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The efficiency of compensation grouting in sands

K. Soga
University of Cambridge, Cambridge, UK

A. Bezuijen
Deltares/Delft University of Technology, Delft, The Netherlands

K. Eisa
Atkins Ltd., London, UK

ABSTRACT: Physical model experiments on compensation grouting in sands were performed in two different setups (Cambridge and Delft). The effect of water-cement (w/c) ratio, bentonite content (b.c.) and injection rate on compensation efficiency was investigated. Results show a considerable drop in compensation efficiency resulted from reducing the soil density. Injection in dense sand (R.D. = 93%) resulted in efficiencies between 40–90%, whereas injection in medium-dense sand (R.D. = 60–75%) yielded in reduced efficiencies between 10–40%. When the w/c ratio increased from 0.5 to 1.5 for a given density (R.D. = 93%) and the b.c. of 4%, the compensation efficiency value decreased. Typical efficiencies were between 60% and 40–50% for w/c ratios of 0.5 and 1.5, respectively. The values of compensation and grout efficiencies were almost equal, suggesting that pressure filtration happens mainly during injection. Increasing the b.c. improved the compensation efficiency. When a higher b.c. of 12% to 14% was used, typical compensation efficiencies in dense sand were 78 and 90% for w/c ratios of 1.5 and 1.8 respectively.

1 INTRODUCTION

When an underground excavation takes place, as in tunnel boring, stress relief occurs in the surrounding soil with a tendency of the soil to move towards the opening produced by the excavation. This causes serious movements to the structures above the ground, which may result in severe damage. In compensation grouting, the grout material is injected between the structures and the excavated area to compensate for the volume loss and therefore counteract the resulting settlement (Mair and Hight, 1994).

The success of any compensation grouting project is assessed by whether the observed settlements were corrected or not and how much grout had to be injected to achieve that target. Soga et al. (1999) defined grout efficiency, η, as the ratio of the increase in soil volume of a volume element local to grout injection points, V_E, to the injected volume of grout, V_{inj} as shown in Figure 1.

Under ideal conditions, the volume increase should be equal to the volume injected, giving a grout efficiency of 1. However, this is not the case in practice. The resulting volume increase is always less than the volume of injected grout due to the fluid being "squeezed" out of the grout mix (pressure filtration) and the grout escaping from the designated area by migration along fractures or existing zones of weakness in the soil. Even when a good ground response is achieved immediately after injection, the grout efficiency tends to decrease with time due to continuing pressure filtration and/or dissipation of positive excess pore pressures in the case of clayey soils (Soga et al., 2004).

Furthermore, compensation efficiency, ζ, is defined as the ratio of the volume of the surface heave created by grouting, V_{SH}, to the injected volume of grout (V_{inj}). This efficiency is affected, in addition to local losses, by the far-field geometry of the site. Figure 1 shows the difference between grout and compensation efficiencies as well as some of the boundary conditions that might affect the latter.

Compensation efficiencies of 3–22% are reported for compensation grouting in the field (Chambosse and Otterbein, 2001; Au et al., 2003). Somewhat higher values, 30–50%, in stiff London Clay (Mair, 2003). Soga et al. (2004) performed grout in the laboratory on clay specimens prepared at different overconsolidation ratios ranging from 1 to 10. For highly overconsolidated clay the compensation efficiency was close to 1 irrespective of grout spacing and injection sequence. For normally consolidated and lightly overconsolidated clays the

