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Fracturing of sand in compensation grouting

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ABSTRACT: The phenomenon of fracturing in sand as a result of compensation grouting was studied. Processes of fracture initiation and propagation were explained and a parametric study was conducted in order to investigate the factors that cause sand fracturing to occur. Experimental results indicate that fracture initiation requires the existence of a local inhomogeneity around the injection position. Grout mixture in terms of water-cement ratio and fines content had major roles in sand fracturing, whereas injection rate had a minor influence under the tested conditions.

1 INTRODUCTION

Compensation grouting has been widely in use to control ground settlements during tunneling processes. Nevertheless, its use is still hindered in many cases by the uncertainties in the grout mechanical behavior. As the current grouting practice is highly dependant on field experience rather than scientific knowledge of soil-grout interaction behavior, issues such as suitable injection pressure, soil fracturing and bleeding (amount of water forced out of the grout mixture) still need further investigation.

In particular, soil fracturing stands out as one of the major challenges that could affect the results of a grouting project. Accidentally-created fractures could cause considerable damage to near-by structures, whereas failing to create fractures when they are required could result in tunneling-induced settlements (for example) not being fully compensated for.

While fracturing of cohesive soils was extensively studied by many researchers (e.g. Jaworski et al. 1981, Mori & Tamura 1987, Andersen et al. 1994, Chin & Bolton 1999, Soga et al. 2005 & 2006), there has been limited work for compensation grouting in cohesionless materials (e.g. Chang 2004). Fracturing of sand was studied in relation to the oil industry (Khodaverdian & McElfresh 2000, Bohloli & de Pater 2006) and horizontal directional drilling (Bezuijen et al. 2002). Recently, the prospected use of fracture grouting in Amsterdam to tackle settlements encountered during the construction of the North-South Metro line triggered a thorough research into the phenomenon of sand fracturing.

This paper follows on from the work reported by Sanders (2007) and Bezuijen & van Tol (2007). Utilizing the reported optimum grout mixture for soil fracturing, a series of laboratory scale grout injection tests was performed in which various factors affecting fracturing of sand were studied.

2 THEORY & BACKGROUND

Hydraulic fracturing is defined as the condition leading to the creation and propagation of a thin physical separation in a soil or rock mass due to high fluid pressures. The fracturing process is mainly characterized by fracture initiation, propagation and orientation. Understanding the factors controlling these parameters is the first step in understanding and predicting the grout fracturing behaviour. The factors affecting fracturing phenomenon could be divided into two groups: factors related to soil, such as soil properties (particle size, shape and distribution, relative density, cohesion, friction angle etc), stress state and the magnitude of confining pressure and factors related to grout itself and the grouting process, such as grout rheology (components and viscosity), injection rate and injection pressure.

2.1 *Fracture initiation*

The two main theories explaining fracture initiation are tensile failure and shear failure. Jaworski et al. (1981) suggested that, for a hydraulic fracture to occur, the effective stress has to become tensile and equal in

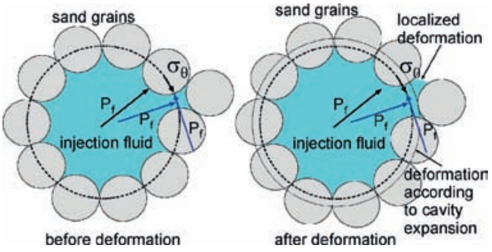

Figure 1. Realistic particle arrangement around an injection hole and possible deformation modes. P_f is the injection pressure to cause plastic deformations in soil and σ_θ in the effective stress around the injection hole. (Bezuijen & van Tol 2007).

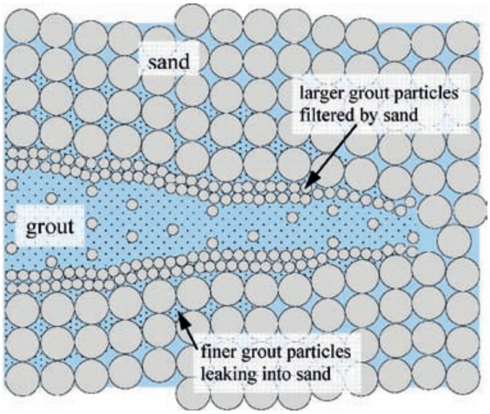

Figure 2. Leak-off and filter cake formation associated with fracturing.

magnitude to the tensile strength of the soil. This situation is clearly unconceivable in case of cohesionless soils like sand. The other theory on fracture initiation proposes a shear failure as the main reason for fracturing in clays. Mori & Tamura (1987) suggested that shear failure occurs within a short duration under a high injection rate, with the duration being too short for the grout to penetrate into micro fissures to create wedge action and/or enter the soil pores to weaken the soil strength.

