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Using fracture grouting to lift structures in clayey sand*

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Abstract: An inclined seven-story reinforced concrete building was leveled by a fracture grouting technique with quick-setting grout on a differential thickness of a clayey sand layer. The permeability and strength of clayey sand were controlled by clay content, although sand was the primary component of the foundation soil. The elevations of the building columns at basement level were closely monitored to record both the heaved volume of mat foundation after grouting and the settled volume during pore pressure dissipation. During the stabilizing stage of grouting, the foundation soil was densified by the repetitive fracturing process, which resulted in the lateral movement of the foundation soil. When the grout is less able to push soil laterally than upwards, the building starts to lift, the so-called lifting stage of grouting. The grouting efficiency is influenced by soil type, soil stress history, and foundation pressure. A final grouting efficiency of 27% and a linear relationship between grout use and percentage of elevation were obtained when this building was successfully and permanently leveled.

Key words: Fracture grouting, Gel time, Mat foundation, Grouting efficiency, Clayey sand
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1 Introduction

Compensation grouting is a technique for offsetting ground subsidence as a result of underground excavation and tunneling. The basic principle is to inject grout into the zone between the tunnel and overlying buildings to compensate for the ground loss and stress relief induced by underground excavation (Mair and Hight, 1994). The compensation grouting is conducted through a series of grouting tubes, collectively known as a Tube A Manchette (TAM), radiating horizontally from a vertical shaft as shown in Fig. 1. Electro-level beams embedded horizontally above the TAM are used to indicate when to begin and when to stop grouting, so that settlements are limited to specified amounts (Boone *et al.*, 1997). The low-viscosity particulate grouts intrude into the soil and introduce solids, enabling the upward displacement, which contributes to the compensation effect for ground settlement associated with tunneling (Soga *et al.*, 2004). The major limitation of this technique is that the high mobility and low viscosity of the grout can cause difficulties in controlling the grout location. Grout with a quick-setting time can be used to partly solve this problem, but problems remain.

The effectiveness of compensation grouting can be evaluated by the amount of soil heave for a given injected grout volume (Soga *et al.*, 2004). Grouting efficiency, η, is defined as the ratio of the soil heaved volume, V_E, to the injected volume of grout, V_{inj}.

$$\eta = \frac{V_E}{V_{inj}}. \tag{1}$$

The grout efficiency is usually less than 1, owing to the loss of fluid from grout bleeding, escape of the grout from the designated area by migration along fractures, and soil settlement by virtue of the dissipation of positive excess pore pressures generated

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during grout injection. Komiya *et al*. (2001) conducted a field trial of shield tunneling in a deep soft clay deposit to investigate the long-term consolidation effect on grouting efficiency. A mixture of cement, water and water-glass with a gel time of 20 s was used as the grout. The grouting program included a tail void grouting operation applied immediately after the machine passage and grout jacking when the machine was approximately 5 m ahead of the injection points. In both cases, the monitoring results showed that the upward displacement, owing to either grouting, is negated by the consolidation settlement, resulting in a net settlement. It is likely that the considerable consolidation of clay after grout injection is due to the dissipation of the excess pore pressures generated when the injected grout shears the sensitive and compressible clay. This indicates that the grouting efficiency in soft clay may be negative.

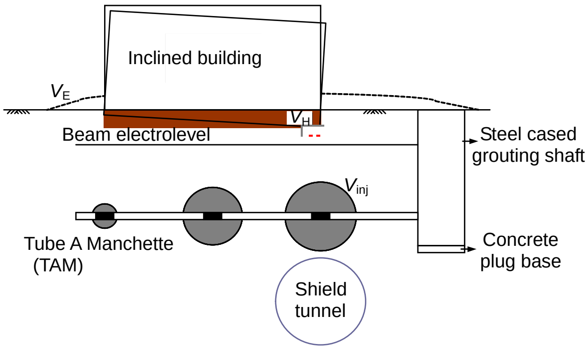


Fig. 1 Conceptual diagram of Tube A Manchette grouting points for compensation grouting (Mair and Hight, 1994)