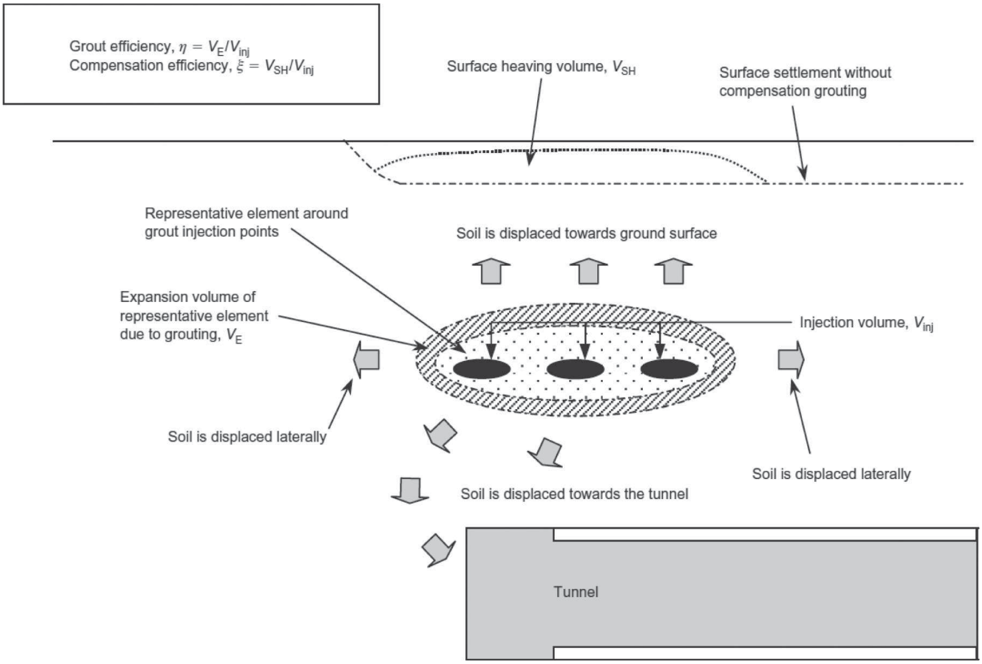


Figure 1. Grout efficiency and compensation efficiency in compensation grouting (after Soga et al., 2004).

grout efficiency increased when the separation in space and time between the injections was reduced (sometimes a negative efficiency). A finite element study of the laboratory experiments (Au et al., 2003) confirmed a mechanism that the grout efficiency of normally consolidated and lightly overconsolidated clays can reduce dramatically with time, owing to (a) soil contraction by extensive shearing during the injection, and (b) soil compression by the ultimate increase in mean effective pressure around the injection point caused by the injection pressure locked in when the grout solidified. For heavily overconsolidated clays, the pore water migrated from the positive excess pore pressure zone around the injection point to the negative zone some distance away from the injection point, during the consolidation stage. Soil compression near the injection point and swelling at some distance away from the injection point resulted in a negligible overall consolidation effect for heavily overconsolidated clays.

There is limited study on compensation grouting in sands and its efficiency. In this study, physical model experiments of compensation grouting in sands were performed in two different setups (Cambridge and Delft). One of the objectives of the experiments was to evaluate the compensation efficiency of cement bentonite grouting in sand. The results of the experiments are presented in this paper.

2 EXPERIMENTAL SET-UP

2.1 *Cambridge set-up*

The Cambridge experimental setup is shown in Figure 2. A steel consolidometer tub of 850 mm in internal diameter and 400 mm in height was used as the model container. To apply confining pressure on the large cross-sectional area of the tub, a latex air bag was fixed to the inner side of the tub cover. In all experiments reported in this paper, a confining pressure of 100 kPa was applied.

An open-ended injection tube was used for grout injection. The zinc-plated steel tube had an outer diameter of 14.5 mm, an inner diameter of 12.5 mm and a total length of 550 mm. The injection tube was inserted approximately at the middle of the sample height with a slope of 1:60 downwards. Cling film was wrapped around at the end of the tube in order to prevent sand from entering. Grout injection was conducted using a progressive helical cavity pump, which is capable of producing a continuous, uniform flow of grout (0.2 to 3.33 litre/min). A pressure transducer was connected to the end of the injection tube, about 250 mm outside the tub to measure the injection pressure.