For fracturing in sand, Bezuijen et al. (2007) and Bezuijen & van Tol (2007) suggested that the local contact forces between sand grains have to be eliminated. As in case of cohesionless soils there is no tensile strength between the grains, this means that the fracturing pressure has to overcome the effective stress in the direction perpendicular to the fracture. In reality, sand is never perfectly homogeneous and therefore, the arrangement of particles around a certain boundary (injection hole, for example) will be in such a way that some particles are in closer contact than others, as shown in Figure 1.

When injection is conducted, grout will fill the space between particles and start to push them apart. Whether this initiated fracture will propagate further or the result will be a roughly symmetric cavity expansion depends mainly on the properties of the injected grout. This explanation of fracture initiation in sand agrees with the findings of Thallak (1991), who, based on the micromechanics of granular media, suggested that hydraulic fracture initiation requires the local contact forces between particles to become zero or tensile. As this requirement is complicated by local force distribution at microscopic scale (which can lead to a wide variation in the fracturing pressure), it was concluded that hydraulic fracture initiation depends mainly on the local microscopic inhomogeneities in the soil.

2.2 *Fracture propagation*

Starting from the condition shown in Figure 1, a roughly symmetric cavity expansion will always be the result if the injection pressure is high enough and close to perfect cavity expansion pressure. Factors that dictate how high the injection pressure will be are mainly the grout materials and rheology, confining pressure and stress state and soil density. Results reported by Kleinlugtenbelt (2005), Gafar & Soga (2006), Sanders (2007) and Bezuijen & van Tol (2007) confirm that high injection pressures are associated with high grout viscosities (low w/c ratio or more cement content for cement-based grouts). Gafar & Soga (2006) reported that injection pressure in the case of no confinement was increased by 15 times when a 100 kPa confinement was introduced. Bezuijen & van Tol (2008) highlighted the influence of the stress state. Unloading of the soil around a cavity as a result of equipment installation leads to plastic deformations in the soil, which may result in lower injection pressures.

Bezuijen & van Tol (2007) explained that, for fractures to propagate, grout mix has to contain enough content of fine bentonite particles and has enough water to ensure good flowability at the same time. In this case, pressure application will cause the water in adjacent sand pores to be replaced with a mixture of water and finer particles leaking from the grout mix, as shown in Figure 2. This permeation action is termed as leak-off. With introduction of fines in the soil matrix, the leak-off will reduce the permeability of sand around the injection hole, causing grout bleeding to be slowed down.

On the sides of the propagating fracture, a filter cake is formed as a result of the accumulation of larger cement particles filtered at the sand-grout boundary. Filter cake formation is crucial for the propagating fracture to be able to keep itself open and to sustain forces induced by grout penetration. At the same time, bleeding is restricted, keeping a good workability of the grout. A suitably high initial water-cement ratio (w/c ratio) will ensure that the grout mix will have

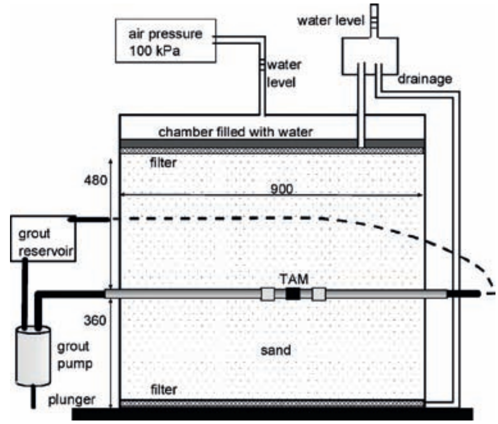

Figure 3. Schematic diagram of the experimental setup, showing the dimensions in mm (Bezuijen & van Tol 2007).

sufficient water content to keep a fracture propagating without the need for very high pressures. Eventually, the pressure at fracture tip will not be enough to overcome the effective pressure in the direction perpendicular to fracture. Nonetheless, the pressure at the tip will still be high enough for leak-off and bleeding to continue. This will cause a filter cake to be formed at the fracture tip, completely blocking further grout propagation.

