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Centrifuge modeling of soil upheave by expanding tubes

Modelisation a l'aide d'une centrifugeuse du rehaussement des sols par tubes expansibles

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ABSTRACT
An investigation has been carried out into a new technique for upheaving soil bodies. An example of where this technique can be applied is a road embankment that has settled at a different rate from a bridge because of the weight and properties of the subsoil. The conventional technique for remedying the situation involves closing the road, removing the asphalt and supplementing the underlying material. All this is expensive, time consuming and causes additional traffic jams. The new method under investigation involves upheaving the road embankment by means of expanding tubes. In this technique, tubes of woven material are thrust horizontally into the road embankment, starting at the slope, by means of steel tubes. The steel tubes are then withdrawn while injecting a filling material to expand the woven tubes to a diameter of approximately 800 mm.

In the interests of gaining a better understanding of the upheave mechanism, small scale tests were carried out in the geotechnical centrifuge of the University of Delft. The investigation looked into the magnitude of the upheave relative to the expansion volume and any differences in effect between applying the tubes singly or in groups.

It was found that expanding tubes can be applied successfully in upheaving soil bodies. At least 5 tubes were required to eliminate boundary effects at the centre. Where a single tube is applied, more pressure is required than for a group.

RÉSUMÉ
Une nouvelle technique pour rehausser les sols a été étudiée. Cette technique peut être appliquée, par exemple, sur un remblais routier qui s'est tassé à un taux différent de celui d'un pont, à cause du poids et des propriétés du sol. Le remède conventionnel à cette situation consiste à fermer la route, enlever l'asphalte et rajouter du remblais. Tout ceci coûte cher, prend du temps et augmente la congestion du trafic routier. La nouvelle technique consiste à soulever le sol à l'aide de tubes expansibles. Des tubes de textile sont poussés horizontalement dans le remblais à partir de la pente, à l'aide de tubes d'acier. Les tubes d'acier sont ensuite retirés alors qu'un matériau de remplissage est injecté pour accroître le diamètre des tubes de textile jusqu'à environ 800 mm.

Afin d'obtenir une meilleure compréhension du mécanisme de rehaussement du sol, des essais à petite échelle ont été menés dans la geo-centrifugeuse de l'Université de Delft. L'étude vise à étudier l'ampleur du soulèvement relative à l'expansion volumétrique et toutes différences liées à l'utilisation d'un tube ou de groupes de tubes. Il est montré que les tubes expansibles peuvent être utilisés avec succès pour rehausser les sols. Au moins 5 tubes sont nécessaires pour limiter les effets de bord au centre. Quand un seul tube est utilisé plutôt qu'un groupe de tubes, une pression plus élevée est requise.

1 INTRODUCTION

A new innovative technique has been developed for upheaving soil bodies, with potential application in road construction, for example, where a road embankment has settled relative to a bridge. In general, a bridge is founded on piles, so that no significant settlement is expected. The road embankment, however, is generally used in regions with a soft subsoil, the additional weight and properties of which may cause the embankment to settle relative to the bridge. The conventional technique for remedying the situation involves closing the road, removing the asphalt, supplementing the underlying material and relaying the asphalt. All this is expensive, time consuming and causes additional traffic jams.

The new method under investigation involves upheaving the road embankment by means of expanding tubes. In this technique, tubes of woven material several metres long are thrust horizontally into the road embankment by steel tubes, starting 2,5 to 4 metres below the top of the slope. The steel tubes are then withdrawn while injecting a filling material to expand the woven tubes to a diameter of approximately 500 or 800 mm. The expansion of the tubes heaves the soil mass, so that the asphalt regains its initial level. Several successful tests have been performed in which a small road was lifted 200 mm, and a tree 300 mm (Wichman, 2002). A large scale test with a real motorway was less successful because of the large deformations of the subsoil.

Several aspects of the upheave mechanism were unknown. The unanswered questions related to the optimum tube spacing, the proportion of the volume involved in the lateral expansion, upheave relative to the expansion volume and the difference in effect between applying the tubes singly or in groups. Lee et al. (2000) performed centrifuge tests on sands in which 3 injectors were filled in different orders. Soil stiffening effects were found.

2 TEST TECHNIQUE

In advance of a field test, small scale tests were performed to gain a better understanding of the phenomena involved. Small scale tests are relatively inexpensive and allow several different configurations to be studied in a short period of time. A disadvantage of small scale tests under 1g conditions is that the self-weight soil stress is very low, which means that the required pressures are too low to allow accurate measurement. Furthermore, the soil behaves differently at low stress levels. In order to simulate the upheave mechanism as accurately as possible, the model tests were carried out in a geotechnical centrifuge. This test technique artificially increases the gravity in the small scale model, so that the self-weight stress is the same as in the prototype situation.

