer readings were taken immediately after the halt and immediately before the restart of the injection. Figure 3 shows these two sets of readings obtained by PZ-1 which was buried at a depth of 5.5m in the upper silty clay layer. As can be noted that the excess pore pressures were minimal before the injection for Bulb 19 which was at the clay/sand interface. Subsequently, the increment of excess pore pressure as each ball was injected exceeded the dissipation of the pressure during the intermission and excess porewater pressure quickly built up. After Bulb 24, the pressure increment was suppressed by the dissipation and the excess porewater pressure gradually decreased.

At the end of the operation in GH-2, the excess porewater pressure was about 5.3 kPa and reduced to -3.7 kPa 10 days later, giving a total reduction of 9 kPa. For a  $m_v$  value of  $2.5 \times 10^{-4}$  /kPa and an effective thickness of consolidating layer of 6m, an excess porewater pressure of 9 kPa, if uniformly distributed, would lead to a settlement of 13.5mm, while the surface heave is estimated to be only 10mm at a distance of 1.6m away from the grout hole based on the information given in Fig. 1. It will not be a surprise if the ground fully settled back to its position

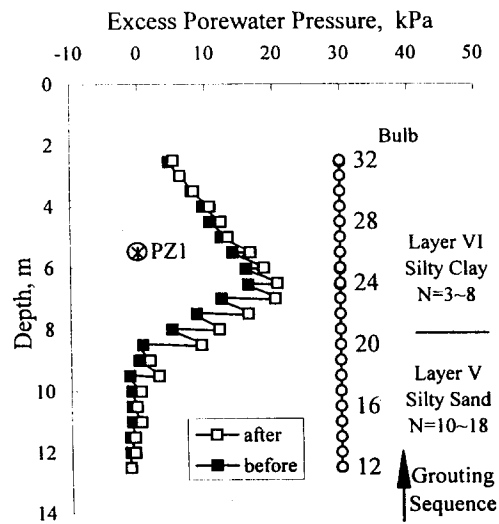


Figure 3. Excess porewater pressures before and after each injection (PZ-1 at 1.6m from Hole GH-2)

before the trial. In fact, compaction grouting was indeed carried out in an attempt to jack up one end of a 4-storey building supported on a mat foundation and a heave of 25mm was achieved. However, the building settled back to its original position in 7 days after the operation.

Cone penetration tests were performed at 2 locations prior to the trial and at 10 locations after the trial. The results indicated insignificant improvement in soil strength even at a distance of 1m away from the grouting holes. This again is hardly surprising because, as mentioned previously, that the grout displaced a cylindrical column of 0.6m in diameter and the effects of grouting are at best equal to pressing a solid pile of the same diameter into the ground. It is a well-established fact that the densification effects are minimal beyond a distance of one diameter away from the perimeter of a pile in soft ground.

Based on these results, it is concluded that a large quantity of grout is needed for ground heave to be significant if compaction grouting is to be carried out in loose to medium sands. In soft clays, ground heave is immediately apparent because of the undrained behavior of the clays. However, as excess pore pressures dissipate, ground will settle back to its original position.

## 2.2 MODIFIED SCHEMES

Since it was proved ineffective, and might even be harmful, to carry out grouting in the upper silty clay layer, it was desirable to perform trials in the underlying silty sands to see if better results could be obtained. Another trial was added to the program and grouting was carried out in the silty sands in such a manner that as much as grout was injected and the grouting pipe was raised only when the line pressure exceeded the capacity of 6 MPa set by the manufacturer. The operation started at a depth of 13m in Hole GH-3 which was located not far from the two previous holes. To enable more grout to be injected, the slump of the grout was increased from 25mm to 60mm. When grouting continued to a depth of 8m, cracks appeared at the ground surface and grout escaped through fissures. However, the ground heaves were insignificant. The total volume of the grout injected was 7 cubic meter and, if a cylindrical body was formed, it would be about 1.2m in diameter.