From laboratory tests, Soga *et al*. (2004) found that the grout efficiency was dramatically reduced to a negative value with time for normally consolidated or lightly over-consolidated clays. This was due in part to extensive shearing during the injection and also to the ultimate increase in mean effective pressure around the injection point caused by the injection pressure locked in when the grout solidified (Fig. 2). However, for heavily over-consolidated clays, during the consolidation stage, pore water migrated from the positive excess pore pressure zone around the injection point to the negative zone some distance away. The compression near the injection point and swelling at a site distant from the injection point resulted in a negligible consolidation effect.

In addition to the efficiency loss discussed above, the efficiency of compensation grouting, ξ, defined as the ratio of building settled volume to total injected grout volume, may be further reduced by far-field geometry effects (e.g., the grout beneath the mat foundation can only contribute the effective lift of the inclined building, V_H) as shown in Fig. 1.

$$\xi = \frac{V_H}{V_{inj}}. \tag{2}$$

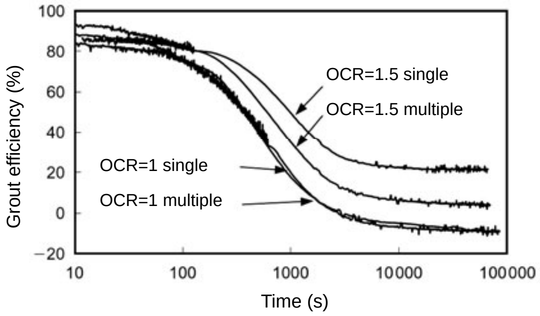


Fig. 2 Fracture grouting efficiency in over-consolidation ratio (OCR)=1 and 1.5 clay (Soga *et al*., 2004)

Linney and Essler (1994) conducted a compensation grouting trial at Redcross Way in London. The grouting program consisted of two phases. The first phase was the conditioning of the ground, in which fracture grouting was conducted to tighten up the ground prior to lifting. Conditioning involved the frequent injection of low volumes of grout, which created fractures in the clay. Conditioning was carried out throughout the fracture zone until movements of the overlying structure were detected. A relatively fluid cement/bentonite grout was injected through sleeved tubes while the movements of the warehouse and ground surface were monitored. The second phase was hydrofracture grouting to provide uplift. After the foundation soil between the warehouse and fracturing zone was tightened, the foundation soil behaved like a raft, rising with the warehouse. The trial demonstrated that heave could be controlled to within 1–2 mm of predefined targets. Some relaxation within the ground was observed after fracture grouting ceased, suggesting that small further injections would be needed in cases where high levels of compensation were required. The results of the trial are promising in terms of using grout injection to compensate for tunnel-induced settlement in the London clay.

There has been limited research regarding compensation grouting in cohesiveless soils, though fracturing of cohesive soils has been extensively studied (Linney and Essler, 1994; Komiya *et al*., 2001; Soga *et al*., 2004). Fracturing of cohesiveless soils was initially associated with the oil industry (Khodaverdian and McElfresh, 2000; Bohloli and de Pater, 2006). Recently, many cases have demonstrated that the compensation grouting technique can be applied to compensate the instantaneous settlement caused by tunneling in cohesiveless soils within the above limits (Lee *et al*., 1999; Sugiyama *et al*., 1999; Lee, 2002). Tunçdemir and Ergun (2009) conducted a series of laboratory tests, associated with fracture grouting in cohesiveless soils via microfine cement grouts. They investigated the volume of grout injected and the fracturing pressure, and then derived a relationship between soil conditions (grain size distribution, relative density, and overburden stress) and grouting parameters (grouting pressure, injected volume of grout, rheological properties of the grout or water/solids ratio). Soga *et al*. (2005; 2006) and Gafar *et al*. (2008) reported that fracture initiation requires the presence of a local heterogeneity around the injection point and that the water/solids ratio and fines content play an important role in sand fracturing. The lower the water/solids ratio, the larger the volume of grout injected and the better the grout efficiency.