Injection tests were conducted in Leighton Buzzard fraction D clean silica sand (particle size 150~300 μm, $e_{max} = 0.988$ and $e_{min} = 0.585$, $k = 5 \times 10^{-4}$ m/s at 93% relative density). The sand

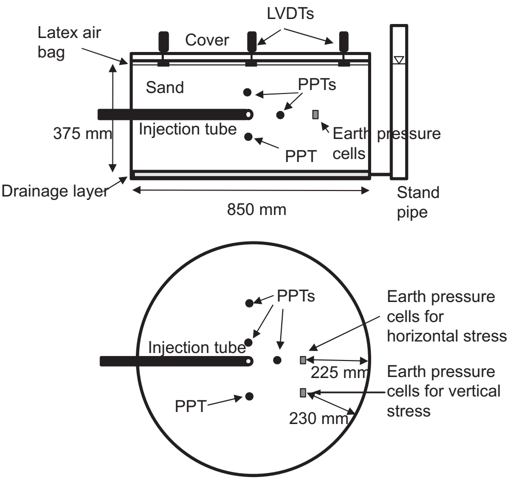


Figure 2. Cambridge set-up.

was poured in the tub in dry condition using a computer-controlled sand hopper. After sand pouring finished, the pores were filled with carbon dioxide and the water table was raised from the bottom in order to saturate the sample. For all the tests, the relative density was 93%. Free drainage at the bottom of the model was allowed through a drainage layer that consisted of 6 mm clean gravel covered with a sheet of geotextile.

The model was instrumented with miniature pore pressure transducers (PPTs, Druck PDCR81), earth pressure cells (EPCs) and linear variable differential transducers (LVDTs) as shown in Figure 2. Holes were made in the air bag to install LVDTs so that the sample surface movement during injection could be monitored. In the current experiments, the pore pressure change was very small because the sand had a relatively large permeability.

Further details of the experimental system can be found in Eisa (2008).

2.2 *Delft set-up*

The Delft experimental setup is shown in Figure 3. Grout injection tests were conducted in a cylindrical steel container of a 900 mm diameter and a changeable height (600 mm or 830 mm). A PVC plate rested on the top of the saturated sand sample, tightly sealing it off from an upper water chamber by means of rubber O-rings. Confinement was applied by means of pressurising this water chamber using compressed air. Air pressure was applied through a glass cylinder that also showed the change in water level resulting from soil heave. This change was measured during the experiment with a differential pressure transducer. In order to raise the K_0 to a value closer to 1, the sand model was "over-consolidated" by applying a confining pressure of 300 kPa at the beginning and then the confinement was reduced to 100 kPa before the grout injection.

A simplified model of the tube à manchette (TAM) ran across the diameter of the cylindrical container as shown in Fig. 3. The tube had an internal diameter of 22 mm, with four 7 mm holes at the middle, equally spaced around the perimeter. A rubber sleeve covered the holes and two rings, one on each side, were used to prevent the injected grout from flowing along the tube. The injection tube position was fixed at 360 mm above the bottom of the container. Grout injection was performed using a plunger pump and an injection rate up to 10 litre/minute. Four pore pressure transducers and two total stress cells were placed around the injection point.

Baskarp sand (particle size 90~200 μm, $e_{max} = 0.88$, $e_{min} = 0.52$, $k = 8 \times 10^{-5}$ m/s at e_{min}) was used in the Delft tests. The sand was wet-pluviated into water inside the model container. Two pumps were used to circulate sand around in a storage tank filled with water and a third one was used to pump the sand into the sample container. This sample preparation technique produced samples of

