Compensation Grouting, Concept, Theory and Practice

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Abstract

Compensation grouting, or the use of grouting techniques to control ground settlement during soft ground tunnelling, has become a well-established technique. While compensation grouting can be applied using compaction grouting (Baker et al., 1983) or soil fracture grouting techniques, the majority of applications to date have used the soil fracture technique. This paper contrasts the concept and theory of the two techniques and describes the application of soil fracture grouting, along with a review of several case histories.

Concept

Compensation grouting has been defined by a number of sources (Rawlings et al., 1998) but broadly can be described as the introduction of a fluid or semi-fluid material into the ground, increasing the local volume at the point of injection. This in turn causes movement by expansion of ground away from the area of injection, either compensating for movement in an opposing sense or causing movement to accumulate in the direction of expansion.

Two processes have been traditionally used:-

- Soil Fracture Grouting, or Soilfrac
- Compaction Grouting

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Soil fracture grouting injection relies on the propagation of in-ground fractures by injection of a neat fluid grout at pressures in excess of the hydro-fracture pressure and is demonstrated schematically by Figure 1. This technique has generally found a commercial niche in its application in fine grained soils where more positive grouting methods such as permeation and jet grouting are not possible.

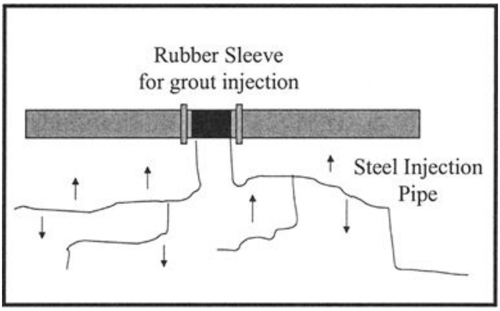


Figure 1. Concept of Compensation Grouting by Hydro-fracture Technique

Alternatively, a relatively stiff sand and cement compaction grout can be injected, generally in granular soils, to cause an expanding bulb of grout to be propagated. Pressures required to initiate this process are high and the process is shown schematically in Figure 2. Unless the cementing binder is very weak, this process cannot be reinitiated from the same position, as the set grout is almost impossible to break through. While compaction grouting has been used successfully as a method of compensation grouting related to tunnel construction, its inherent

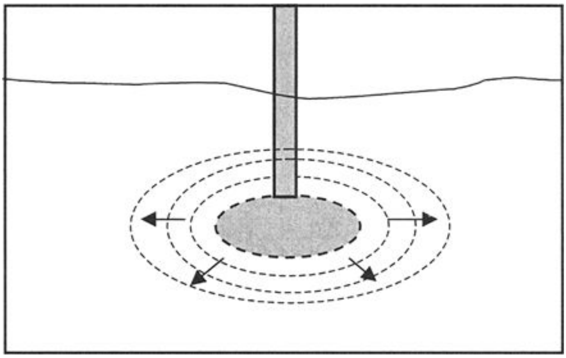


Figure 2. Schematic Representation of Compaction Grouting

high pressure of injection limits its application in close proximity to a tunnel face. Compaction grouting is further limited in its ability to react to settlements quickly because injection pipes are not reusable, thus requiring the installation of additional pipes for added injections

Theory

A number of publications have attempted to describe this grouting process theoretically (Rawlings et al., 1998). Compaction grouting can be modelled as an expanding bulb or cavity and hydro-fracture grouting as propagation of fractures in the ground.

When considering compaction grouting or the injection of stiff grouts, it is clear that the grout will only enter the ground following plastic failure in fine grained soils and compaction of coarse grained soils. This may be compared to bearing capacity failure or pile failure and hence the pressure or stress required to achieve this is high. Considering the failure of a pile, ultimate capacity may be four to six times the in-situ shear stress (Cu) and hence for a thick paste, the injection pressure could be expressed as $6Cu + \sigma h$ (horizontal overburden stress).

For hydro-fracture, a fluid grout is simply required to exceed the overburden and shear strength. For normally consolidated materials the vertical stress is higher than the horizontal stress and hence fractures are initially vertically orientated. The action of repeated injections increases the horizontal stress and eventually this equals the vertical stress. At this point lift can be generated.

During the process of stress change, horizontal movements will take place as resistance is built up. This can be compared to strengthening the sides of a box, and trial works on the Docklands Light Railway project in London have demonstrated this effect.

