Interlock friction in a sheet pile wall: laboratory tests

Frottement dans les griffes d'un rideau de palplanches: essais de laboratoire

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ABSTRACT: Reduced scale tests were performed in laboratory to evaluate the interlock shear force transmission between the interlock of two sheet piles. Tests were performed in a circular container filled with sand. A sheet pile specimen was vibratory driven into the sand tank between two receptive clutches to form two interlocks. The force-displacement relationship between two clutches was measured during a pull-out test of the specimen. The geometry of the clutches was the same as those used on real sheet-piles. It was observed, from the tests results, that the time needed to drive the sheet-pile in a dry sand had a considerable influence on the shear resistance in the interlock. A long vibrodriving increased the densification of the sand in the interlock and could even modify the soil grain size distribution by crushing some grains. This high densification caused a solidification of the sand within the clutch. The interlock resistance could be interpreted as the shearing of a quasi solid body. On the other hand, tests performed with saturated sands showed a very low shear transmission capacity. The load transfer model derived from the test results will be implemented in a finite elements code that evaluates the influence of the interlock friction on the flexural stiffness of sheet pile walls.

RÉSUMÉ: Des essais de laboratoire à échelle réduite ont été réalisés afin de déterminer la loi de comportement de l'interface entre palplanches au niveau des griffes. Les essais ont été réalisés dans une cuve circulaire remplie de sable sec ou saturé. L'essai consiste à enfoncer par vibrofonçage une palplanche réduite dans des griffes réceptrices et ensuite à arracher cette palplanche afin de déterminer la relation résistance-déplacement de la griffe. La géométrie de la griffe utilisée est comparable aux griffes réellement utilisées sur chantier. Les résultats des essais montrent que la résistance offerte par la griffe dépend principalement du temps nécessaire pour vibrofoncer la palplanche. Des temps de vibrofonçage élevés peuvent provoquer, dans certaines conditions, le broyage de grains contenus dans la griffe, entraînant une solidification du sable contenu dans celle-ci. Dans ce cas, le comportement du sable dans la griffe se rapproche plus de celui d'un solide soumis à cisaillement que de l'effondrement d'une structure granulaire. Par ailleurs, les essais réalisés avec le sable saturé montre une faible résistance de la griffe lors de l'essai d'arrachage. Les résultats de cette recherche seront introduits dans un code d'éléments finis afin d'évaluer l'influence de la griffe sur la raideur en flexion des murs de palplanches.

1 INTRODUCTION.

The evaluation of the flexural stiffness of sheet-pile walls becomes more and more important since the Eurocodes require to take into account the deformation of the wall for the design at Serviceability Limit States (SLS). The stiffness of one pile can be easily calculated based on its geometric shape and the characteristics of the constitutive steel. However, for a sheet-pile wall built up with U shaped sheet-piles, the calculation of the wall stiffness must consider the transfer of shear force between each pile. Indeed, for a such wall, the position of the interlock corresponds with the location where the shear force is maximum. If the interlock resistance (shear force transmitted from one clutch to the other) is not high enough, a deficit of shear force transmission could develop and result in a decrease of the wall stiffness.

In order to understand the importance of this phenomena, it is useful to distinguish 2 theoretical extreme cases:

- Full shear force transmission in the interlock: the wall stiffness is 100%.
- No shear force transmission in the interlock: the wall stiffness is drastically reduced to about 30%.

In reality, the degree of shear force transmition depend of several parameters such as geometry of the clutch, grain size and installation method.

The purpose of this paper is to present the results of an experimental investigation on the shear force transmission through the clutches of two sheet-piles. This transmission was observed on reduced scale tests. A sheet pile specimen was driven into a sand tank equipped with two receptive clutches to form an interlock. The force-displacement relationship between two clutches was measured during a pull-out test of the specimen.