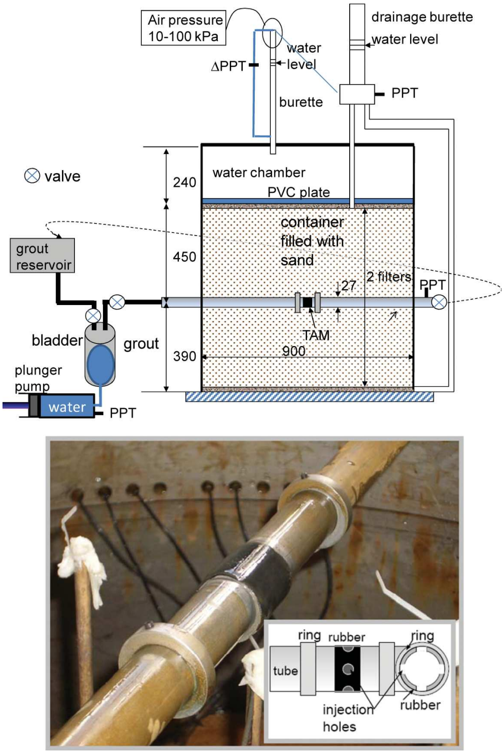


Figure 3. Delft Setup.

about 10% relative density. The loose sand model was then densified to required relative densities (60% or 70%) by dropping the whole container over a height of 25 mm as many times as required. At the end of the densification stage, the sample was trimmed to the desired height and the actual relative density was checked by means of weight and volume measurements. The model had a double drainage system.

Further details of the experimental system can be found in Sanders (2007) and Rietdijk et al. (2010).

2.3 *Testing programme*

Using the two experimental setups, 28 successful grout injection tests were performed for the conditions described above (see Table 1). The tests investigated the effect of water-cement (w/c) ratio, bentonite content (b.c.) and injection rate on soil-grout interaction. Only selected data will be presented in this paper to report the effect of these parameters on grouting behaviour in sandy soils. Further details can be found in Kleinlugtenbelt (2005), Sanders (2007) and Eisa (2008).

Ordinary Portland cement (OPC)-bentonite mixtures were used. The OPC used at Cambridge (Rugby by Rugby Cement and Blue Circle-ProCem by Lafarge Cement) conform to the British/European Standard BS EN 197–1-CEM I and have a density in the range of 2800–3200 kg/m^3 and a mean particle size of 5–30 μm. The OPC used at Delft (Lengfurt CEM I, 42.5R) develops strength more rapidly than the other types used. However, this has no effect on the results of the grout injection tests since all the processes that are of interest to this study take place during and shortly after injection before cement hardens.

The tested grouts had w/c ratios ranging from 0.5 to 200. In the Cambridge mixes, sodium bentonite (GWB Wyoming, Steetley Bentonite & Absorbents) was used. The b.c. was varied as 0.4%, 4% and 8% by weight of mixing water. For the Delft tests, sodium-activated bentonite (Colclay D90, Ankerpoort NV) was used. The b.c. was varied as 4% and 7% by weight of mixing water.

The method of grout mixing is very important because different mechanical properties could be obtained by using different mixing methods even with the same grout constituents. A high-shear roller mixer (R14 Roller Mixer by Colcrete Eurodrill company (Cambridge) and T50 basic Ultra Turrax by IKA Laboratory (Delft)) were used. They operate on the principle of the colloidal mill and wets or hydrates each particle of powder by an intensive shearing action, which results in complete dispersion by mechanical means. Before mixing, bentonite was hydrated using de-aired water and left for 24 hours. De-aired water was used for mixing so as to reduce the possibility of having air bubbles in the injection system. OPC was then gradually added to the pre-hydrated bentonite while being mixed. The time needed for this process varied depending on the amount of the cement and the bentonite to be introduced, but it was kept constant for similar mixes.

Table 1. Testing programme.

Set up	w/c	Bentonite %	Injection rate (l/min)	Injection volume (l)
Cambridge	0.5	0.4	0.385	0.98
(14 tests)	–5.0	–8	–3.33	–1.38
Delft	1.0	4	2	0.67
(14 tests)	–200	–7	–10	–1.0

3 TEST RESULTS

3.1 *Cambridge tests*

The surface heave of the soil sample during injection was measured by means of 5 LVDTs. Using these point-measurements, the heaving profile along the diameter of the soil sample could be drawn. A curve-fitting technique has to be used in order to calculate the heaved volume and consequently the compensation efficiency.