Application To Tunnel Construction

If consideration is given to magnitude of injection pressure, then Figure 3 shows the relationship of compaction grouting to fracture grouting. Clearly compaction grouting has the potential for inducing higher pressures on tunnel linings. While this may not be significant for situations where the fracture zone is remote from the tunnel, in many cases the compensation grouting process may lead to unacceptably high stress build up on the tunnel lining. The degree of stress increase is therefore very dependent on the grout formulation and while thick grouts offer economies of pretreatment they may cause more problems during the actual compensation grouting phase.

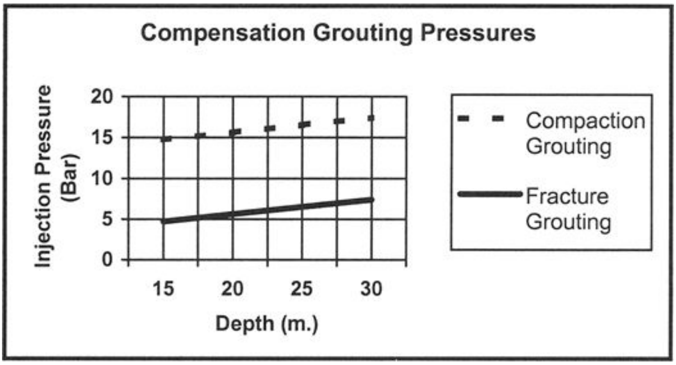


Figure 3. Compensation Grouting Pressure Comparison

A further complication of compensation grouting in association with a slurry pressure Tunnel Boring Machine (TBM) is the possibility that the process may cause changes in pressure at the face which could disrupt the TBM pressure balance. However compensation grouting carried out on the Docklands Light Railway close to a pressure balance TBM did not cause such problems. As further research work continues it is likely that further restrictions will be placed on grouting pressures to reduce the risk of damage to segments.

The mechanism whereby fracture grouting reinforces the ground is not fully understood. It has been shown on a number of projects that the introduction of the fracture injection pipes and the pre-injection prior to tunnelling can, in itself, dramatically reduce settlements.

An acceptable method of compensation grouting is to use this reinforcing effect to stiffen the ground, limiting the application to only pre- and post-settlement grouting. Such a system was employed at Bielefeld in Germany (Otterbein and Raabe, 1990) where the compensation grouting zone was too close to the tunnel to be used with the New Austrian Tunnelling Method (NATM). The buildings were therefore kept within tolerance by pre-heaving before tunnelling and compensating after tunnelling. While this may not be a strictly true form of compensation grouting, which is normally reserved for injection of grout *during* tunnelling, it provides an equally acceptable form of protection to the structures in question and may be more cost effective. This solution is very structure specific and also is related to magnitude of settlement. It can be an option where settlements are only marginally too high.

Ground treatment can be carried out to create a protective canopy (See Figure 4) that would not allow the settlements to migrate to the surface. The design would assume that the ground treatment would act as an arch, protecting the ground above during passage of the TBM. Back grouting of the tunnel rings would have to be carefully undertaken to ensure no possibility of long-term movement develops.

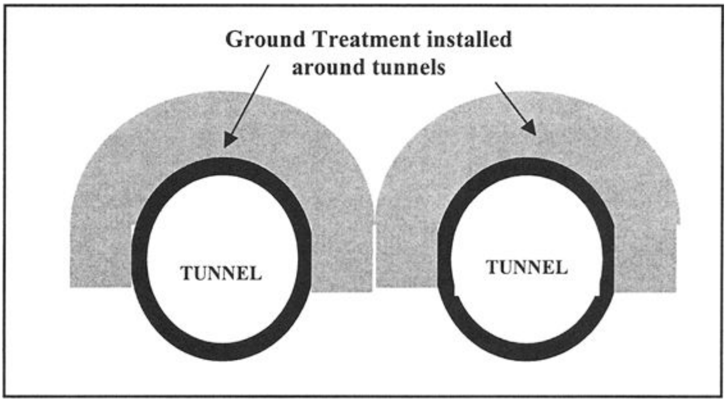


Figure 4. Canopy Ground Treatment

Finite element analysis work carried out in the USA indicates that the thickness and strength of such a zone can materially effect the degree of surface settlement reduction experienced. As an example, for a 7-m diameter tunnel with its crown at 10 m in medium dense sands, the optimum ground treatment thickness is given as 2 m assuming an insitu strength of 0.5 N/mm^2. Increasing the thickness of treatment yields decreased benefit as the additional cost generally outweighs the reduction gained in settlement. When considering the use of compensation grouting for tunneling or other processes, due consideration must be given to the way the settlement is propagated. Figure 5 below shows a typical settlement trough that will result when a 7-m diameter tunnel is bored through granular material at a depth of 25 m with an average 1 percent face loss.