2 EXPERIMENTS.

2.1 *Experiment principles*

The purpose of the test is to establish the force-displacement relationship between two clutches in a simple and economical pull-out test. The aim of the tests was not to investigate the behavior of a sheet-pile wall in realistic solicitations (transversal and longitudinal bending, torsion) but to provide the interlock constitutive relationship to be used as input for numerical models, e.g. FEM, composite beam. These numerical models allow for simulating realistically the behavior of a sheet-pile wall.

The main concern in the design of the experimental setup of the pulling test in the laboratory was to place the sheet-pile in a such way that the condition of the soil in the clutch was very similar to its in situ condition. Therefore, the vibratory driving technique was used to place the tested sheet-pile because it is nowadays the most common method encountered in practice.

An other concern was the choice of each element's size. To reduce the shaft friction of the sheet-pile, the perimeter of the sheet-pile had to be reduced to a minimum. Concerning the size of the clutch, it was clear that the interlock friction depends directly of the dimensions and the shape of the clutch and of the grain size. Therefore, it was decided to use a clutch cut from a PU16 sheet-pile.

2.2 *Experimental Setup*

The tests were performed on a reconstituted soil specimen in a cylindrical container with a diameter of 0.625m and a height of 1.50 m. The sand box represents the local behavior of soil around the interlock.

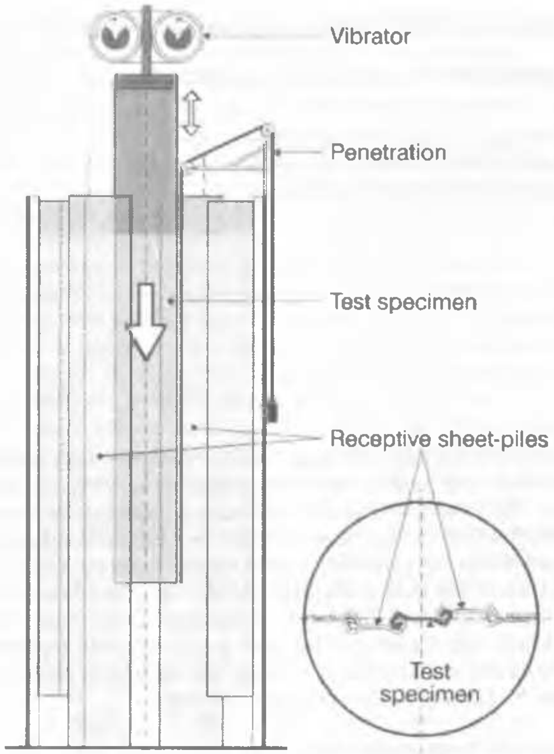

Figure 1 Installation of the tested sheet-pile by vibratory driving

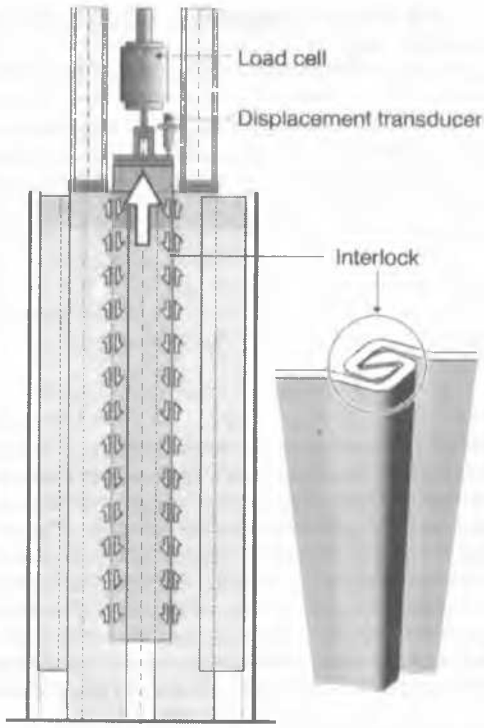

Figure 2: Pull out test

The first step in the preparation of the test is to place the 2 receptive clutches in the container and verify that the test specimen can freely enter into the receptive clutches.