For most of the Cambridge tests, the heaving profile was found to have a maximum value directly above the initial location of the injection point; with lower values recorded towards the sides of the soil samples. This suggests that the heaving profile could be approximated by a Gaussian distribution. Taking the point of injection as the origin, heaving at any point, h, is then given as:

$$h = h_{\max} e^{-0.5(x/i)^2}$$

Where: h_{max} is the maximum heave above the injection point, x is the distance from the origin to the point at which heaving is required, and i is the standard deviation or the distance from the origin to the point of inflection.

The Gaussian distributions obtained for several Cambridge tests using the Least-squares method are shown in Figure 4, along with the point-measurements of the actual heaving at the end of injection. Although further experimental investigation is needed to verify the applicability of Gaussian distribution to approximate the ground displacement profile by a point source, a reasonably good fitting was obtained in most of the tests, with the exception of tests using grouts of w/c = 5.0. Fracture grouting was experienced in these cases and the

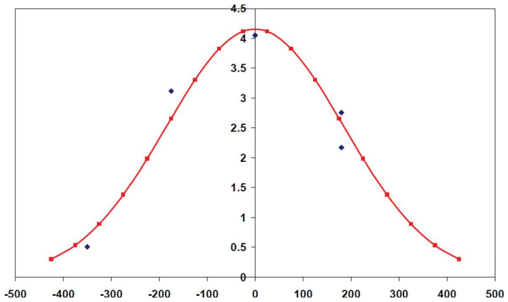


Figure 4. Examples of LVDT readings and the fitted Gaussian curve (scale in mm).

heaving patterns were affected by the non-uniform movement of grout inside the soil model. Based on the fitted Gaussian distributions, the total heaved volume from each test was calculated.

The grout efficiency for the different injection tests was calculated as the ratio between the volume of the hardened grout (24 hours after the injection test) and the injected grout volume. Water displacement was used to obtain the volume of the hardened grout. The grout material was left submerged into water for 2–3 minutes for any voids to be filled before it was dipped into a container filled with water and the displaced volume was measured. The end w/c ratio was calculated assuming that the difference between the injected and the hardened grout volumes is solely due to the loss of water by pressure filtration. The volume of the hardened grout was not measured for some of the tests because they yielded sand fracturing or due to experimental difficulties.

3.2 *Delft tests*

Heaving of soil sample was continuously measured during injection in the GeoDelft setup. This was done by means of a differential pressure transducer that measures the pressure at the base of a glass cylinder filled with water and connected to the compressed air supply system. As a result, it is possible to plot the change in compensation efficiency as the injection progresses. Figure 5 shows the change in efficiency for different injection tests. The unexpected surges in efficiency in some of the tests resulted from the readings of heaved volume being affected by some air bubbles in the measuring glass cylinder.

In general, the compensation efficiencies for almost all the GeoDelft tests were lower than the values of the Cambridge tests because of the lower relative density of the soil samples (R.D = 70%, compared to 93% in the Cambridge tests). The grout efficiency was not measured in this series of tests.

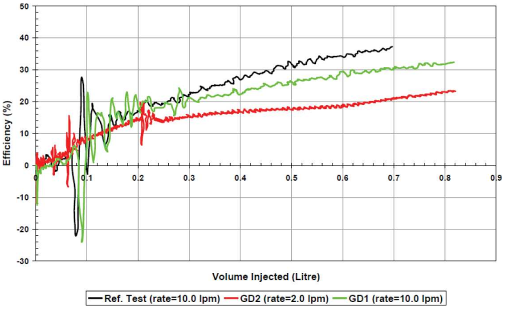


Figure 5. Change in compensation efficiency with injection volume.

