Summary

Compensation Grouting in Sand
Experiments, Field Experiences and Mechanisms

Compensation grouting was developed to compensate for settlement during underground construction. The successful deployment of the technique depends on being able to inject several times at the same injection point. This can be achieved with fracture grouting (the grout creates fractures in the soil so that not all grout remains around the injection point, where it would block further injections). This process has been successfully applied in clay and the results of full-scale field trials and a limited number of projects abroad have demonstrated that it is also possible in sand. However, our understanding of the actual process in sand is limited and so we lack theoretical models.

Compensation grouting will be used in Amsterdam during the construction of the North-South underground line, where compensation grouting is planned as a mitigation measure for possible settlement during tunnelling. A better understanding of the processes involved is needed to reduce the risks and evaluate the results.

The aim of this study was to improve our understanding of the process, and the relevant process parameters, of compensation grouting in sand. On that basis, we hope to establish a sounder theoretical basis for the description of compensation grouting in sand.

The mechanisms present during compensation grouting in sand have been investigated in laboratory experiments. Compensation grouting in sand differs from the same procedure in clay because, in sand, the water in the grout mixture can drain from the grout, something which is highly unlikely in clay, which is much more impermeable. Furthermore, the sand itself will behave in a drained way when fractured and the clay will behave in an undrained way. The models for fracture initiation and propagation developed in clay cannot therefore be used in sand. Without any fracturing in the sand, heave is very local and compaction of the sand may occur, impairing the efficiency of the process. At the other extreme, there could be very long, thin fractures, which make it difficult to create local heave. The ideal situation would therefore be some fracturing, but with fractures of limited length (a maximum of a few metres in field conditions).

The literature shows that it is difficult to achieve fractures in sand in a laboratory set-up when injecting a cement-bentonite grout, as in compensation grouting. However, excavations in the field have shown that fractures have been created by the injection of a cement-bentonite grout in sand.

Experiments and theory have demonstrated that the maximum injection pressure is given by the cavity expansion theory. Cavity expansion will lead to the symmetric expansion of the soil around the cavity during injection with grout. Fracturing of the soil may occur at a lower injection pressure. This study provides a qualitative description of a possible mechanism that leads to fracturing in sand, as well as a quantitative demonstration of a relation between the shape of a fracture and the injection pressure. Relatively low injection pressures may be associated with thin fractures. Higher injection pressures in sand will result in broader and shorter fractures. The shape of fractures occurring during compensation grouting is influenced by

the water that is pressed out of the grout into the soil during injection, a process known as "pressure filtration". A thin impermeable filter cake is needed between the injected grout and the sand to create a fracture in the sand. A filter cake that is too thick hampers fracture formation and only short fractures or no fractures at all will be formed.

Four series of grout injection experiments were performed involving a total of 34 tests. The grout properties, injection rate, confining pressure, relative density of the sand and the sand itself were varied. In three test series, the grout was injected directly into the sand. The fourth test series simulated the installation procedure used in the field.

We found, in agreement with the developed theory, that more cement in the grout results in a thicker filter cake and therefore to higher injection pressures and shorter and thicker fractures. We also found that, in the conditions prevailing during the test, a low cement concentration in the grout leads to pressure infiltration: the liquid and solid particles in the grout are pressed together into the grain skeleton without deformation of the soil skeleton.

The efficiency of the grouting process (the ratio between the volume of heave created and the volume of grout injected) proved to be dependent on the density of the sand. Low relative density of the sand results in low efficiency. Efficiency increases at higher relative densities of the sand and also when the grout used contains more solid material. When grout is injected in sand with a low relative density, there will be densification of the sand, compensating for the volume of grout injected. At very high relative densities, there may even be dilatancy of the sand during deformation, resulting in higher efficiencies. However, it was not possible to prove this on the basis of the results of the measurements, because only overall efficiency was measured, with the amount of heave always being much less than the volume of grout injected.

If the installation procedure of the grout injection tubes is taken into account, as in the fourth test series, lower injection pressures result. The process of pressure filtration is also present in the sleeve grout, reducing the load on the sand around the sleeve grout, and therefore the confining stresses in the sand directly around the sleeve grout. These lower confining stresses lead to lower injection pressures. As a consequence, there is less pressure filtration during the injection (the driving parameter for pressure filtration – the pressure – is lower). The limited pressure filtration in the fourth series leads to a thinner filter cake, and therefore thinner fractures. These tests showed that, comparable to what was found in the field at several locations, grout not only concentrates in fractures, it also concentrates around the sleeve grout and forms a thin cylinder around it. This can cause heave at quite some distance from the injection point. The results from the fourth and last test series showed that it is essential to take the influence of the installation procedure into account to simulate the compensation grouting process as it occurs in the field.

At the end of this study, the bearing capacity of the pile foundations under houses at the Vijzelgracht location, which had settled after a leak through a diaphragm wall, was restored using the compensation grouting technique. Although the technique is the same, this is not compensation grouting because compensation grouting is used before settling occurs. When used after settling, the technique is known as "corrective grouting". Analysing the measurements showed that, in this case, the achieved efficiency was only very low at less than 1.7%, while normal efficiency figures are in the range of 4 to 22% (Chambosse and Otterbein, 2001[b]). The corrective grouting resulted in a maximum heave of 10 mm in the buildings. After the end of the grouting campaign, there was settlement for a period of 5.5 months. During this time, most of the heave that had been achieved disappeared. This ongoing settlement was much higher than at

other locations in Amsterdam in "undisturbed" soil conditions. It was not caused by consolidation of the grout but probably by the consolidation of the soft soil layers overlying the bearing strata.

The consequences of this study for practice are that, for sand with a relative density higher than 60%, compaction or fracture grouting result in broadly similar efficiencies. Compaction grouting will result in more localised heave than fracturing. Efficiency is determined more by the amount of solids in the grout: the more solids, the higher the efficiency.

Grout and soil properties determine the length of the fracture during compensation grouting. This was modelled in an analytical calculation model. For a fracture with a plane shape, the ratio between the thickness of the fracture and its length can be calculated using the stiffness of the soil and the grout properties. The model showed that the injection rate, the effective stress, the permeability of the grout cake and the shear modulus of the soil determine the ratio between the thickness and length of the fracture. The results of the model concur with experiments for situations where the pressure infiltration of the grout during injection is negligible.

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