The geotechnical centrifuge of the University of Delft (Fig. 1) (Allersma, 1994a) is a relatively small device. The advantage of the size is that the tests can be carried out quickly and the costs are very reasonable. The weight of the model containers is low enough that they can be carried by one person. The small size allows the samples to be reproduced accurately and simple testing techniques to be applied. A special feature is that the on-board camera is connected to an image processing station, so that displacements can be visualized and digitized by processing the images (Allersma, 1990).

Fig.1 Geotechnical centrifuge of the University of Delft.

Fig.2 Test setup for simulating expading tubes in the centrifuge; a) location empty tubes; b) syringe system for expanding tubes.

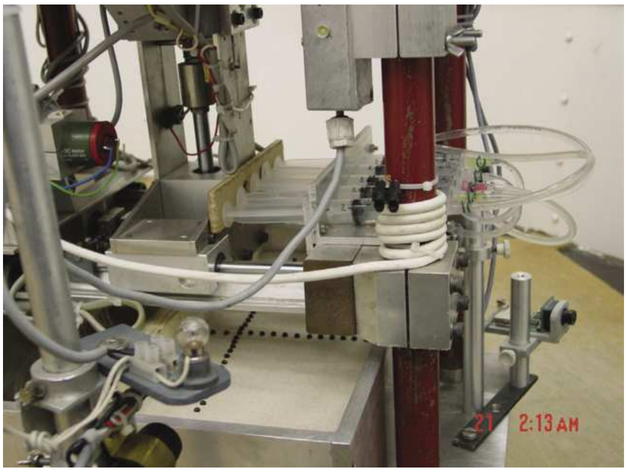


Fig.3 Position of the syringes in the loading system.

Several in-flight tools are available for performing tests. The devices are controlled by a PC located in the spinning part of the centrifuge. For this test programme, an in-flight loading system (Allersma, 1994b) was used to expand empty tubes in the subsoil. The test setup is shown in Fig. 2. A metal box with inner dimensions of 340x300x130 mm was divided into two segments by a wooden panel with holes. The sand layer was prepared in one of the segments.

Part way through the preparation of the sand layer, the expanding elements were installed through the holes in the wooden panel, after which preparation of the sand layer was resumed to the desired height. The expanding elements used were thin-walled metal salve tubes, which are available in a variety of sizes from pharmacy stores. The tubes were closed at the end by a metal disk, and the screw tops were modified to allow a hose to be connected. Before installation, the salve tubes were bended with a crossection in the form of a star, so that they could be expanded as much as possible in all 4 directions (Fig. 2a). The tubes were expanded in flight by means of a syringe system (Fig. 2b). Each individual tube was connected to a separate syringe to allow the tubes to be expanded independently. The syringes were operated simultaneously by the loading system (Fig. 3). One tube was equipped with a pressure sensor. After expansion the tubes were cylindrically shaped.

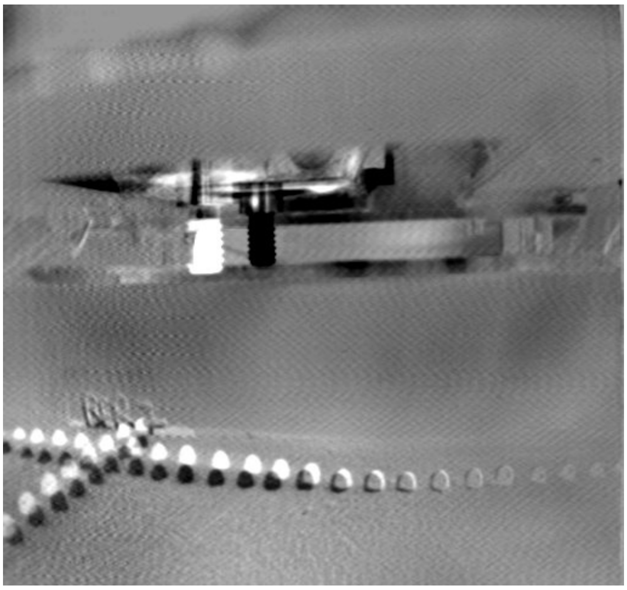


Fig.4 Test with 5 expanders (BER7). Position of the markers at the sand surface, before (black) and after expansion (white).

In order to observe the upheave effect, black markers (4 mm in diameter) were positioned on the surface, spaced 10 mm apart (Fig. 3). Two cameras were installed to monitor the displacements. During the test, the effect can be visualized by subtracting images (Fig.4). In the course of a test, several images are stored on the hard disk for later detailed processing.