Trials were carried out in two more holes, namely H2 and H3, by the contractor of Contract CH219 of the Hsintien Line. Grouting was carried in Hole H2 between depths of 11.5m and 10.2m on December 18, 1992. The grout contained sand, fly ash and water, but no gravel. The ratio of sand to fly ash was

3:1 by weight. The slump of the grout varied from 150mm to 200mm. Figure 4(a) shows the ground response measured by inclinometers I1 and I2 and rod extensometers D1 and D2 when grouting was carried out at depths between 11.5m and 10.2m (Bulb H2-1). A total of 6 cubic meters of grout was injected and the diameter of the bulb would be 2.4m. A maximum lateral displacement of 6.5mm was measured by Inclinometer I1 installed at a distance of 3.7m away from the bulb while Inclinometer I2 installed at a distance of 5.5m away from the bulb showed little response.

The nozzle was raised to a depth of 8m and the second bulb was injected (Bulb H2-2). When the total quantity of grout reached 3.8 cubic meters, a crack of 10mm in width and 5m in length was observed at ground surface and the operation was halted. Figure 4(b) shows the incremental ground response during the injection of this bulb which combined with the first bulb to form a tumbler with a head diameter of 1.6m. It should be noted that, since the both grout holes were inclined at an inclination of 75° from the horizontal, the distances from the grout bulbs to the inclinometers and rod extensometers varied from bulb to bulb.

Grouting resumed at a depth of 12m in grout Hole H3 on December 20 with a grout containing sand, bentonite, and water, but no gravel. The sand/bentonite ratio is 8 to 1 by weight. The slump of the grout was 50mm to 70mm. When the quantity of the grout reached 14 cubic meters (Bulb H3-1), the casing for Inclinometer I1 ruptured at a depth of 1.5m and grout escaped to surface. The diameter of the bulb is estimated to be 3m. The ground response is shown in Fig. 4(c).

The trial was resumed two days later (December 22) in Hole H3 and the slump of the grout was increased to 100mm. Grouting was carried out at a depth 10.5m and was halted because of bursting of the grouting pipe after 3.5 cubic meters (Bulb H3-2) of grout was injected. Four more days later (December 26), grouting was resumed in the said hole at a depth of 9m and 4.1 cubic meters of grout was injected (Bulb H3-3). Unfortunately, ground response was not monitored for these two bulbs.

An additional amount of 4.1 cubic meters of grout (Bulb H3-4) was injected on the following day (December 27) at a depth of 8m when cracks showed up at ground surface. The diameter of the bulb is estimated to be 2.4m. Surface heaved up by 15mm during this operation.

The ground heaves at the end of grouting in each hole and 5 days after the trial are as follows (in mm):

	Settlement Markers			
	SM11	SM12	SM18	SM19
End of H2	21.4	18.6	13.6	11.9
End of H3	10.5	9.1	15.8	19.0
5 days later	7.9	6.7	9.5	10.5

Measurements obtained on the 7th day after the trial showed no subsequent settlement.

Grouting was indeed conducted to jack up a row of 8 columns of a 4-storey shop house supported on footings in the Panchiao Line. A maximum heave of 25mm was achieved and subsequent settlements were with 20% of the heave. Minor cracks did show up on the floor and the sidewalks. Other than that, no other damages were observed.

### 3 HEAVE MECHANISM

Figure 5 is a plot summarizing the observations discussed above. Hollow circles represent cases in which little ground response was observed. Solid squares represent cases in which cracks were observed, however, little ground movements were observed. Solid discs represent cases in which appreciable amounts of ground heaves were observed. Also shown in the figure are the supplemental data obtained in Contract CH218 of Hsintien Line and Contract CT201A of the Tamshui Line.

A relationship appears to exist between the depth and the diameter of the grout bulb when cracks occurred or when ground heaves became significant. It is hypothesized that in the initial stage of grouting, the bulb simply expanded, as illustrated in Fig. 6, in all the directions and the surrounding soils were expelled outward to make space for the grout to fill. This continued till the resultant of vertical components of the forces acting on the upper half of the bulb equals the weight of the soil cone above the bulb. Cracks showed up at ground surface as soon as this critical condition was reached and ground heaves then followed. The critical condition can be expressed as follows:

$$\pi \left( \frac{D}{2} \right)^2 p \geq \frac{\pi \gamma}{3k^2} \left( \left( H + \left( \frac{kD}{2} \right) \right)^3 - \left( \frac{kD}{2} \right)^3 \right) \quad (1)$$