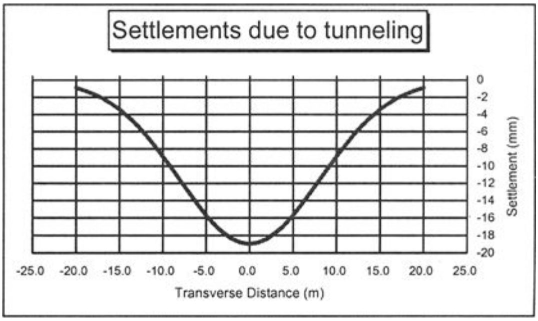


Figure 5. Settlement Trough Due To Single Tunnel

Positioning of any compensation grouting zone needs not only to consider this transverse effect but also a similar effect in advance of the tunnel. Figure 6 below demonstrates the dangers of ignoring this effect.

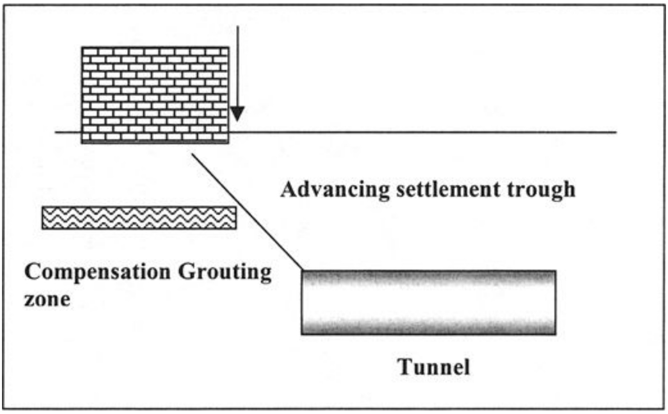


Figure 6. Position of Compensation Grouting Zone

Clearly the compensation grouting zone needs to be extended towards the advancing tunnel in order to intercept the forward settlement trough.

When a building is offset from the tunnel this effect still needs to be considered and the following zonal placement shown on figure 7 should result.

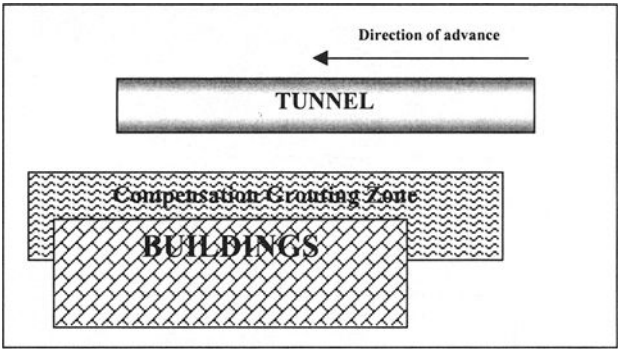


Figure 7. Plan Showing Relative Position of Compensation Grouting Zone

The relative position of the foundations also need to be considered as piled foundations may be close to the tunnel and hence cause both larger and more localised differential settlement.

