Effect of compaction grouting in loosely packed sand on density

Effet de compactage solide sur la densité de sable très laches

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ABSTRACT

Randstadrail is the future light-rail link between the cities of Rotterdam, The Hague and Zoetermeer, the Netherlands. In the city area of Rotterdam a shield tunnel will be built for two single track tunnels. The tunnel crosses an intensively used railway track, called the Gouda Link, built on an embankment of saturated loose sand, constrained by very soft clay and peat layers, and reaching almost the Pleistocene sand layer. Boring through and just beneath this loose sand imposes some geotechnical risks, in particular the risk of liquefaction due to monotonic loading. In order to reduce the risks of uncontrolled movements (liquefaction, settlement) during the boring process several design options have been investigated. This paper describes the model test for one of the considered options, densifying the embankment by compaction grouting. The aim of the test was to gain insight in the mechanism and effectiveness of compaction grouting in loosely packed sand. Two effects of compaction grouting are discussed in more detail: i) the change on density and ii) the change on stress level.

RÉSUMÉ

Randstadrail est une future liaison light-rail entre les villes de Rotterdam, La Haye et Zoetermeer. Dans la ville de Rotterdam un tunnel avec deux voies séparées sera installé à l'aide d'un tunnelier. Le tunnel passe en dessous de la ligne de chemin de fer vers Gouda. La cunette du chemin de fer est composé de sables très laches saturés, qui descendent en général jusqu'aux sables du Pleistoncène et qui se situent entre des couches d'argiles très molles et de tourbe. Afin de diminuer le risque que des déplacements excessifs se produisent lors du creusement des tunnels (liquéfaction, tassements) différentes mesures ont été examinées. Cet article décrit les essais à modèle reduit qui ont été réalisé afin d'étudier une option : le compactage solide. Deux phénomènes du compactage solide sont discutées en détail = i) le changement de la densité et ii) le changement des contraintes.

1 INTRODUCTION

RandstadRail is the future light-rail link between the cities of Rotterdam, The Hague and Zoetermeer in the Netherlands. It connects the local public transportation systems in these cities such that people can travel between the inner cities without change of trains.

The Rotterdam section involves the construction of two single-track shield tunnels with an outer diameter of 6.5 m and a length of 2.4 km each.

In the northern part of the alignment the shield tunnels cross an intensively used double railway track. This railway connects Rotterdam and Utrecht via the city of Gouda and is called the Gouda Link. The railway track should stay in use during tunnel construction.

Figure 1: Overview railway crossing Gouda Link

2 RAILWAY CROSSING GOUDA LINK

The Gouda Link crossing is a very oblique crossing (20^0) and therefore quite long (approximately 40 m). See Figure 1 for an overview.

The shield borings cross the embankment with a crown level of approximately 15.5 m minus surface level (NAP - 17 m). The cover underneath the embankment is relatively shallow due to the nearby connection with the existing railway track Hofplein line, situated at ground level.

3 GEOTECHNICAL CONDITIONS

The northern part of the city of Rotterdam is known for its very bad ground condition. The natural soil consists from surface level (at 1.5 m below reference level NAP) to a depth of NAP – 17.0 m of very compressible peat (Holland peat) and organic clay (Gorinchem clay), overlying the Pleistocene sand layer. The groundwater level is close to the surface at NAP – 2.0 m.

The railway embankment consists of anthropogenic saturated very loose sand to a depth of NAP - 16 m. The embankment was constructed around the year 1900 using the displacement method. Big amounts of sand were supplied in an initial shallow ditch and the sinking fill almost reached the firm Pleistocene sand layer. From the results of the soil investigations it was concluded that probably the crown of one of the tunnels will cut the loose sand. See Figure 2.

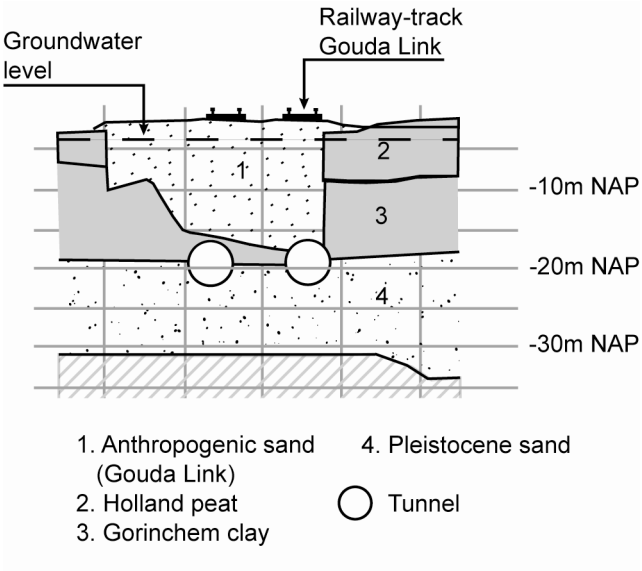

Figure 2: Soil layering and location of the shield borings.