3 EXPERIMENTAL SETUP

Grout injection tests were conducted in a cylindrical steel container of a 900 mm diameter and changeable height. Two sample heights were used: 840 mm (for Tests 1 and 2) and 600 mm (for the rest of the tests). Figure 3 shows a schematic diagram of the experimental setup. The injection tube position was fixed at 360 mm above the bottom of the container. A PVC plate rests on the top of the saturated sand sample, tightly sealing it off from an upper water chamber. Confinement is applied by means of pressurizing this water chamber using compressed air. Air pressure is applied through a glass cylinder that also shows the change in water level resulting from soil heave. This change is continuously measured during the test by means of a differential pressure gauge. Two tubes connect the top (through the water chamber) and the bottom of the soil sample to another graduated glass cylinder which rests on the top of the setup, providing a double drainage system.

A simplified model of the tube à Manchette (TAM), as shown in Figure 4, runs across the diameter of the cylindrical container. The tube has an internal diameter of 22 mm, with 4 equally spaced 7 mm holes at the centre. A rubber sleeve covers the holes and 2 rings, one on either side, prevent the injected grout from flowing along the tube.

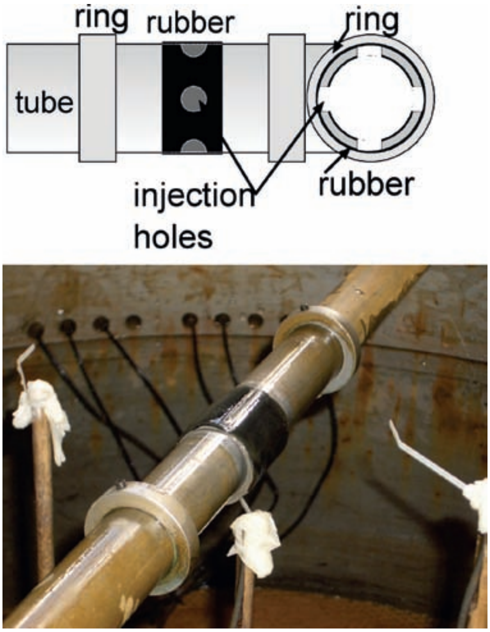

Figure 4. Simplified model of Tube à Manchette (TAM) used for injection. Actual space between the two rings is 40 mm during injection (Bezuijen et al. 2007).

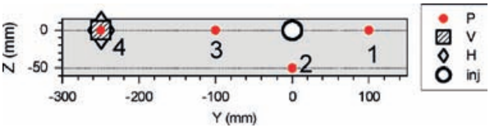

Figure 5. Location of instruments with respect to the injection tube (inj). P are the pore pressure transducers, V measures the vertical pressure and H the horizontal (Bezuijen et al. 2007).

Changes in pore water pressure during injection were monitored by four pore pressure transducers, distributed around the injection point as shown in Figure 5. The readings from these transducers were not used in this paper. Two total stress cells were used to record the change in horizontal and vertical pressures.

Two types of sand were used: Baskarp sand ($d_{50} = 130\,\mu m$) and Leighton Buzzard type D sand ($d_{50} = 234\,\mu m$). In both cases, sand was wet-pluviated into water in the model container. Loose sand was then densified to required relative density (70%) by dropping the whole container over 25 mm as many times as required.

In order to raise K_0 to a closer value to 1, sand was "pre-stressed" by applying a confining pressure of 300 kPa at the beginning. Confinement was reduced to 100 kPa prior to grout injection. This pre-stressing

Table 1. Summary of conducted experiments.

No	W/C ratio	Rate (l/m)	Bentonite (%)	Materials/ sand	Remarks
1	5.0	10.0	7.0	GD/Ba	Repeatability test
2	5.0	2.0	7.0	GD/Ba	Slower inj. rate
4	5.0	10.0	7.0	GD/Ba	Wall friction effect
5	5.0	10.0	7.0	Ca/Ba	Effect of materials
6	1.0	2.0	4.0	Ca/LB	Lower w/c ratio
7	1.0	10.0	4.0	Ca/LB	Faster inj. rate

Notes: Rate = injection rate, GD = GeoDelft cement and bentonite, Ca = Cambridge cement and bentonite, Ba = Baskarp sand, LB = Leighton Buzzard sand. Bentonite percentage is by weight of mixing water.

was only partially successful and values of starting K_0 were still less than, but close to, 1.

Grout injection was conducted using a plunger pump. A bladder (not shown in Fig. 3) was used as an interface between pumped water and injected grout in order to avoid damaging the pump by the grout. The injection pump was capable of reaching a maximum pressure of 4 MPa. Injected grout was allowed to set for 24 hours before the sand was dug out and the shape of hardened grout was photographed.