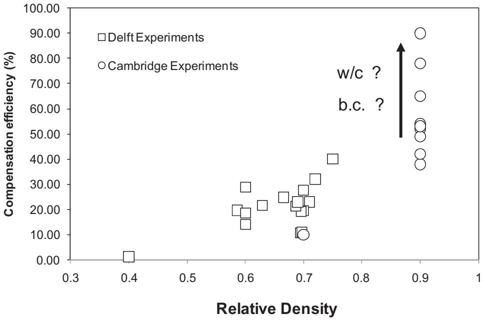


Figure 6. Effect of relative density on compensation efficiency. The arrows next to w/c and b.c. show that the compensation efficiency increases with decrease in w/c and increase in b.c.

3.3 *Effect of soil density*

A considerable drop in compensation efficiency resulted from reducing the soil density as shown in Fig. 7. Injection in dense sand (R.D = 93%) resulted in efficiencies between 40–90%, whereas injection in medium-dense sand (R.D = 60–75%) yielded in reduced efficiencies between 10–40%. The variation for a given density is due to differences in water-to-cement ratio and bentonite content, which will be discussed in later sections. One injection test was performed in a soil model with R.D. = 40%. In this case, the compensation efficiency was close to zero percent.

When grout was injected in medium-dense or loose sand, soil had to be compacted before any heaving would occur, whereas the response of dense soil was much quicker. This may explain why in practice a pre-conditioning stage, in which a grout mix is injected to compact soil, is usually performed prior to the commencement of compensation grouting.

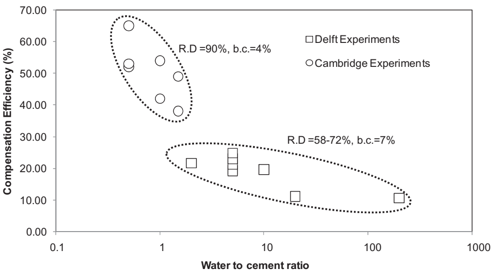


Figure 7. Effect of water-to-cement ratio on compensation efficiency.

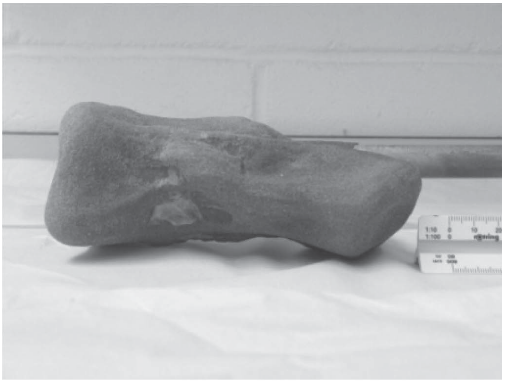
3.4 *Effect of w/c ratio*

Figure 7 shows the effect of w/c ratio for a given soil density of R.D. = 93% (Cambridge experiments). Only the data with a bentonite content of 4% is presented (the effect of benonite content is presented later). For grout mixes of the low w/c ratio of 0.5, typical grout and compensation efficiencies were around 60%. As shown in Figure 8, most of the grout remained close to the injection point, creating a reasonably regular shape of hardened material due to the limited amount of free water in the grout mix. Therefore, no significant change in compensation efficiency with the injection rate is to be expected.

When the w/c ratio increased from 0.5 to 1.5, the compensation efficiency value decreased. As shown in Figure 7, typical efficiencies were between 45–55% and 40–50% for w/c ratios of 1.0 and 1.5, respectively. There was some influence of the injection rate on the efficiency. With more free water in the mix, faster injection allows less time for pressure filtration to take place during injection and so the loss in injected volume becomes less. Furthermore, fingering starts to take place when mixes of moderate w/c ratios are injected faster. This causes the grout to cover a larger area, but the shape of the hardened material becomes thinner, as shown in Figure 9. The difference in efficiency due to the change in injection rate was about 11–12%.