The object of this study includes two aspects: (1) trying to establish a proper grouting program to lift an inclined building in a soft clayey sand deposit and a method to evaluate the grouting efficiency through a suitable monitoring system; and (2) recommending a model of linear relationship between the accumulative grout volume and the elevated percentage of the inclined building. The intercept and slope of this relation may be dependent on soil type, soil stress history, building foundation pressure, and this relationship is observed in other independent similar projects.

2 Background

2.1 Subsurface conditions

The subsurface profile at the site has changed radically from southwest to northeast (Fig. 3). The foundation soils consisted of soft clayey sand, sand and gravel, and siltstone bedrock, and the surface of sand and gravel layer has dropped toward the east, where it is overlain by 7 m of normally consolidated clayey sand (borehole BH-2). This site was located at the toe of foothills, and the long-term groundwater level in confined sand and gravel layer was 1 m above the ground surface due to groundwater pressure from the hill. The seven-story reinforced concrete building, with a one-story basement, was supported on a mat foundation of 30 m by 20 m, 4.5 m below the surface. The deep excavation and dewatering activity at a nearby construction site lowered the groundwater level in the sand and gravel layers significantly, and this resulted in the dissipation of excess pore pressure from the clayey sand layer to the sand and gravel layer. Since the compressible layer of the clayey sand was the thickest at the building's northeastern corner, the structure was inclined to the northeast at 1/99.

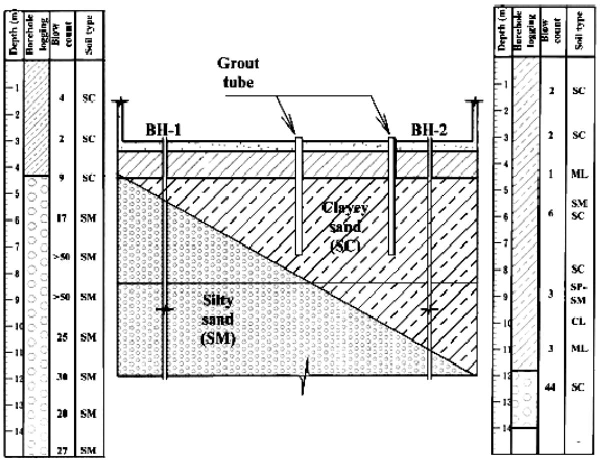


Fig. 3 Subsurface profile, building basement and injection pipe

2.2 Grouting design

The permeability and shear strength of clayey sand deposit were controlled by the clay particles. Unified soil classification system defines clayey sand as those sands containing clay of 12% or more by weight. A sufficient amount of clays can effectively separate each sand particle, and this explains why the minor clay particle controls the shear strength and permeability of clayey sand. D′Appolonia (1980) also found that sands with a bentonite content of 15% or more showed the same permeability as bentonite (Fig. 4). Therefore, fracture grouting was selected as the injection method. A series of grouting tubes were installed 2.5 m below the mat foundation and quick-setting grouts were injected repetitively through the end of grouting tubes. The grout hole spacing was

2 m on center. Drill casings were 1 m in length, and were drilled, with small equipment for grout casing insertion through reinforced concrete floor in the mat foundation. Water was used as the flush medium.

Because of cost considerations, traditional grouting pumps were used. To improve the compensation efficiency and to limit the travel of grout, the grout hose system of 1.5 shots and quick-setting grout mix shown in Table 1 were adopted. Two grouting stages were planned. The first stage of grouting was used to stabilize the clayey sand layer below mat foundation. The grouted clayey sand layer and underlying sand and gravel layer provided the reaction for the second stage of grouting.