The second step is to fill in the container with dry sand. The soil was placed using the pluviation technique. The soil was compacted using vibratory methods to a specific relative density. When required, the soil was saturated slowly from the bottom.

The next step consists in vibrodriving the tested sheet-pile in the receptive clutches placed in the sand box (Fig 1). During the vibratory driving, the penetration of the sheet-pile was continuously monitored.

The pile extraction was done using a hydraulic piston with a constant speed of 0.01mm/s up to a maximum displacement of 20 mm. (Fig 2) The speed was considered to be low enough to be representative for quasi-static phenomena. The vertical reaction forces were applied on the receptive clutches to prevent these being pulled out simultaneously with the test specimen. During the extraction, the vertical load, vertical displacement and horizontal displacement were continuously measured.

After the 20 mm pull out, a cone penetration test was performed in the sand box close to the test specimen to evaluate the relative density of the soil in the container.
Pulling out tests were performed, for different soil densities, with the test specimen outside the receptive clutches in order to evaluate the friction between the sand and the test specimen. The curve corresponding to sand only was later subtracted from that measured with the specimen threaded to the receptive clutches to obtain the interlock resistance.

2.3 *Sand characteristics*

Two sands were used in this investigation. The choice was led by two criteria. First, the average grain size had to be smaller than a typical interlock gap of about 3 mm to ensure that the particles would enter in the interlock. Second, for representative reasons, both fine and coarse sands were tested. The grain size curve of both sands is shown on Figure 3. The different sand characteristics are presented in Table 1.

Table 1. Sands characteristics.

		Fine sand	Coarse sand
Mean diameter	d_{50}	0.18 mm	0.63mm
Coefficient of uniformity	Cu	2.22	2.65
Specific weight of grain	γ_s	25.97 kN/m³	25.88 kN/m³
Minimum unit weight of dry soil	γ_{dmin}	11.98 kN/m³	15.2 kN/m³
Maximum unit weight of dry soil	γ_{dmax}	17.0 kN/m³	17.5 kN/m³

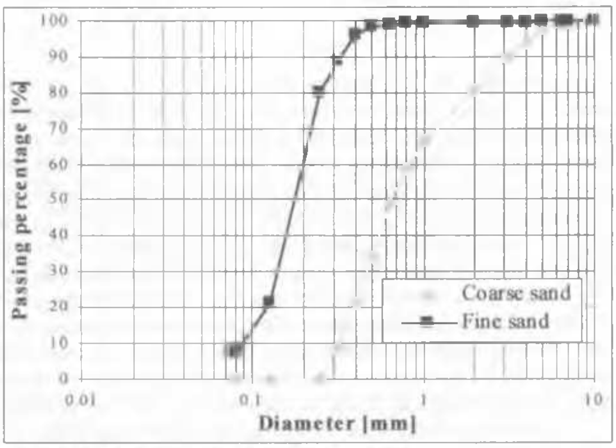

Figure 3: Grain size curve of used sands

3 TESTS RESULTS.

3.1 *Typical force-displacement curve of a pull-out test*

The tests results show a non elastic and non linear behavior of the interlock resistance. The shape of the displacement curves observed during all the tests can be generalized as follows (Fig. 4):

1. A positive resistance initiated by very small displacements
2. An increase of the resistance with a relatively low stiffness for displacements between 0 and ±0.5 mm.

3. A second phase of increase of the resistance with higher stiffness between displacements from ±0.5 mm and ±4 mm.
4. A decrease of the stiffness and reaching of a maximum of resistance for a displacement between 4 mm and 8 mm.
5. A decrease of the resistance for larger displacements.

3.2 *Evaluation of the friction between soil and sheet-pile.*

Figure 5 presents the results of the pull-out tests performed with the dry fine sand on the tested sheet-pile when the test specimen is not threaded. The tests were performed with different densities as shown on the results of the CPT tests (Fig 5). The friction between the soil and the sheet-pile is very low compared with that measured during a regular pull out test (from 2 to 10% of the total extraction force). The similar tests performed with the coarse sand also showed a low friction between the sand and the sheet-pile.