Figure 10 shows a comparison between the compensation efficiencies and the grout efficiency for experiments using grouts with w/c ratio ranging from 0.5 to 1.5. As described before, compensation efficiencies are calculated at the end of injection, whereas grout efficiencies are based on the volume of the hardened grout 24 hours later. The values of compensation and grout efficiencies were almost equal, which suggests that pressure filtration happens mainly during injection. In the dense sand (RD = 93%) there will be hardly further densification during the injection and since the container prevents lateral deformation all grout volume present after injection results in the same volume of heave. At lower relative densities of the sand the compensation efficiency will be less than the grout efficiency due to densification of the sand.

Figure 8. Hardened grout for w/c = 0.5 and b.c. = 4%.



(a) Slow injection 0.385 l/min

(b) Fast injection 3.33 l/min

Figure 9. Hardened grout for w/c = 1.5 and b.c. = 4%.

With the Cambridge set-up, it was not possible to calculate the efficiency for grouts with very high w/c ratios, since the injected grout spread unevenly

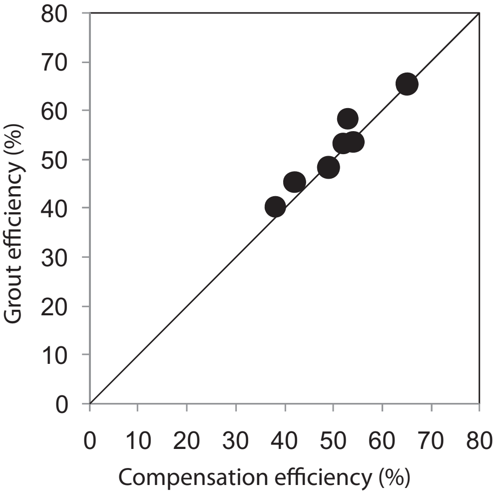


Figure 10. Comparison between grout efficiency and compensation efficiency from the experiments using grout with w/c = 0.5 to 1.5.

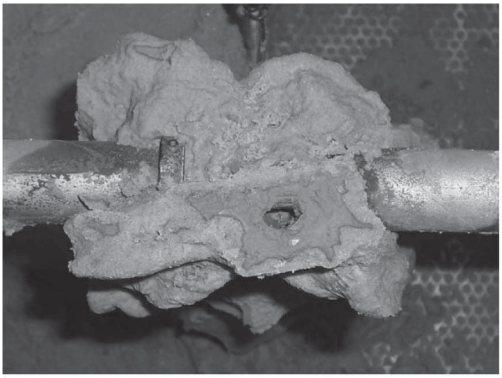
within the soil and it was not possible to compute the heaved volume accurately, as discussed before.

On the other hand, it was possible to evaluate the compensation efficiency using the Delft setup irrespective of hardened grout shapes. Experiments performed in medium dense sand (R.D. = 58–72%) resulted in efficiencies of between 10–30%. It was found that the efficiency decreased with the water-to-cement ratio as shown in Figure 7. The effect of injection rate becomes more evident for the high w/c ratio of 5.0. The grout tends to spread more for a faster injection rate as shown in Figure 11. The compensation efficiency was 23% when the injection rate was 2.00 litre/minute, where it increased to 32–37% when the injection rate was 10.00 litre/minute. With more free water in the mix, faster injection allowed less time for volume loss by pressure filtration and so, higher efficiencies were achieved.

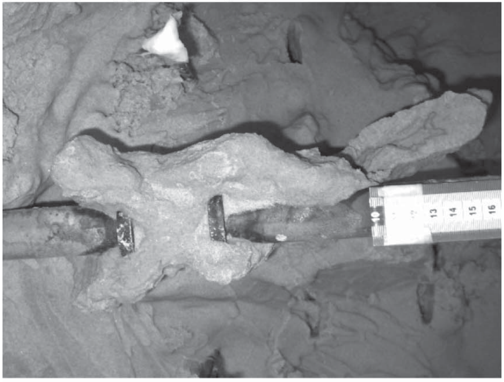
For a grout with a WCR of 2 and 8% of betonite (percentages given by weight), the volume of solids is only 20% of the total volume. Assuming a porosity between the solids of 40%, the total volume of solids and pores is 33% of the total volume. This means that the loss of water can already have a large influence on the efficiency as defined above.