4 RESULTS & DISCUSSION

Using the same injection setup, Sanders (2007) and Bezuijen & van Tol (2007) reported that the best grouting efficiency was attained by using a cement-bentonite grout of a w/c ratio of 5.0 to fracture Baskarp sand. Ordinary Portland cement and sodium-activated bentonite (7% by weight of mixing water) were utilized. Injection was made under an injection rate of 10 liters per minute (l/m).

The current series of tests adopted the above mentioned test as a reference and Table 1 summarizes some of the experiments carried out. Two sets of grout materials were used: (a) rapid hardening, ordinary Portland cement and sodium-activated bentonite (GeoDelft, the Netherlands), and (b) normal hardening ordinary Portland cement and sodium bentonite (University of Cambridge, UK). Injection pressures resulting from all the tests are shown in Figure 6.

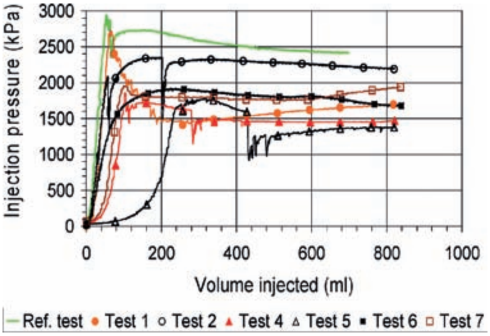

Figure 6. Change of injection pressure with injected volume for different tests.

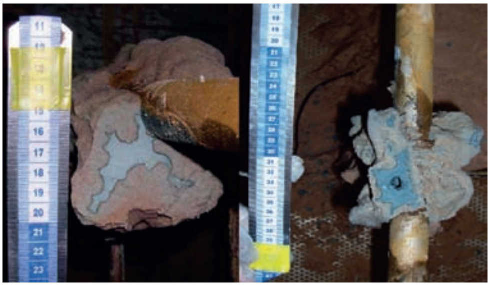

Figure 7. Fractures from (a) reference test (left) and (b) Test 2 with slower injection rate (right).

4.1 *Repeatability check*

Due to a problem with sample preparation that yielded a sample which was not perfectly homogeneous, the repeatability test (Test 1, using grout with w/c ratio of 5.0) resulted in a single fracture which propagated to near the container wall. Nevertheless, the initial pressure was similar in magnitude to the starting pressure of the reference test (2.7 and 2.8 MPa respectively). The pressure during injection was about 40% less than the injection pressure during the reference test, which highlights the effect of soil inhomogeneity.

4.2 *Effect of injection rate*

Reducing the injection rate in Test 2 by a factor of 5 still yielded fracturing of the sand model. The grout mix contained enough water and fine particles. Recorded injection pressure was about 10% lower than the value for faster injection rate. Sectioning of hardened grout revealed that thicker fractures were formed, with narrower leak-off zone and thicker filter cake, as shown in Figure 7b.

Under the slower injection rate, there is more time for the filter cake to develop. According to Bezuijen et al. (2007), the thickness of filter cake increases with the square root of the time that the grout is pressurized. For a given injection pressure and injected volume, reducing the injection rate by a factor of 5 will lead to approximately 2 times thicker filter cake. Formation of a thicker filter cake will hamper further leak-off, as the finer particles are blocked by the filter cake that is already formed.

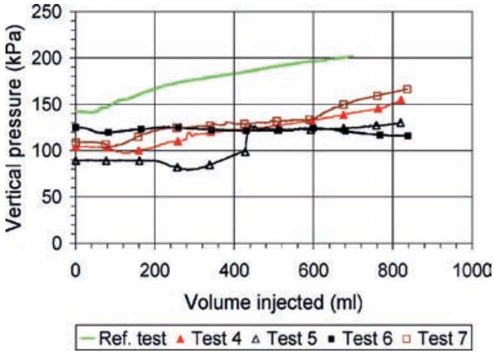

Figure 8. Comparison of the change in vertical pressure with injected volume between the reference test and the tests with reduced sample height.

4.3 *Side wall friction*

The sample height for the rest of the tests was 600 mm. Test 4 was a repetition of the reference test under the new sample height. Results showed that the injection pressure under the new testing condition was about 1 MPa lower, even though the injected grout managed to fracture the sand in a similar way. The change in overburden pressure that corresponds to changing the height of sand above the injection point is only a few kilo Pascals. Therefore, it could not have been the reason for this reduction in injection pressure. However, measurements of total vertical stress showed that the friction between the sand and the walls of the container have reduced the vertical stress at the injection level from that applied at the top of the sample (Fig. 8). This explains the reduction in recorded injection pressures for all the tests conducted under the new sample height.