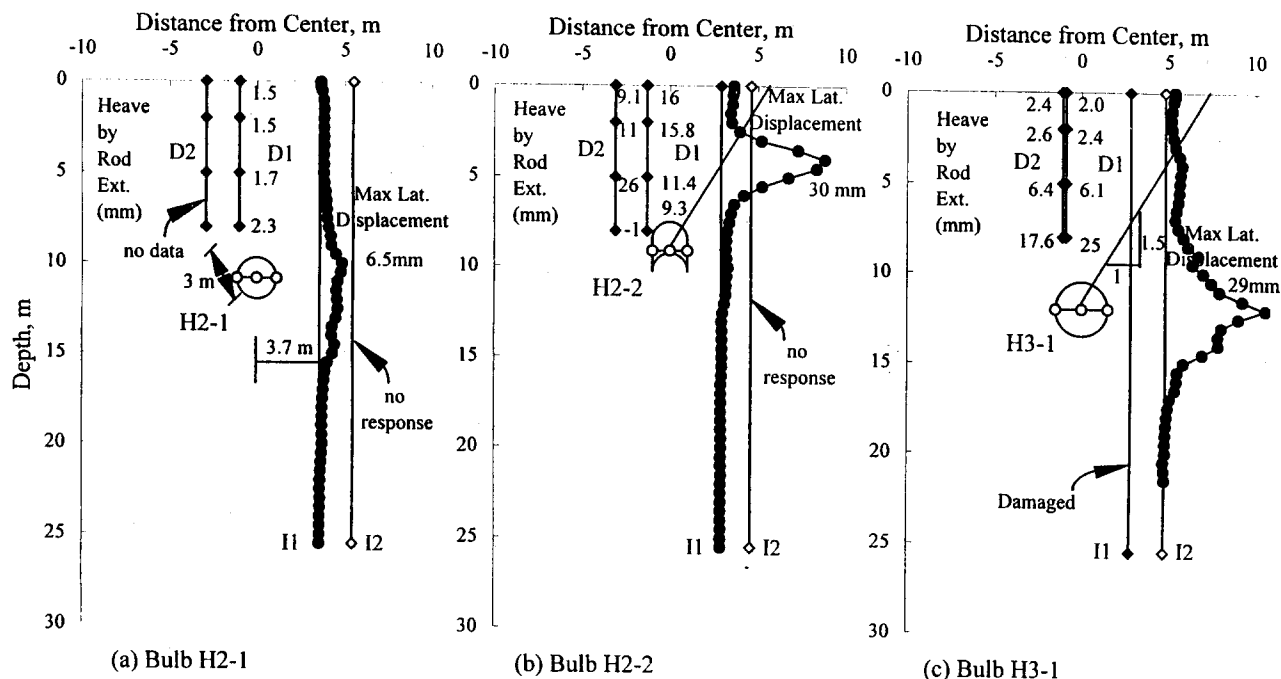


Figure 4. Ground movements (incremental) due to grouting in Holes H2 and H3 (CH219)