3.5 *Effect of bentonite content*

The change in bentonite content had an influence on the compensation efficiency as shown in Fig. 12. For tests with grout of w/c = 1.5 (injection rate = 3.33 litre/minute), increasing the bentonite content from 4% to 8% improved the compensation efficiency by about 30%. When a higher bentonite content of 12% and 14% were (??) used, typical compensation efficiencies were 78 and 90% for w/c ratios of 1.5 and 1.8 respectively. This is attributed to the influence of bentonite content on pressure filtration.



(a) Slow injection 2 l/min



(b) Fast injection 10 l/min

Figure 11. Hardened grout for w/c = 5.0 and b.c. = 7%.

The substantially high efficiency of 90% was the result of sand fracturing, as the accompanying

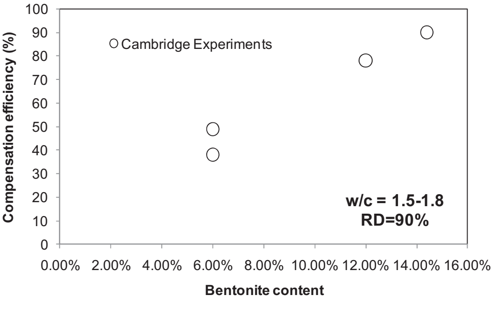


Figure 12. Effect of bentonite content on compensation efficiency from the tests using grout of w/c = 1.5 to 1.8.

formation of a low permeability particle accumulation around the fractures would limit the occurrence of pressure filtration.

4 CONCLUSIONS

Physical model experiments on compensation grouting in sands were performed in two different setups (Cambridge and Delft). Although there were difference in the way soil heave was measured in the two setups used, different approaches were adopted to assess the compensation efficiency of the grouting tests by the end of injection. Nonetheless, a reasonable agreement was found between the results obtained from the two setups.

The effect of water-cement (w/c) ratio, bentonite content (b.c.) and injection rate on compensation efficiency was investigated. Results show that a considerable drop in compensation efficiency resulted from reducing the soil density. Injection in dense sand (R.D = 93%) resulted in efficiencies between 40–90%, whereas injection in medium-dense sand (R.D = 60–75%) yielded in reduced efficiencies between 10–40%. When an injection test was performed in a soil model with R.D. = 40%, the compensation efficiency was close to zero percent (Kleinlugtenbelt, 2005).

When the w/c ratio increased from 0.5 to 1.5 (a bentonite content of 4%) for a given density (R.D. = 93%), the compensation efficiency value decreased. Typical efficiencies were between 60% and 40–50% for w/c ratios of 0.5 and 1.5, respectively. Using the Cambridge set-up, it was possible to compare the compensation efficiency to the grout efficiency. The values of compensation and grout efficiencies were almost equal, suggesting that pressure filtration happens mainly during injection and sideways deformation is negligible.

A similar finding was made when the w/c ratio was varied from 2 to 200 using the Delft setup. Experiments performed in medium dense sand (R.D. = 58–72%) resulted in decrease in compensation efficiency from 30% to 10% when the w/c ratio increased from 2 to 200.

Increasing the bentonite content improved the compensation efficiency. When a higher bentonite content of 12% to 14% was used in dense sand, typical compensation efficiencies were 78 and 90% for w/c ratios of 1.5 and 1.8 respectively. The higher content of fine particles led to a considerable reduction in pressure filtration, which is in agreement with the literature review (Rawlings et al., 2000 and Bruce et al., 1997). Consequently, more fingering took place and a significant improvement in efficiency was achieved.

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