The anthropogenic sand was investigated from the shoulder of the embankment with inclined Cone Penetration Tests (CPT's, see Figure 3), electric conductivity measurements and borings. The purpose of the electrical conductivity tests was to determine the local density of the sand. In the laboratory classification tests, direct simple shear tests wet critical density tests and special triaxial tests were performed.

The natural soil layers on both sides of the embankment consist of Holland peat and Gorinchem clay and were investigated using a more standard investigation approach of CPT's , borings and a laboratory program of oedometer and triaxial tests. Relevant test results are presented in respectively Tables 1 and 2.

Table 1: Characteristics of the antropogenic sand.

Properties	Mean value	Dimension
CPT (q_c – value)	1 to 2	MPa
Local density Index I_D	20 to 30	%
Wet critical density I_D	35*	%

* procedure "wet critical density" (Lindenberg & Koning, 1981) at a stress level of 120 kPa.

Table 2: Characteristics of peat (Holland peat) and organic clay (Gorinchem clay).

Properties	Mean value	Dimension
Unit mass of peat	1020	kg/m^3
Assumed shear modulus of peat	0.3	MPa
Unit mass of organic clay	1400	kg/m^3
Assumed shear modulus of clay	0.6	MPa

For a more detailed description of the sand characteristics and performed special laboratory investigation see Groot, et al., (2005) and Pachen et al.(2005).

Figure 3: Execution of an inclined CPT.

4 MAJOR GEOTECHNICAL RISKS

The extreme loose sand of the railway embankment imposes some serious geotechnical risks during construction of the shield tunnel crossing the Gouda Link. The following risks were identified:

- Liquefaction of the loose sand due to monotonic loading;
- Densification of the loose sand;
- Cyclic liquefaction of the loose sand.

Liquefaction due to monotonic loading may occur when the sand is in a loose state. The grain skeleton is in a meta stable state and any small disturbance may cause the grain skeleton to collapse (Stoutjesdijk et al (1998)). Failure of the grain skeleton in one part may induce a collapse in adjacent parts, thus creating a progressive failure. A large area may be influenced in such a case. As it is an instantaneous and uncontrolled process it cannot be stopped once it has started. This possesses a severe safety risk. In Pachen et al. (2005) and Groot et al. (2005) a more elaborate description of this process is given.

During boring of the tunnel vibrations are emitted from the TBM. Cyclic loading of sand is known to result in densification and, in case of saturated sand, also in the generation of excess pore pressures. The surface settlement due to these vibrations for the selected design option was estimated to be in the order of 0.02m (best estimate) to 0.10 m (upper bound), see Pachen et al. (2005). As these settlements will develop gradually, monitoring the surface level is an adequate measure to avoid the risk of unacceptable rail deformations. When the settlements tend to become unacceptable the construction process can be stopped and the railway tracks can be relevelled.

The cyclic induced excess pore pressure during shield boring was assessed to be small due to the low densification rate, the limited area of densification and ample possibility of dissipation. The risk for liquefaction due to cyclic loading was therefore considered low.

The risks of densification and cyclic liquefaction can be dealt with during construction using an appropriate monitoring program. The risk of liquefaction due to monotonic loading is considered a severe risk that has to be reduced. Several options were considered during design. One of them was to densify the soil in the railway embankment using compaction grouting.

5 PRINCIPLES OF COMPACTION GROUTING

In EN 12715 (2000); compaction grouting is defined as a displacement grouting method which aims at forcing a mortar of high internal friction into the soil to compact it without fracturing.

Compaction grouting is used in the United States on a rather large scale to compact loose sand in place or in fills in order to reduce settlements and to avoid liquefaction. Compaction grouting is also used as remediation e.g. when sand layers have been loosened after tunnelling.

During compaction grouting an expanding cavity is created within the soil. As the grout mass expands, a complex system of radial and tangential stresses develop. Significant displacement shearing and plastic deformations occur in the soil adjacent to the grout interface.

Although the compaction grouting method has been used during several decades now, not so much research has been performed to understand what really happens in the soil during the compaction grouting. This is mainly due to the fact that it is very difficult to measure variations of stresses and void ratio's in sandy soil, in an accurate way.