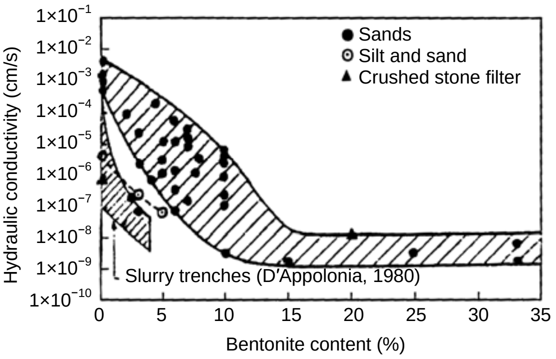


Fig. 4 Correlation between hydraulic conductivity and bentonite content

Table 1 Grout mix adopted (1000 L)

Grout mix	Value
A liquid (500 L)	
Cement (kg)	400
Water (L)	355
B liquid (500 L)	
Na_2O-$3SiO_2$ (L)	125–250
Water (L)	250–375

3 Monitoring system and grouting performance

The elevations of building columns in the basement and ground surface (SM-1 to SM-14) along A- and B-line outside of building (Fig. 5) were monitored before and after each day's grouting program. The equal heave contour lines of the mat foundation were plotted on a daily basis, and were used to adjust the daily grouting plan. To protect the integrity of building's structure from warping damage due to improper grouting, the intervals between each contour line were kept as uniform as possible. The final contour lines at the end of grouting program are shown in Fig. 6, and the mat foundation remained a plane throughout the entire grouting program.

The difference in contour lines between pre- and post-grouting provides the elevated volume for the inclined building at the end of each day, and also provides the overnight settled volume due to the dissipation of excess pore pressure from the grouting. Fig. 7 shows the cumulative daily injection, elevated