The results of these tests confirm that the choice of the experimental setup is well adapted for the evaluation of the friction in the interlock between 2 sheet-piles.

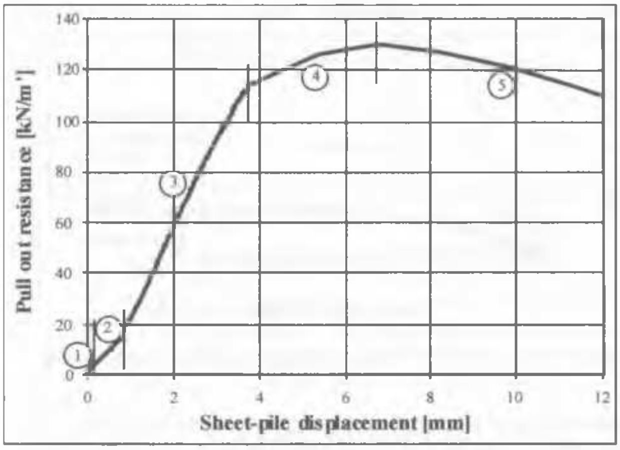

Figure 4: Typical force displacement curve of a pull out test.

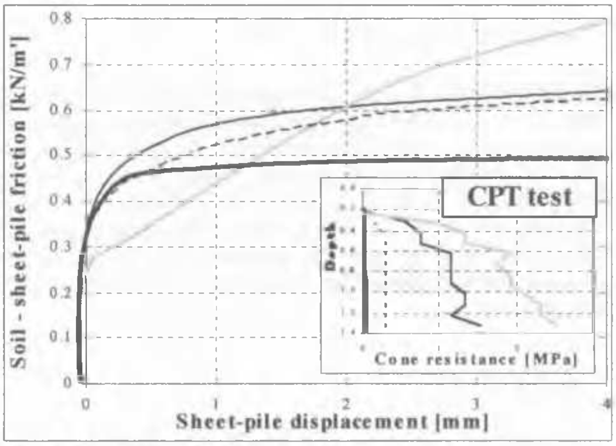

Figure 5: Soil – Sheet-pile friction evaluation

3.3 *Results from tests performed with the fine sand.*

Figure 6-a compares the interlock resistance measured during the pulling tests with fine sand. Figure 6-b presents the evolution of penetration during the installation of the test specimen using the vibratory driving technique. Figure 6-c shows the corresponding cone resistance measured close to the pile after the pulling test.

Three groups of stiffness can be distinguished to characterize the interlock resistance: a fisrt group with a very high stiffness of about 20 MN/(m'.m), a second with a low stiffness of about 2 MN/(m'.m) and finally a third group, with intermediate stiffness. The comparison of these groups with the CPT test results show that there is not a direct relationship between the soil density and the interlock resistance. A parameter that seems to better correlate with the stiffness of the interlock is the time needed to vibrodrive the sheet-pile into the receptive piles. A long vibrodriving increases the densification of the sand in the interlock and can even modify the soil grain size distribution by crushing some grains. This phenomena was observed when the experimental setup was disassembled. Solidified, rock like sand could