3 TEST CONDITIONS

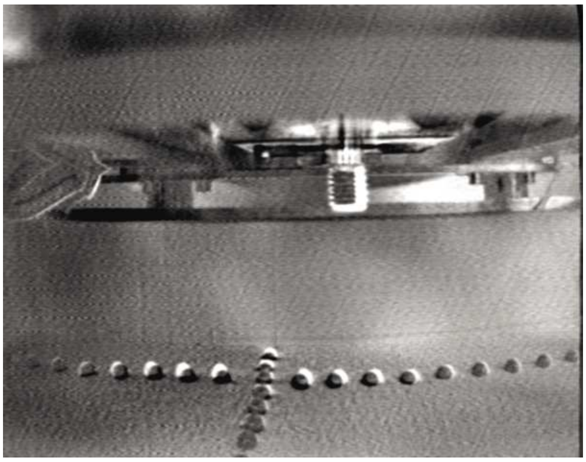
Five successful experiments were performed. Table 1 gives the test conditions. The density of the dry sand was 15.8 kN/m^3. The tests were performed with a gravitation of 50 g. The diameter of the tubes was 13 mm, the length 61 mm and the distance between the tubes 20 mm. The tubes were positioned 50 mm from the bottom of the sand and covered with 50 mm of sand. The effective scale factor for the above dimensions is 50. The pressure was measured in the expander at the centre of the wooden panel.

Table 1 Test conditions of the centrifuge tests,

name	number of expanders	geometry of test
BER4	3	the tubes were located in the 3 central holes
BER5	4	all holes were used, but tube no. 4 at the centre-right (Fig.3) remained unfilled because of leakage.
BER7	5	all holes were used
BER8	3	the rightmost 3 holes were used; a slope was made 20 mm on the left side, under 32° and depth 50 mm.
BER10	1	1 expander in the centre hole

4 RESULTS

Figure 5 shows the results for 1 completely filled expander. The right side of Fig. 5a may be compared with Fig. 4, where 5 expanders were 100% filled. It can be seen that in the case of one expander the orientation of the displacements is more lateral, and less vertical.



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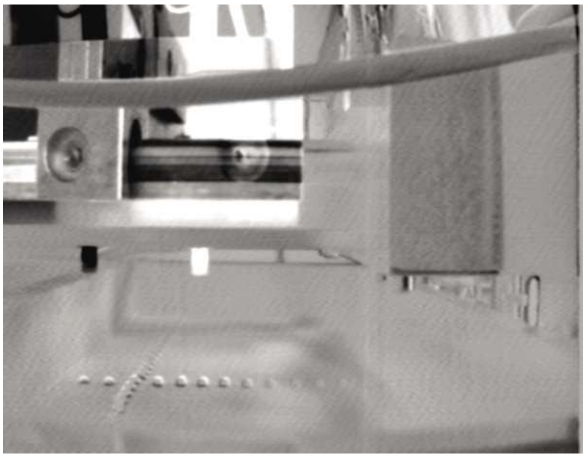

B

Fig.5 Digitally subtracted images for 1, 100% filled expander (test BER10); a) front view; b) side view.

In Fig. 4 the displacement at the centre of 34 cm was significantly larger than the theoretical 1 dimensional vertical heave of 22.7 cm (neglecting dilatancy). This might be related to the sharp peak in the vertical heave (see figures 6 and 7), which causes dilatancy. For 3 expanders, this heave was significantly smaller than the theoretical one dimensional vertical heave (Fig. 6).

It can be seen in Fig. 5b that the orientation of the markers changes from vertical at the centre to 35 degrees at the edge, also perpendicular to the wooden sheet. It can be seen in Fig. 7 that the maximum displacement for BER7 was only obtained in a small area.

For 1 expander, roughly 41% of the volume had to be injected before heave became visible. For the other tests, heave was visible after 20% was injected. Fig. 8 shows the pressure increase associated with the filling of one tube. This can be compared with the pressure in the central expander during filling of 5 expanders (Fig.9).

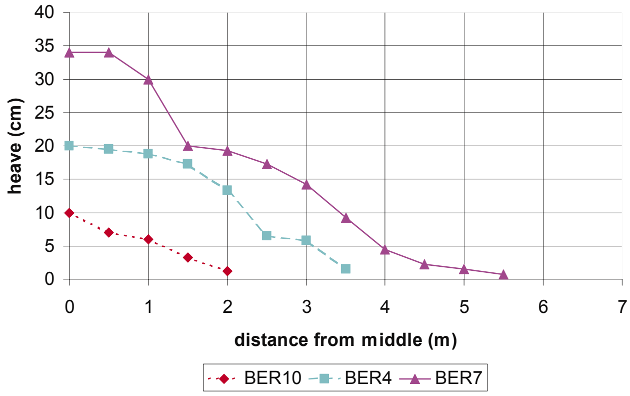

Fig. 6 Front view: Comparison of vertical heave for 1 (BER10), 3 (BER4) and 5 (BER7) expanders filled. The dimensions have been scaled by a factor of 50.