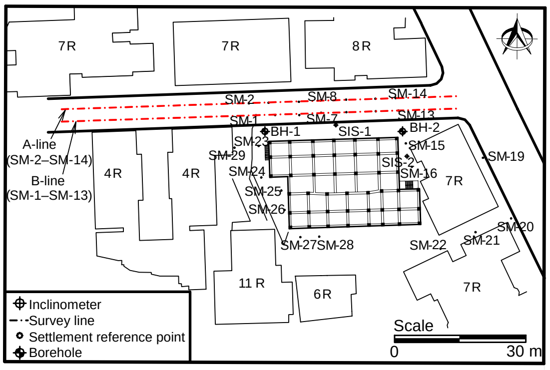


Fig. 5 Site plan and monitoring system layout

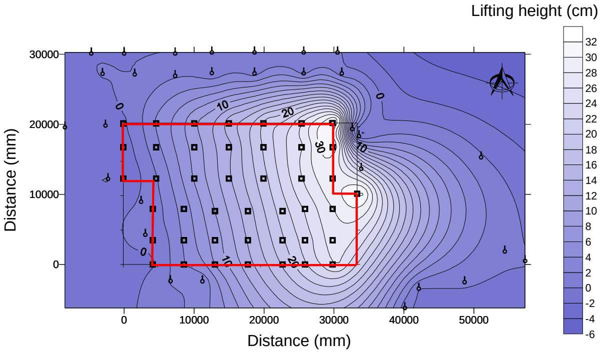


Fig. 6 Final contour lines of equal lifting height

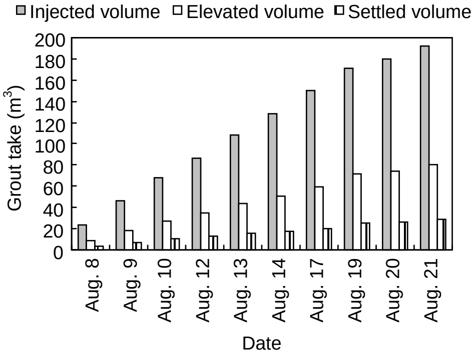


Fig. 7 Bar chart of accumulative injected, elevated and settled volumes

and settled volumes of grouts. From the first day, the elevated volumes were always larger than the settled volumes. The elevated volume and settled volume per unit of injected grout are shown in Fig. 8. At the end of the grouting program, a total injection volume of approximately 460 m^3 was measured by a flow meter, and the building's northeastern corner was raised by 32.37 cm. The final compensation efficiency of 27% is obtained by subtracting settled volume of 15% from the elevated volume of 42% in 1 m^3 injected grout (Fig. 8). The compensation efficiency of 27% is much larger than a reported 9.78%, wherein an eight-story reinforced concrete building was leveled in a thick soft clay deposit (Ni and Cheng, 2009). This is because clayey sands are a lot less compressible than soft clays. As a result, it is logical to expect positive compensation efficiency in clayey sands in contrast to negative efficiency in soft clays at the early grouting stage, and to observe much higher final compensation efficiency in clayey sands than in soft clays (Au *et al.*, 2003; Ni and Cheng, 2009).

An in-ground inclinometer SIS-1 was installed in an open half-space between the building and front sidewalk, and an inclinometer SIS-2 was installed in a confined space between two building basements as shown in Fig. 5. They were used to monitor the lateral ground displacement during injection. The lateral displacements of SIS-1 in Fig. 9 corresponded to various elevated percentages ranging from 1.6% to 100% of the maximum raised height of 32.37 cm at the building's northeastern corner. The first stage of grouting was used to improve the shear strength and minimize the compressibility of clayey sand by repetitive fracture grouting. For a homogeneous and isotropic soil, fractures initially developed radially in equal distances, centered at the tip of the injection pipe. The grout pressures dissipated along the fractures and decreased to in-situ mean stresses at a spherical boundary, which expanded radially due to repetitive fracture grouting. Then fractures started to migrate more sideways when fractures halted by the mat foundation above and by a competent soil layer

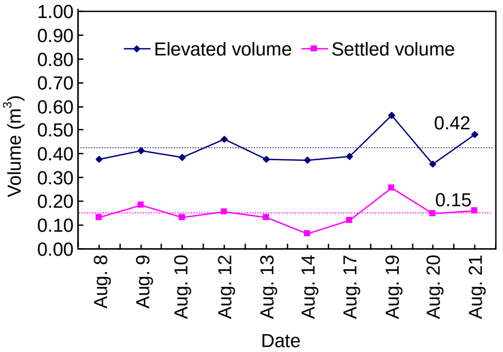


Fig. 8 Variation of elevated and settled volumes per unit injected grout

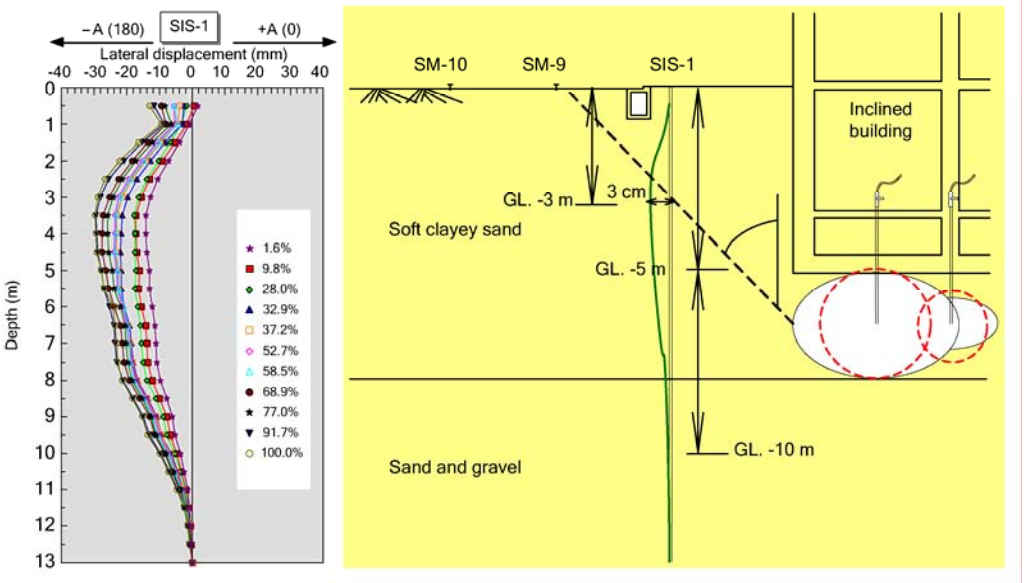


Fig. 9 Lateral displacement of in-ground inclinometer SIS-1 during grout injection