During the last years several efforts have been made to elaborate a model for compaction grouting El-Kellesh et al (2001). However these models are not yet validated.

In the available literature only a few data can be found about the increase of the density due to compaction grouting and this information is not consistent. In Warner (1993) it is stated that near to the soil-grout interface lower densities have been found than at some distance.

The effectiveness of compaction grouting is normally checked by means of SPT, CPT or PMT. Until now it is not clear if the increased resistance measured by SPT, CPT or PMT is due to the increase of the horizontal stresses or to the increase of the density. However from the fact that considerable amounts of grout can be injected into the ground it may be assumed that some increase in density takes place and that the increase in resistance, measured with SPT, CPT and PMT is not only due to the increase of the horizontal stresses.

6 MODEL TEST

In order to test the effectiveness of compaction grouting a simple model test was performed in the test facilities of GeoDelft. The aim of the test was to gain insight in the mechanism and effectiveness of compaction grouting in loosely packed sand. For the test a cylindrical container with a radius of 0.6 meters and a height of 1.0 m was used. In this cylinder a rubber balloon was placed. The aim of the balloon is to contain the injected volume of grout and prevent the occurrence of soil fracturing instead of compaction. The balloon was connected to a flexible tube. Before filling the container with sand the balloon was de-aired in order to reduce the volume of it before the test as much as possible. The cylinder was filled with sand (Baskarp sand) in a loose state. After filling of the container grouting was performed by injecting an amount of grout into the balloon.

From the used dry weight of sand and the volume of sand in the container it was derived that the average void ratio is 0.773. The minimum and maximum void ratio of the used sand is respectively $e_{min} = 0.515$ and $e_{max} = 0.883$. The relative density of the sand in the test is thus $I_D = 0.30$.

Compaction grouting was modelled by filling the rubber balloon with grout. By injecting grout in the rubber balloon a grout body developed (see Figure 6). After excavation of the grout body it turned out that the volume was 540 cm^3. The top of the grout body was at 63 cm below surface level and the bottom at 90 cm below surface. The shape of the groutbody appeared to be mushroom-like.

Before and one day after the grouting process also a CPT test was performed in the sand bed. For this a small size penetrologger (diameter of the cone 20.5 mm) was used. Figure 4 shows the results. The cone resistance increased significantly due to the grouting process. Above the grout body the increase was a factor 2 to 3 and next to the grout body the ratio increase is a factor 7 to 8.

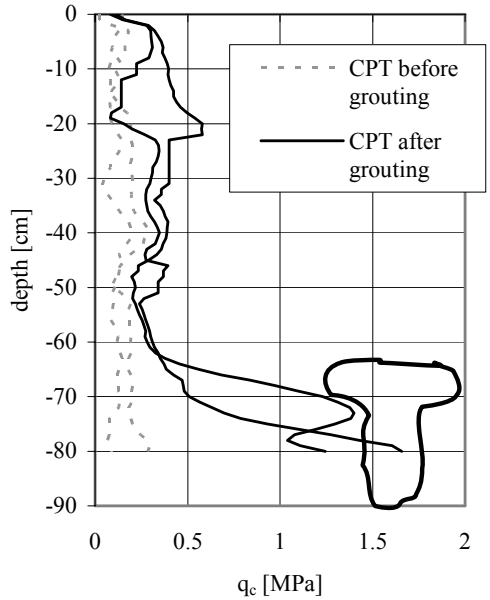

Figure 4: Cone penetration test results before and after grouting.

Besides cone penetration testing the volume change was measured with core cutters. Figure 5 shows the void ratio as function of depth. For the top layers the measured void ratio after grouting agrees well with the average void ratio of e = 0.773 before the test. As can be seen the void ratio increases at the level of the grout body, indicating that the soil becomes looser at this level. It must be concluded that, contrary to general believe, in this case compaction grouting results in loosening of the soil.

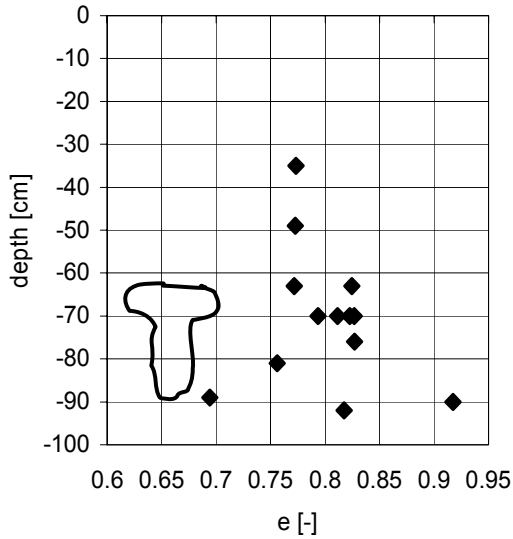

Figure 5: Results of the density measurements.