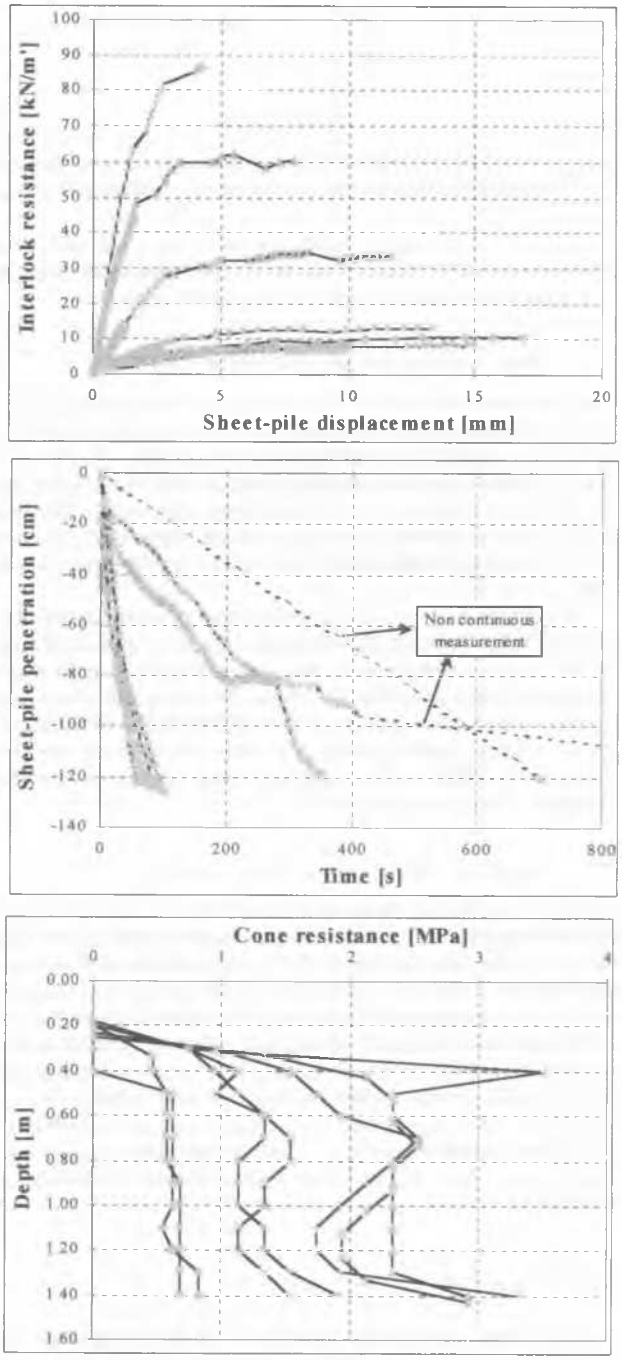

Figure 6: (a) Results of pull out tests performed on fine sand, (b) Penetration log of the sheet-pile during the vibratory driving (c) CPT tests results corresponding to the pull out tests

be found jammed into the clutch. A screw driver was needed to remove it. The grain size analysis of that sand presents a modification in the granulometry from that of the original sand: the largest grains were crushed into smaller ones (Fig. 7). This high

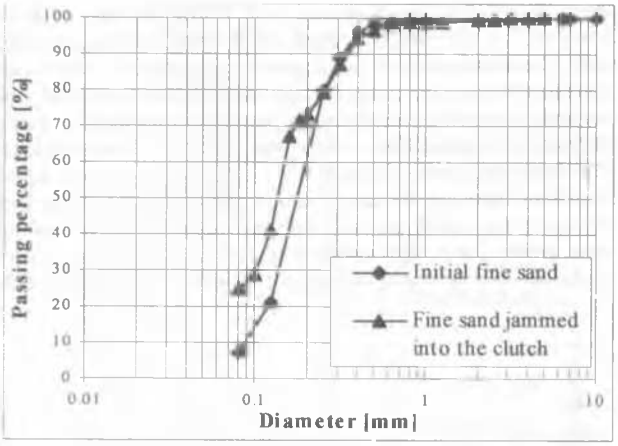

Figure 7: Comparison between the initial grain size curve of fine sand and the grain size curve of the sand jammed into the clutch after the test.