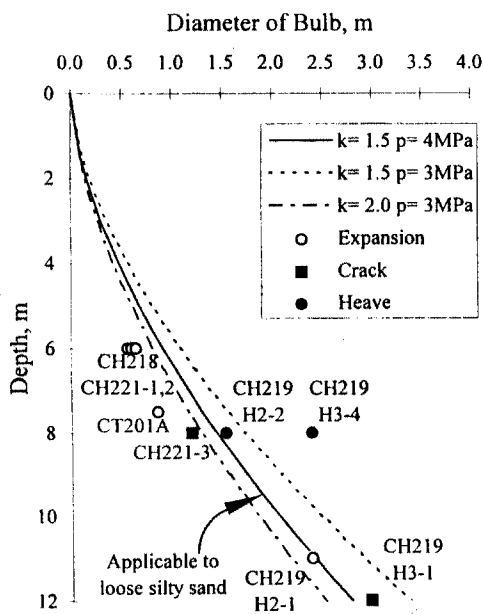


Figure 5. Observations - grouting in loose silty sands

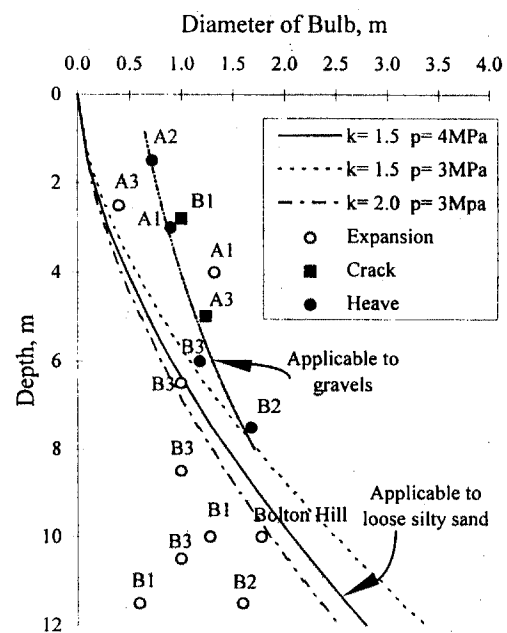


Figure 7. Observations - grouting in dense gravelly sands

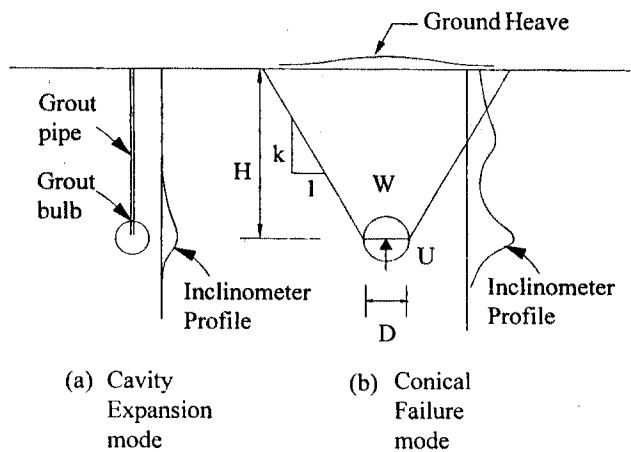


Figure 6. Heave mechanism

where

- $p$  = pressure in the bulb
- $H$  = depth of the center of the bulb
- $D$  = diameter of bulb
- $k$  = side slope of failure cone, i.e., slope of slip surface
- $\gamma$  = unit weight of soil

The data appear to suggest pressures of 3 to 4 MPa in bulbs and slopes of 1.5:1 to 2:1 (vertical : horizontal) for the slip surfaces. Contrary to what was believed, the occurrence of cracks appears to be unaffected by the slump of the grout.

#### 4 GROUTING IN HARD GROUND

Trials have also been carried out in six holes, A1~A3 and B1~B3, in a gravelly sand layer by the contractor for Contract CC275 of the Chungho Line. The layer contains gravels up to 90mm in size with SPT blow counts varying from 25 to 100. The results are shown in Fig. 7. In these trials, different types of materials, with slump varying from 15 mm to 250mm, were injected. A maximum ground heave of 122mm was achieved when grouting was carried out in Hole B3 at a depth of 6m. Subsequent settlements were generally less than 10% of the heaves.

As can be noted from the figure that, similar to the cases for soft ground, a relationship does exist between the depth and the diameter of grout bulb at the critical stage when cracks and/or heave occurred. However, more grout is required (i.e., larger diameter of the bulb), in comparison to the cases of soft ground, to reach the critical condition. One of the reasons is that the fast drainage in sands released much of the pore pressures and increased internal friction in the bulbs. Again, observations does not suggest any correlation between the occurrence of cracks and the slump of the grout. Tests showed that, if the amount of water increased from 426 kg to 475 kg in each cubic meter of grout, corresponding to an increase of water contents from 28% to 32%, the slump would increase from 25mm to 250mm. It is hard to believe that this extra amount of water should promote premature hydraulic fracturing.

#### 5 CONCLUSIONS

1. The predominate factor governing the effectiveness of compensation grouting using the compaction grouting technique for the purpose of lifting up structures is the permeability of soil.
2. Compaction grouting is most effective in dense sand and is effective to a certain extent in loose silty sand. If compaction grouting is to be applied in clays, the operation shall be carried out in an extremely slow pace to allow excess pore pressure to dissipate. Additional grout should be continuously injected if ground keeps on settling.
3. The heave mechanism is fully explainable using the theory of conic failure in soil.
4. Slump, varying from 25mm to 250mm, of the grout does not appear to affect the occurrence of cracks and/or heaves.

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