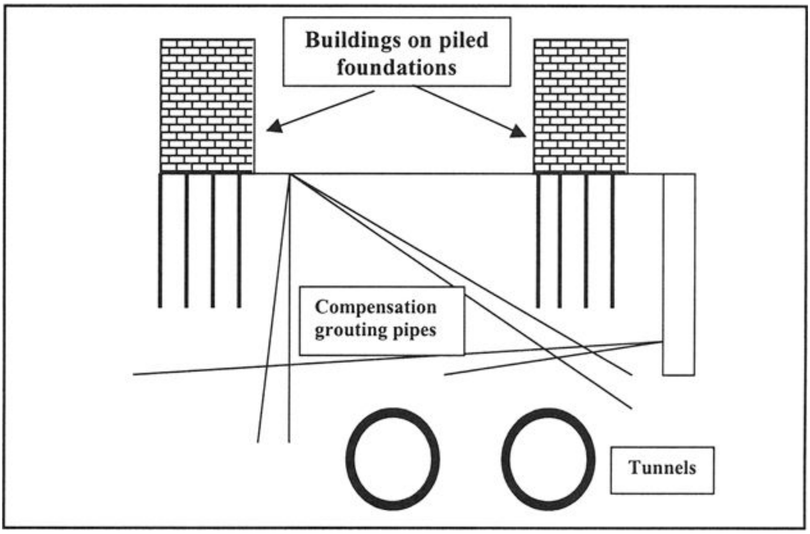
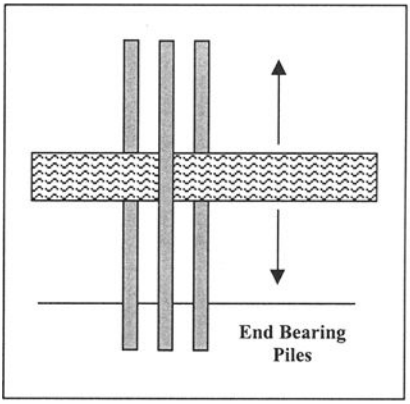


Figure 8. Section Showing Effect of Piles on Zonal Placement

In summary both building fabric, foundation level and relative tunnel position need consideration when designing such a scheme.

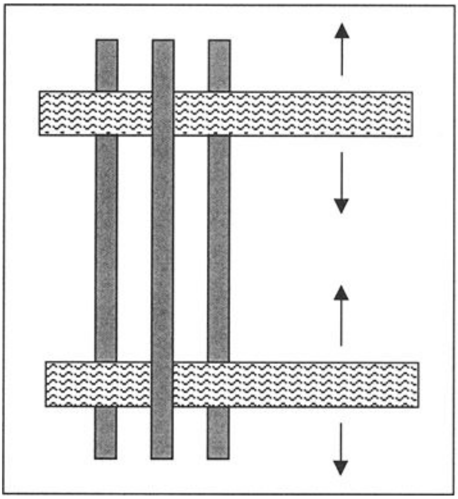
Compensation grouting in close proximity to piles needs careful consideration. Work carried out by the authors have shown that piles can both be moved or not by the compensation grouting process. Whether a pile will move will depend on the relative position of the pile and the compensation grouting zone. Compensation grouting will cause the underlying ground to move during preconditioning (the injection phase in advance of tunnelling) and this needs to be designed with regard to the piles.

Generally if the compensation grouting zone is below the pile toes then the piles will move during compensation grouting as the upward force is below the pile. If the zone is between the pile cap and pile toe then movement will be determined by the combination of ground conditions and pile design. If compensation grouting is being carried out in very soft clays above end-bearing piles then clearly skin friction support will be small and the ground will move relative to the piles. If the piles are designed as frictional then they may or may not move depending on the relative position of the zone. The piles will move if the frictional support above the zone exceeds the frictional support below the zone. Figures 9 and 10 demonstrate this.



Side friction is low for end bearing piles and hence the relative movement of the ground will exceed the side friction on the piles and no movement of pile results.

Figure 9 : End Bearing Piles



The zone near the top of frictional piles will not be able to move the piles as there is insufficient friction above the zone to fail the side friction below the zone.
The zone near the toe however will move the pile as the side friction above the zone will exceed that below.

Figure 10 : Frictional Piles

Figures 11 and 12 below from a project in the north of England show conditioning of a ground floor slab (Figure 11) and adjacent pile caps (Figure 12). Ground conditions consisted of 3-4 m of made ground overlying 6-8 m of very soft alluvial clays/silts which in turn overlaid glacial tills. The graphs show that movements are identical, indicating that the piles were lifted with the floor slab. Conversely for another project, where the injection zone was 6 m deep but the end bearing piles were 14 m deep in very soft clays, the piles did not move.

