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Centrifuge modelling of a soil-nailed wall

Étude en centrifugeuse d'un ouvrage en sol cloué

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ABSTRACT: Soil-nailing has been developed in the 70s but still raises questions concerning the distribution of loads between the inclusions. The instrumentation of full-scale structures is expensive and does not allow parametric studies. Thus, an original protocol has been developed and used in IFSTTAR Nantes for centrifuge modelling of soil-nailed walls. The excavation in front of a beforehand set up facing was realized inflight using geotextile baskets wrapping around the axis of a motor. The inclusions in the central profile were replaced by Bragg grated optic fibers bounded to a metallic conduit. The container in which the model was realized has a translucid face and the use of an image based technique called GeoPIV allowed to observe failure mechanisms of soil-nailed walls. The influence of nail length on the SLS displacements has been highlighted and the shape of tensions along the nails has been studied.

RÉSUMÉ: Le clouage des sols est une technique mise au point dans les années 1970 mais soulève encore des questions quant à la répartition des efforts entre les inclusions. L'expérimentation sur des ouvrages réels en sol cloué étant coûteuse et ne permettant pas d'étude paramétrique, un protocole original pour leur modélisation en centrifugeuse a été mis au point et utilisé à l'IFSTTAR de Nantes. L'excavation devant la paroi préalablement mise en place a eu lieu en rotation à 50g à l'aide de feuillets de géotextile enroulés progressivement autour de l'arbre d'un moteur électrique. Les renforcements du profil central ont été remplacés par des fibres optiques solidaires d'une gaine métallique et équipées de réseaux de Bragg. Le caisson dans lequel le modèle réduit a été réalisé, possède une face transparente en verre épais. L'utilisation d'une technique d'imagerie appelée GeoPIV a permis d'observer les mécanismes de rupture des ouvrages en sol cloué. L'influence de la longueur des clous sur les déplacements en tête de paroi a été mise en evidence et le profil des efforts le long des clous a été étudié.

Keywords: Soil-nailing; Centrifuge Modelling; Optic Fiber; GeoPIV

1 INTRODUCTION

Real scale study of geotechnical structures is expensive, difficult and often limited concerning the loads applied. Reduced scale models offer a valuable alternative. Among them, centrifuge models have a plus: strains and stresses conserved between model and prototype (corresponding real scale structure).

The first centrifuge model of soil-nailed wall (Shen, 1982) was built under 1 g (*i.e.* the usual gravity) and then centrifuged. The gravity was increased until the failure of the wall. Displacements were monitored using grease coated pins stuck to observation window and supposed to follow the soil displacement. This way, Shen observed a failure surface in accordance to his previsions.

Then, multiple tests were carried on in Cambridge (Tei, 1993) willing to take into account the phases of construction. Thus, the walls were built in flight (under macro gravity) using bags of fluid emptied with a pump to simulate the excavation. Dynamic tests have also been carried on (Tufenkjian, 1993) and showed that soil-nailed walls are quite resilient to seismic loadings.

In order to simulate the soil excavation, there are mainly three methods: digger robot, geotextile wrapping and fluid emptying (Kundu, 2014). All these methods imply that the facing is present before the excavation. Therefore, the deconfinement of soil is limited.

Usually, the dimension of reduced-models forbids any monitoring of the nail tensions. Here, optic fibers were inserted in the centre of nails giving access to these data. The displacements inside the soil were monitored by a method called GeoPIV (Stanier, 2015).

The experimental protocol is described and some results are presented.

2 PRINCIPLES OF CENTRIFUGE MODELLING

In the same way as for fluid mechanics, the study of reduced-scale models implies the consideration of similarity rules. In particular, a crude reduction of particles size is not suitable because the rheology of a material depends on its granularity. The choice is often made to keep the same soil between the prototype and the model.

The rheology of geomaterials is often described in terms of stresses and strains. Therefore these two quantities are usually kept equal between the prototype and the model.

This way, if the lengths are reduced with a factor *N*, the gravity has to be increased by the same factor in order to keep constant the quantity γh where γ is the volumic weight of soil. The forces are then divided by N^2.