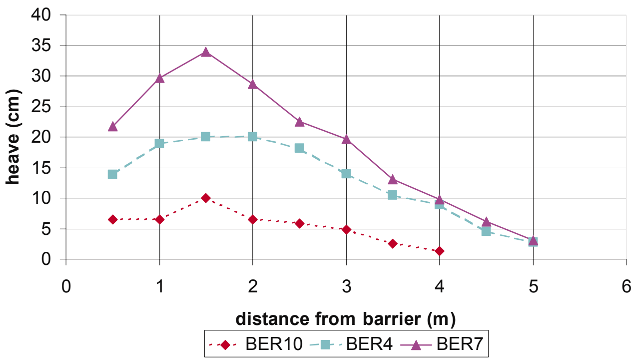

Fig. 7 Side view: Comparison of vertical heave for 1 (BER10), 3 (BER4) and 5 (BER7) expanders filled. The dimensions have been scaled by a factor of 50.

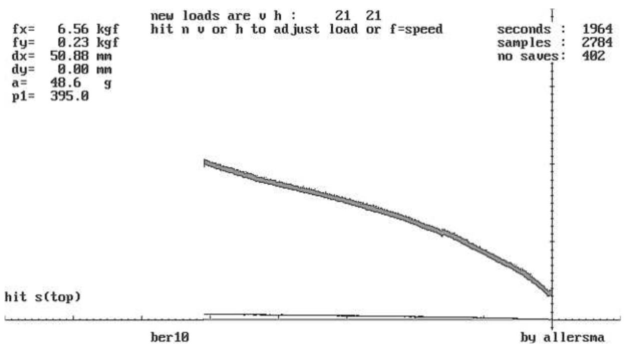

Fig. 8 Pressure in expander for BER10 (1 tube) during filling. Initial pressure is 64 kPa, maximum pressure is 399 kPa.

When comparing Figs. 8 and 9, it can be seen that the pressure during the first 18% of the filling is identical. After that, the pressure in Fig. 9 is clearly less. This can be explained by the fact that initially no uplift is visible and the soil is compacted (the same in both cases), after which the soil is gradually heaved. In the case of 1 tube, a wedge-shaped soil body is pushed up, resulting in a larger pressure than that measured in the central tube of the 5.

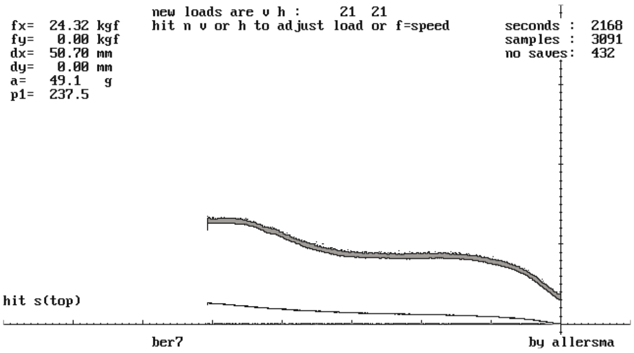

Fig. 9 Pressure in centre tube during filling for test BER7 (5 expanders). Initial pressure is 64 kPa, maximum pressure is 256 kPa.

The values of the curves resulting from tests BER4 (3 tubes) and BER5 (4 tubes) are also lower than those from BER10 (1 tube), but less so, where the difference depends on the number of expanders filled. For test BER8 (3 tubes), the pressure measured in the expander closest to the slope is clearly much lower than the pressure in the central expander of test BER4. In addition, the deformations close to the slope are larger than when the slope is absent (BER4). It may be concluded that deformation is easier where the required pressure is lower. For test BER5, the distance between tubes 3 and 5 was twice as great (40 mm). The deformations were still substantially uniform, gradually decreasing towards the edges.

5 CONCLUSIONS

It is concluded that it is feasible to lift a road embankment by means of filling a horizontal array of expanders. The distance between the expanders can be 3 times the diameter of the expander or more, depending on the depth, because the deformations decrease only gradually. At least 5 expanders are needed to eliminate side effects. Side effects are also significant in the longitudinal direction of the tubes. When 5 expanders were used, a uniform vertical heave was only possible in a limited region. The pressure is strongly dependent on the number of expanders filled at one time. The pressure is at a minimum when the heave is 1 dimensional, which is approximated with 5 expanders. The proximity of a slope also results in a lower pressure, because deformation then becomes easier.

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