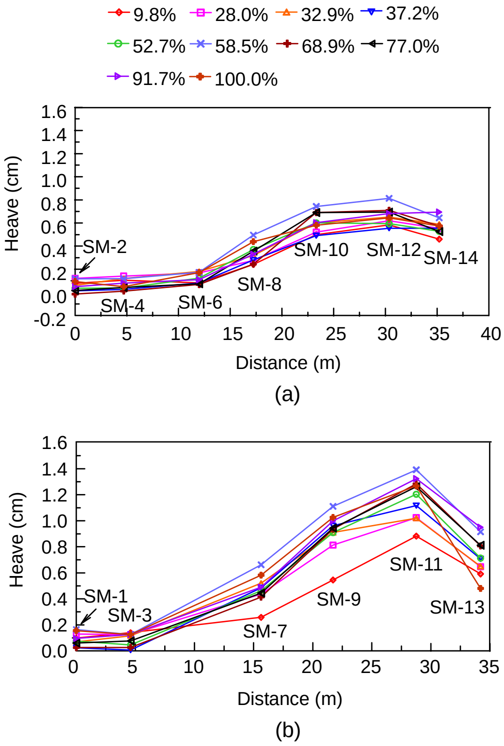
GL: depth below the ground surface. The lateral displacements of SIS-1 correspond to various elevated percentages ranging from 1.6% to 100% of the maximum raised height of 32.37 cm at the building's northeastern corner (sand and gravel) below. While horizontal stresses of soils within the ellipse boundary were increasing to vertical stresses equal to the overburden soil and building weights, the soils experienced significant lateral displacement and the building started to lift at this point. Due to tight budget, core drilling was not performed in this project although it could apply to show the evidence for how the grout spread underneath the foundation. Fig. 9 shows that the clayey sands experienced 47% of total lateral movement when the building was lifted by 1.6%.

The lateral displacement can cause heaves along the sidewalk as shown in Fig. 10, and in a similar way the heaves at the early lifting stage were about 60% of the total heaves. On the other hand, the soils around inclinometer SIS-2 moved only 10% of the total lateral displacement during the early lifting stage (Fig. 11). This is because the adjacent basement provides resistance against the expansion of the spherical grouting zone. This results in the soils around SIS-2 to undergo positive excess pore pressure. Then the soils began to consolidate and gradually give way to the expanding grout zone during the lifting stage. This explains why the lateral movements were much larger in the lifting stage than in the stabilizing stage.

Fig. 12 shows the variations of total grout volumes at various elevated percentages of this inclined building. The linear regression of this relationship can be expressed as

$$\text{Grout take}=344.35\times\text{Elavated percentage}+121.27, \quad (3)$$

where the intercept of 121.27 m^3 is the minimum amount of grout needed to stabilize the soft clayey



(a)

(b)

Fig. 10 Ground heaves along sidewalk at the beginning and the end of the building lifting stage
(a) A-line survey; (b) B-line survey