However, the dimensions of the model cannot be reduced limitlessly. In order to stay in the scope of validity of continuum mechanics, the size of particles has to be much smaller than the smaller characteristic length of the structure (the diameter of nails here).

In the same way, in order to ensure the existence of a law governing the interface between soil and nails, a sufficient number of particles have to be in contact with the nails. This criterion is investigated through pull-out tests carried out using an adapted direct shear box. These tests allow to determine a lateral friction coefficient q_s whose value is constant when the vertical stress is higher than 30 kPa.

3 EXPERIMENTAL PROTOCOL

Ten experiments were carried on in the centrifuge of IFSTTAR Nantes (France) whose radius is 5.5 m and maximal acceleration of a 2 tons model 100 g. Three different nail lengths were studied. A more complete description of this protocol can be found in (de Sauvage, 2018).

3.1 Excavation mode

Since the behaviour of soil-nailed walls is driven by the phasing of their building, it is desirable to realise the excavation in-flight. Otherwise the stress-path of the soil would be upset. Therefore a choice had to be made between a digger robot, fluid emptying and geotextile wrapping.

The availability of the digger robot could not be ensured during the whole set of experiments.

The emptying of a fluid is a clever method: The soil to be excavated is replaced by bags of fluid progressively emptied by a pump during the experiment.

However, it has a notable drawback: the coefficient of lateral pressure K_0 of a fluid is always equal to 1. In order to apply a correct initial vertical stress on the trench floor, a fluid can be chosen with a volumic weight equal to the one of the soil (Sodium- or Zinc-chloride can be used for example). This way, the lateral pressure confining the soil-nailed wall is high and the soil is not initially at rest. Furthermore, the pumping system creates a perturbation of the soil under the trench floor and can prevent the development of some mechanisms.

The method chosen was then the wrapping of a geotextile: the soil to be excavated is wrapped in a geotextile tied to the axis of a motor as shown in Figure 1.

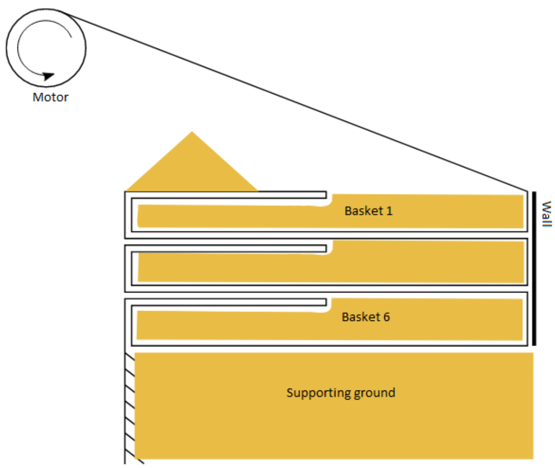

Figure 1. Principle of geotextile wrapping excavation mode

This method has a major drawback: the soil to be excavated is reinforced. In order to simulate as much as possible its natural state, the geotextile has to be laid loosely. This method was initially designed for the excavation of cohesive soils and a granular side could flow through the sides of the layers. In order to prevent this, the layers are transformed into baskets by the mean of lateral faces.

3.2 Reconstitution of the soil

The scope of validity of similarity rules impels to use a very fine soil, while remaining granular and not clayey. The choice fell on the HN38 Hostun sand whose characteristics were already determined (Schiavon, 2016). Its granularity is quite homogeneous and its median diameter d_{50} is equal to 120 µm.

The soil dry density (1480 kg/m^3) is controlled by pluviation, a process illustrated on Figure 2. For granular materials, this operation takes place in the air. The sand is stored in a carriage moving above the container in which the model is made and flows through a slot at the bottom of the carriage. The speed of the carriage is automated which ensures the homogeneity of the soil and the repeatability of the experiment. The target density is empirically bound to the slot width, the fall height and the carriage speed.