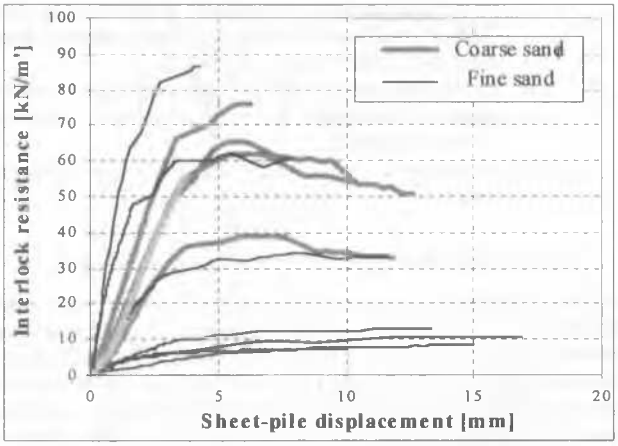

Figure 8: Comparison of interlock resistance for fined and coarse sands

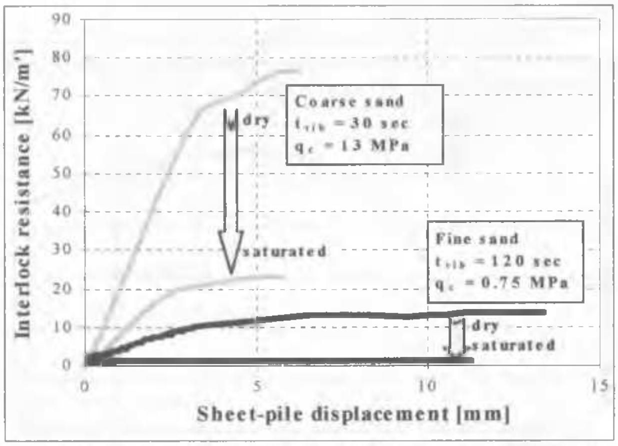

Figure 9: Comparison of interlock resistance for saturated and dry sand

densification can cause a solidification of the sand within the clutch. The interlock resistance can be estimated as the shearing of a quasi solid body in place of granular collapsing.

3.4 *Comparison between fine and coarse sands.*

The test procedure used with the coarse sand was identical to the procedure used for the fine sand except that a more powerful vibrator was needed to install the tested sheet-pile. During these tests, the same kind of relationship between the interlock resistance and the duration of the vibrodriving than for the fine sand was noticed. However, no grain crushing and no solidification was observed in the clutch after the removing of the tested sheet-pile.

The comparison of the tests performed with the two kinds of dry sands (fig 8) shows that the grain size has a direct influence on the interlock resistance: in the limits defined above, the larger the grains, the higher the resistance. However, that trend does not hold when solidification of the sand in the interlock occurs due to a long vibratory driving. In that special case, the phenomenon is different. The interlock resistance results from the shearing of a quasi solid body.

3.5 *Comparison between dry and saturated sand.*

Figure 9 compares the measurements performed during the pulling test with the dry sands and the saturated sands. For each sand, the tests have the same CPT cone resistance and the same duration of vibrodriving. However, liquefaction was observed during the vibrodriving of the sheet-pile into the saturated sands.

The interlock resistance is reduced of about 80% when the pile is installed in a saturated media. This observation is probably the consequence of liquefaction induced during the vibrodriving. The liquefaction of the sand increases mobility of sand in the interlock and it can thus escape from it. Consecutively, there is less sand in the clutch and the interlock resistance is reduced.

4 CONCLUSION.

An original experimental setup has been presented, enabling the collection of results of pull test of a sheet-pile out of 2 receptive clutches. The purpose was to measure the interlock resistance between 2 sheet-piles to calibrate a FEM code to analyze the influence of that interlock friction on the flexural stiffness of a sheet-pile wall.

The test results have shown that the main parameters correlated to the interlock resistance are the method used to install the sheet-pile and the behavior of the soil during its installation. For fine dry sand, densification was sometimes observed. That phenomenon provided a very high resistance to the interlock. On the other hand, liquefaction induced during the vibrodriving in saturated media provides a loss of resistance of the interlock.

5 ACKNOWLEDGMENT

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