4.4 *Grout materials*

The ordinary Portland cement used in the experiments was CEM I cement and either sodium bentonite or sodium-activated bentonite was mixed. Bruce et al. (1997) reported that sodium bentonite is the best type of bentonites to be added to cement grouts. This is mainly attributed to its swelling potential, as it swells up to 18 times its original volume. Sodium-activated bentonite, on the other hand, could swell up to 10 to 15 times.

Results showed that there was no significant difference resulting from using sodium bentonite instead of sodium-activated bentonite in terms of fracturing sand. Comparing the injection pressures of tests 4 and 5 (Fig. 6), the only difference is the slightly slower build-up of pressure in case of sodium bentonite. This should have resulted from a problem with the injection system at the beginning of injection, as almost no heave or drainage was recorded over the delay period. The hardening speed of the used Portland cement (rapid for GeoDelft and normal for Cambridge) did not affect the results, as most of the processes that influence sand fracturing happen well before hardening. In terms of grouting efficiency (defined as heaved volume divided by injected volume), both types of bentonite gave more or the less the same efficiency.

Figure 9. Dehydrated layer around the boundary of hardened grout for (a) Test 6 (left) and (b) Test 7 (right).

4.5 *No-fracture tests*

Two injection tests were conducted using a low w/c ratio grout (w/c ratio of 1.0, 4% sodium bentonite added; see Tests 6 and 7 in Table 1). The tests were carried out in sand models of type D Leighton Buzzard sand ($d_{50} = 234\ \mu m$).

Injection under both slow (Test 6) and fast injection rates (Test 7) yielded no fracturing. The injection pressures were very close to each other, but slightly higher than the values for fracturing experiments. The slower injection rate gave more uniform shape of hardened grout (Fig. 9a), whereas some fingering was observed for the faster injection rate (Fig. 9b). In both cases, sectioning the hardened grout revealed a layer of dehydrated material around the grout-soil boundary.

With higher cement content and less water in the grout mix, no leak-off occurred and there was limited amount of free bentonite to develop a filter cake. Bleeding did occur and this in turn reduced the grout mobility. It is possible that the calcium in the cement changes the coagulation structure of the bentonite by cation exchange, increasing the permeability of the consolidated grout and accelerating bleeding (Sanders 2007). Most of the grout stayed around the injection point. The existence of a dehydrated layer at the grout-soil boundaries suggests that more bleeding happened around the boundaries, which is in agreement with the theory suggested by McKinley & Bolton (1999). The faster injection rate allowed less time for bleeding and hence, the grout managed to create some fingering before it became too viscous to flow.

Consolidation of the grout leads to the possible local irregularities at the boundaries of an injection hole to be filled up, or plastered, in the way shown in Figure 10.

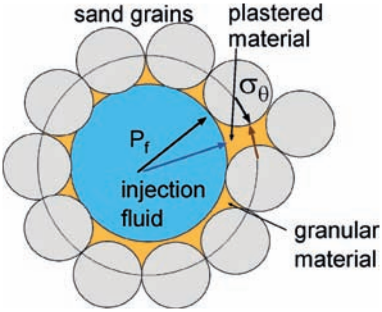

Figure 10. Influence of plastering on fracture initiation (Bezuijen & van Tol 2007).

Such plastering will hamper fracture initiation, as it prevents the fluid pressure from penetrating into the space between sand particles. As the created plaster will have a certain strength, part of the injection pressure will be acting on the plaster rather than being used to push particles away from each other to initiate a fracture.

5 CONCLUSIONS

The experimental work conducted confirmed that fracture initiation in sand requires some local inhomogeneity around the injection point, rapid development of a filter cake with a limited thickness and a grout with low viscosity and a limited yield stress. Whether the initiated fractures will propagate or not depends mainly on the grout mixture. Water-cement (w/c) ratio and fine particles content play a major role in fracturing of sand. Grouts with high w/c ratios and enough fines will exhibit a leak-off of fine particles, accompanied with the formation of a filter cake, which results in fracturing. For grouts with low w/c ratios and large grout permeability, bleeding is the dominant process, leading to non-fracturing of sand.

For a suitable grout mixture, faster injection rates will result in thinner fractures, whereas slower rates give thicker fractures with less leak-off and thicker filter cake. If the w/c ratio is too low, no fractures will be formed, regardless of the injection rate.

The longer fractures experienced under relatively low injection pressures in the field are mainly due to the natural inhomogeneity of sand layers. Injection in almost perfectly homogeneous sand in the laboratory gives shorter fractures and requires higher injection pressures.

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