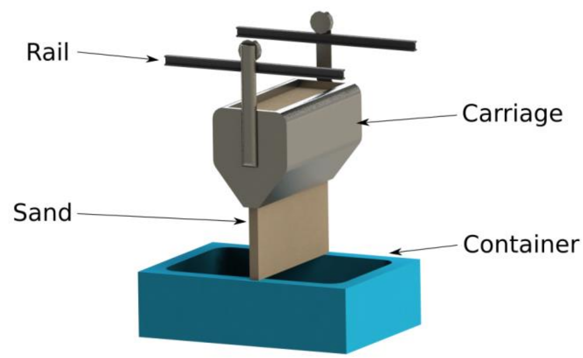

Figure 2. Illustration of pluviation method

3.3 Making of the wall

The wall (nails and facing) is installed in the soil before the excavation and this limitation has to be considered in the interpretation of results.

3.3.1 Nails

Inclusions are realized using steel bars with a diameter of 2 mm. In order to simulate the friction behaviour of prototype nails, they are coated with glue and cement.

The ball-joint link between the nails and the facing is realized with the help of a hole in the facing and a conical nut screwed on the nail.

The presence of nails during the pluviation process could disturb the density of the reconstituted soil. The void ratio around the nails has been estimated using agar injection (Ternet, 1999) and the relative difference with the undisturbed soil is less than 5 %.

3.3.2 Facing

If the facing is composed of a continuous steel plate, the soil deconfinement is limited at each excavation step and a moment appears at the bottom of the facing.

On real soil-nailed walls, the facing is not really continuous and the construction joints between each excavation step induce a local weakness.

Therefore, it was decided to use an articulated facing. This way, the deconfinement of soil is still limited but a rotation of the facing at its bottom is allowed. This articulated facing was realized using aluminium scales glued on a geotextile as indicated on Figure 3.

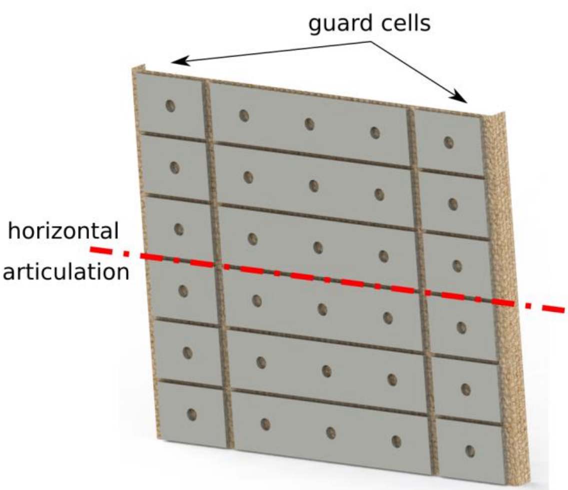

Figure 3. Realization of the articulated facing

The same articulation principle was used to realize the guard cells in order to prevent any edge effect.

3.3.3 Model dimensions

The container used was 36 cm high and, in order to allow the development of mechanisms circumventing the bottom of the facing, it was decided to realize an 18 cm high model wall. In order to simulate a 9 m high prototype wall, the level of gravity was set to $N = 50$.

The excavation is then divided into 6 phases. Each one is 1.5 m high on the prototype (3 cm high on the model).

Three lengths of nails were investigated: 8, 12 and 18 cm leading to aspect ratios (L/H) equal to 0.44, 0.66 and 1.

Eventually, the allowable torque of the motor used for the excavation imposed to limit the width of the model to 22 cm.

4 MONITORING

4.1 Displacements

The settlement of the soil surface above the soil-nailed wall was monitored with vertical LASER as shown in Figure 4. Two LASER pointed the central profile (3 and 9 cm from the facing) and one pointed the area in the guard cells. It has shown that edge effect can be neglected.