The increase in CPT value and the decrease in void ratio can be explained with the analysis of the stress level. In the container a low effective stress level is present. Because of that the sand also has a low critical density. According to the critical state theory at large shear deformations the soil density will tend to the critical density. In this case this resulted in loosening of the soil.

The increase in cone resistance can be explained from the increase in horizontal stress level due to the grouting process. The expanding grout body pressed the soil against the wall of the cylinder, thus increasing the stress level. The same mechanism is expected to be responsible for the mushroom shape of the grout body. After the horizontal stress has become equal to the vertical stress it is easier for the grout to move the overlying sand upward. In fact the grouting process becomes a kind of compensation grouting.

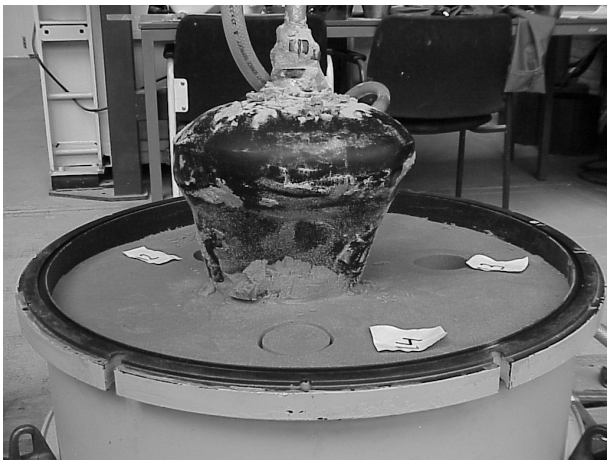

Figure 6: Partly excavated grout body and locations of some of the core cutters.

7 RISK REDUCTION

For the considered sand and stress level the effect of compaction grouting on local density proved to be poor as no substantial densification of the sand occurred. An increase in cone resistance was measured but this is attributed to the increase in horizontal stress and not to densification of the sand.

It cannot be excluded that the test results are influenced by the relative small size of the test. Consequences of the small size are the small distance between grout body and wall of the container, the absence of overlapping deformation patterns from different grout bodies and the relatively low vertical stress.

Near to the grout-soil interface high shear deformations take place and these deformations may result in an increase of the soil volume. At a larger distance of the grout-soil interface smaller shear deformations take place which should normally lead to a decrease of the soil volume, certainly at higher stress levels.

An increase in vertical stress is known to increase the critical density. According to the critical state theory it may therefore be expected that, at higher stress levels (larger depths) as used in the test some densification becomes more likely.

The only way to prove these suppositions is to perform a large scale test in which the soil displacements both horizontally and vertically are monitored during the execution of the grouting. The execution of such a full scale test was not possible. Therefore it could not be verified if compaction grouting will result in sufficient densification to prevent liquefaction under monotonic loading.

As the effect of compaction grouting on local density in the test proved to be limited it will also hardly influence the amount of densification and excess pore pressure due to vibrations of the TBM. Reduction of settlements due to densification and the risk of liquefaction due to cyclic loading are therefore negligible with this method.

An increase in horizontal stress will reduce the risk of liquefaction due to monotonic loading. This stress increase is thus considered a positive effect. For the railway embankment however the increase in horizontal stress is to be provided by the soft clay and peat layers adjacent to the railway embankment. It is expected that these layers will show some horizontal deformation during compaction grouting due to the increased horizontal stress. This process will continue afterwards because of consolidation of these layers. The increased horizontal stress will decay in time, thus reducing the stress increase. Therefore one cannot rely on this effect as measure of risk reduction.

8 CONCLUSIONS

The performed test showed that compaction grouting results in higher horizontal stresses (seen in higher CPT values) but not necessarily in densification of the sand. It can not be excluded that the relatively low stress levels and / or small distance between the grout body and the wall of the container influenced the results of the model tests. Expectations however are that the increase in density due to compaction grouting is limited and not sufficient to reduce the risk of liquefaction under monotonic loading for the crossing of the Randstad rail shield tunnel with the Gouda Link. Therefore this design option has been abandoned.

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