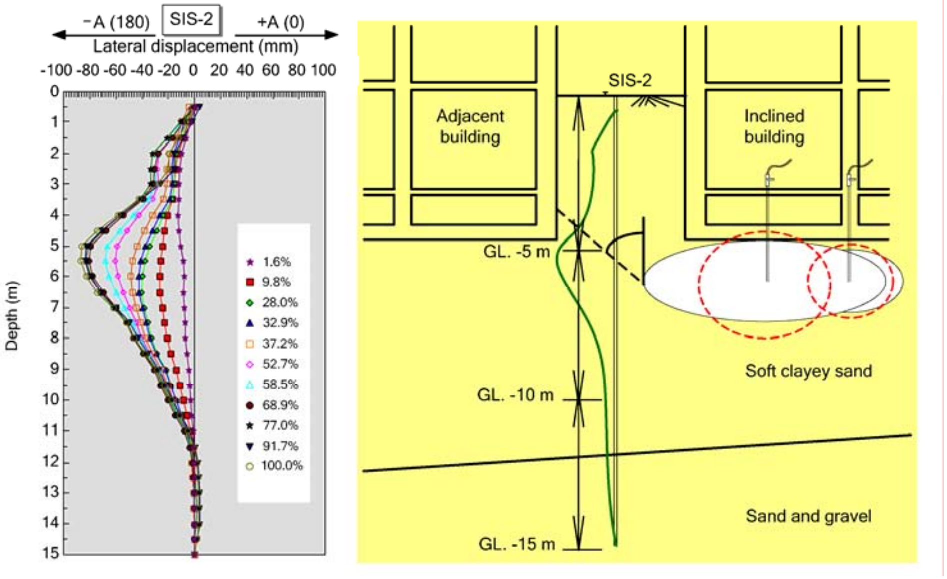


Fig. 11 Lateral displacement of in-ground inclinometer SIS-2 during grout injection
GL: depth below the ground surface. The lateral displacements of SIS-2 correspond to various elevated percentages ranging from 1.6% to 100% of the maximum raised height of 32.37 cm at the building's northeastern corner

sand before the lifting stage of grouting is initiated.

The intercept and slope of this relation are dependent on soil type, soil stress history, and building foundation pressure. In general, the more compressible the soil, the more the grout required to stabilize the foundation soil and lift the structure. The higher the foundation pressure (e.g., a taller building), the more grout the required. If these relations can be defined from sufficient field data, then the total grout required can be estimated from the linear equations if the soil type, stress history, and mat foundation pressure are known. Fig. 13 shows the building before and after grouting.

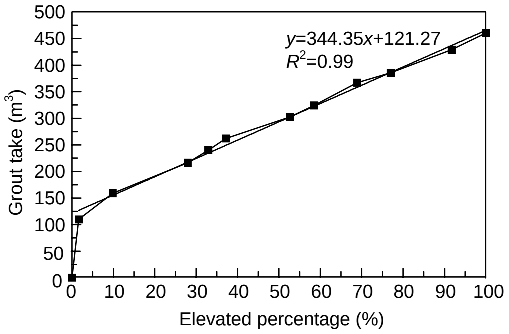


Fig. 12 Variation of grout take and elevated percentage

(a) (b)

Fig. 13 Grouting performance before fracture grouting (a) and after fracture grouting (b)

4 Conclusions

1. Fracture grouting with a 1.5-shot grout hose system and quick-setting grout is an effective and economical method for leveling inclined structures in clayey sands.

2. Fracture grouting with a short gel time grout in soft clayey sands exhibits positive compensation efficiency initially, because clayey sands are a lot less compressible than soft clays. The final compensation efficiency in leveling an inclined seven-story reinforced concrete building is 27%, much higher than that with compressible soft clays.

3. The total grout required to level an inclined building can be estimated by a linear equation in which the intercept and slope are influenced by soil type, soil stress history, and mat foundation pressure. The intercept represents the grout required to stabilize the foundation soils and provide the initial reaction. Once the building starts to lift, the additional grout required (related to the slope of that linear equation) is used to compensate for the consolidation effect, which is again controlled by soil type, soil stress history, and mat foundation pressure.

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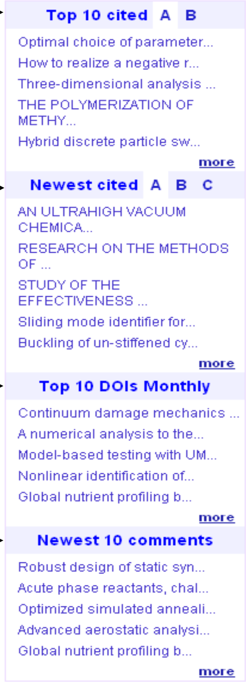

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