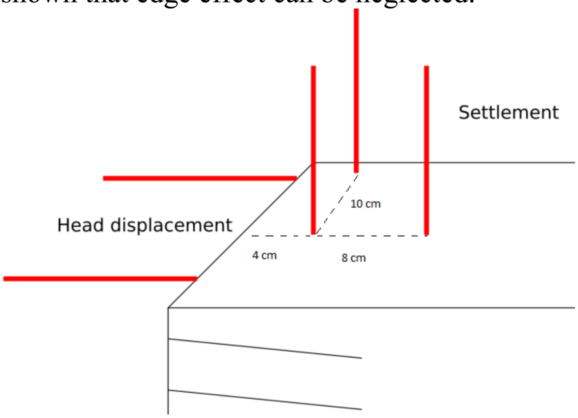

Figure 4. Displacement monitoring

Two LASER were also used to monitor lateral head displacement of the facing.

The displacements inside the soil bulk were monitored by technique called GeoPIV (Stanier, 2015). The soil was observed through the translucid face of the container and photos were taken at regular time intervals. The comparison between two successive photos allows to estimate the displacement of soil patches.

The accuracy of this analysis depends on the photo contrast and, in this case, the sand is very fine and its color quite homogeneous. In order to improve the analysis, 10 % of the sand mass was dyed with methylene blue. This ratio of colored sand offered a strong contrast without notable change of the internal friction angle (45° vs 44°). This last point was checked with simple shear tests.

To limit the friction edge effects, the observation window of the container is lubricated.

4.2 *Nail tensions*

The size of the nails did not allow the use of strain gages. It was then decided to replace the nails of the central profile by steel capillaries whose core consists of monomod optic fibers. In these fibers, Bragg networks are placed at 5 mm intervals (25 cm on the prototype).

Bragg networks reflect a unique wavelength of light and this natural wavelength varies with the strain imposed to the fiber (Ferdinand, 1999).

The fibers are then connected to an optic reflectometer able to send a light signal and analyse the returned signal. This way, the variation of Bragg networks wavelengths can be measured and the strain imposed on the fiber (assumed equal to the strain in the nail) is deduced. Knowing the Young's modulus of the steel, the nail tension can be computed.

What is more, the measure of nail tension is not polluted by the potential flexion because the fiber is at the core of the nail.

However, this method raises a difficulty: the fibers have to be connected to the reflectometer and the connecting fibers are passing either through the bulk soil or through the soil to be excavated.

In the first case, they can increase the soil reinforcement and in the second case, they can disturb the excavation process.

To quantify these modelling approximations, both connection modes were compared to control experiment with no fiber at all. It appeared that the less intrusive connecting mode was by passing through the bulk soil.

Eventually, the wavelength of Bragg networks depends also on temperature. To improve the accuracy of measurements, the temperature of the model was monitored by a resistance thermometer (Pt100) buried in the sand.

5 RESULTS

5.1 *SLS quantities*

The first observed quantities are the Serviceability Limit State indicators: the settlement of soil surface and the lateral head displacement of the facing.

The monitoring of settlements highlights the influence of nail lengths on the serviceability of the wall. Their evolution during the excavation is shown on Figure 5 for the three nail lengths. It clearly appears that longer nails tend to reduce the settlement. It has to be noticed that the displacement are ten times higher than the one observed in Clouterre for example.

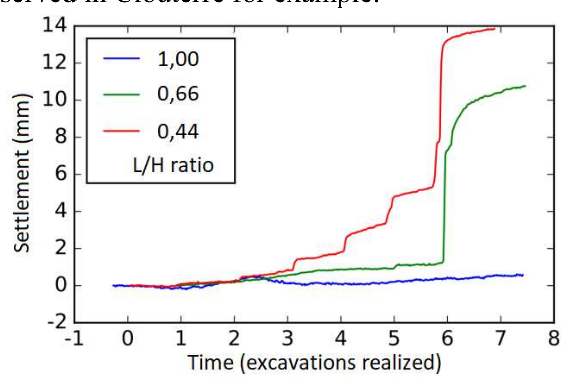

Figure 5. Settlement of the soil surface for different nail lengths

The Figure 6 shows the evolution of head facing displacement during the excavation for nails of 8 cm, 12 cm and 8 cm with bedrock.

In the same way as the settlement, the displacement facing decreases when the nail lengths increase. However, for nails of 8 cm, the presence of a bedrock tends to decrease the head facing displacement. The bedrock prevents the mechanisms circumventing the bottom of the facing and it seems that it induces a diminution of displacements.