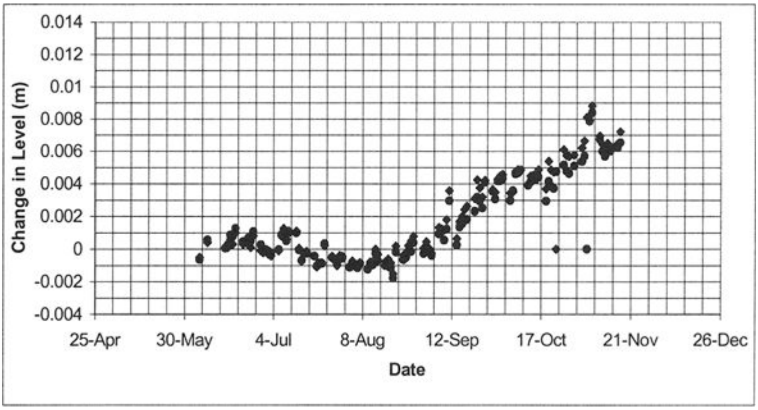


Figure 11. Movement of Floor Slab During Grout Injection

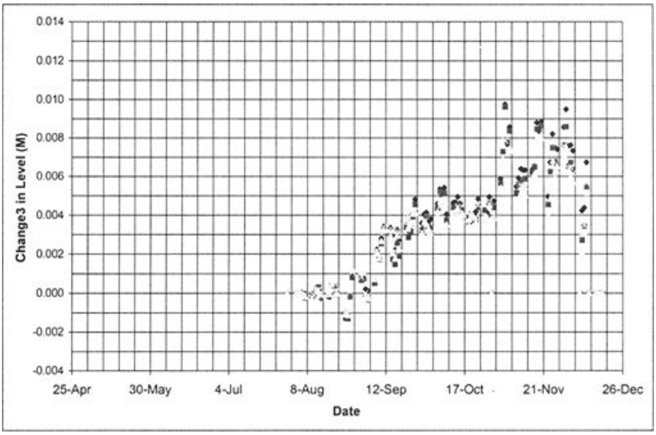


Figure 12. Movement Of Pile Cap During Grout Injection

Dissipation of pore pressure when carrying out compensation grouting in clays needs careful consideration, particularly when working with soft clays. Figure 13 below shows pore pressure dissipation following trial injections in London clay, an overconsolidated very stiff clay. Dissipation was rapid, with complete return to original values within two weeks

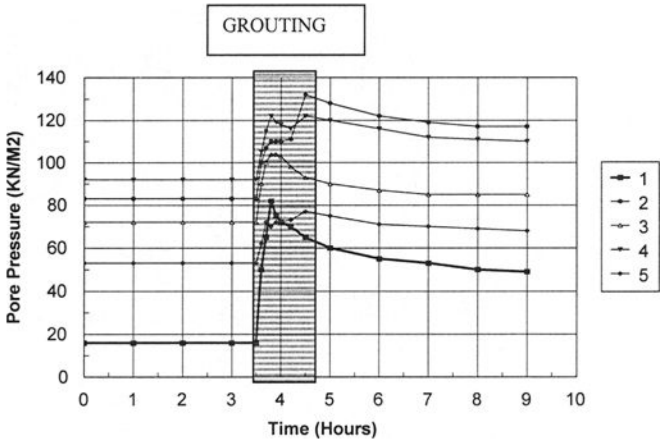


Figure 13. Pore Pressure Changes During Injection in London Clay

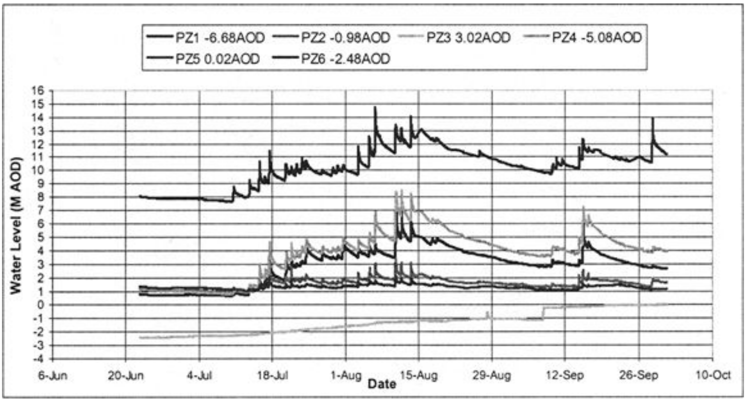


Figure 14. Pore Pressure Response in Soft Clays

This should be compared with the pore pressure response for injection in a soft clay which is shown on Figure 14 above. In this case, repeated injections were carried out through the summer, causing a steady build up in pore pressure. If the final section