It can be noticed that, contrary to the common observations, lateral and vertical displacements are not in the same order of magnitude.

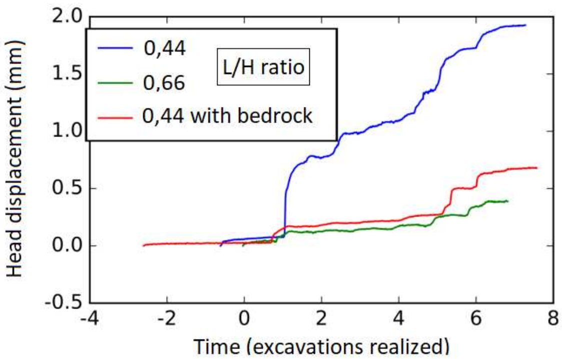

Figure 6. Head displacement of the facing for nails of 8 cm, 12 cm and 8 cm with a bedrock

5.2 Soil displacements

The monitoring of displacements inside the soil bulk with help of GeoPIV does not provide precise quantitative results but it allows to observe the involved mechanisms. The Figure 7 shows the displacement field observed for 12 cm nails during the 6th excavation. It evokes the failure mechanism highlighted by Vezole and Simon (Simon, 2008; Vezole, 2012).

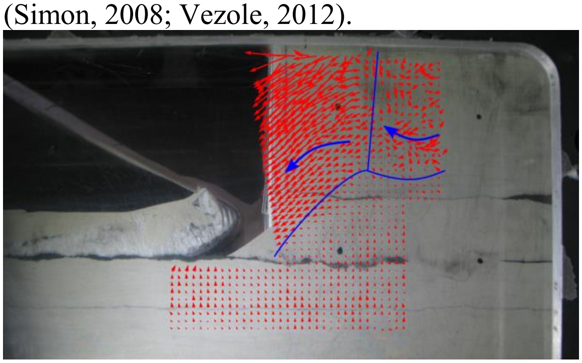

Figure 7. Failure mechanism observed with 12 cm nails

5.3 Nail tensions

The Figure 8 shows the tension along an 18 cm nail (the second from the bottom) during the last two phases of excavation. This result differs from the usual observations in two ways.

The nth nail is highly loaded during the nth excavation whereas the main loading is generally observed the n+1th excavation. This can be due to the fact that nails are set before digging.

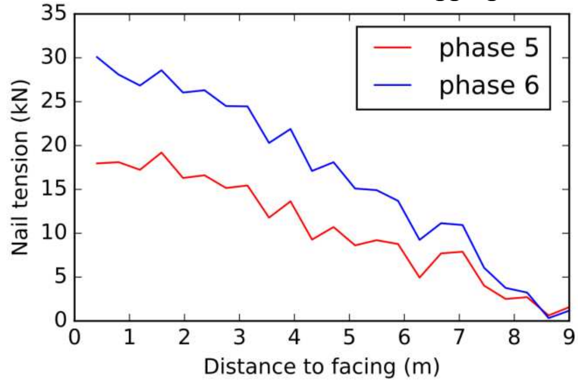

Figure 8. Tension along an 9 m nail (18 cm on the model) during the last two phases of excavation

Usually, nail tension is said to admit a maximum value inside the soil bulk. However, here the maximum tension is reached at the connection with the facing. However, finite element computations show that the shape of tension along the nail strongly depends on the characteristics of the soil-nail interface (de Sauvage, 2018).

6 CONCLUSIONS

A new set-up designed to study soil-nailed walls in centrifuge has been elaborated with an in-flight excavation so that the phasing of building can be respected. The use of optic fibers provided an access to nail tensions despite the small dimension of the inclusions.

The first set of experiments highlighted the link between SLS displacements and the length of nails. It also allowed to observe a failure mechanism already predicted by computations. These observations have to be confirmed by a broad set of experiments.

Eventually, the tension along the nails could be studied. Its shape raises questions and impels to centrifuge models realized with different soil-nail interfaces.

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