Arching effect in a granular soil subjected to monotonic or cyclic loading: kinematic analysis

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ABSTRACT: An experimental approach to analyze the arching effect in granular soils is to perform trap-door-like tests. A granular mattress is lying in a rigid box of plane section 1m x 0.4m, with a central trap-door of width 0.2m, instrumented with a load cell and a displacement transducer. The mechanisms are first studied under monotonic and quasi-static conditions, by lowering slowly the trap door. For the study under cyclic load, a foam element which mimics a compressive soil is placed over the trap door and cycles of uniform surface loading and unloading are applied. For all tests, the displacement field of front grains of the mattress is measured and analyzed by the use of the Digital Image Correlation technique. The DIC analysis indicates that full arching does not occur in the soil mass and shows a slight increase of the vertical displacements during the cycles.

1 INTRODUCTION

The arching effect in granular soil is a transfer of forces between a yielding mass of soil and adjoining stationary members. The intrinsic shearing resistance of granular matter tends to keep the yielding mass close to its original position, which results in a change of the pressure on both the yielding part and the adjoining part of soil (Villard *et al.*, 2009). This phenomenon is one of the most universal encountered in soils.

Arching effect occurs in geotechnical structures such as soil platforms placed over soft soil improved by rigid piles. It has been recently studied during the French research project ASIRI “Amélioration des Sols par Inclusions Rigides” (Jenck *et al.*, 2007; Thorel *et al.*, 2010; Chevalier *et al*., 2012; IREX, 2012). In this technique, when the granular mattress is monotonically loaded, differential settlements appear between the soft soil and the rigid piles, leading to arching effect in the mattress and thus to a surface settlement reduction. Nevertheless, the question of the evolution of the mechanisms under cyclic load deserves now a particular attention.

A first approach to study the arching effect in granular soils is the well-known trap-door problem (since Terzaghi, 1936) and different theoretical solutions have been proposed, considering different approaches (experimental or numerical; elastic or plastic soil behaviour; continuum or discrete modelling, etc.).

The mechanisms have been widely studied under monotonic load but the issue remains open concerning cyclic loading.

In the present paper, trap-door tests are performed on a device that allows soil displacement field observation using Digital Image Correlation (DIC) analysis.

First, ‘classical’ trap door experiments are performed by lowering the trap door, to study the phenomenon under monotonic loading. Three different thicknesses of the granular layer are tested. Displacement fields and stress distribution between trap-door and adjacent part of the box are analyzed.

Experiments are then performed on the device adapted in order to study the effect of cyclic loading applied on the granular layer surface. Indeed, the trap-door cannot be arbitrarily lowered, as the granular layer and the moving part at the base are in strong interaction. A compressible foam block replaces the trap-door, which can settle freely under the application of the cyclic loading. Only the case of a low thickness granular layer compared to the trap width is studied (corresponding to some situations in soil improvement by rigid piles).

The present two-dimensional experiment is a preliminary study of the mechanisms under cyclic loading with displacement field analysis, as it is mainly qualitative and in plane-strain conditions, before performing three-dimensional small-scale experiments (Houda *et al*., 2013). However, the experiment is well adapted for two-dimensional DIC analysis and thus experimental procedure can be calibrated under the case of cyclic loading, with a similar granular material (gravel).

2 EXPERIMENTAL SET UP

2.1 *Trap-door device*

The trap-door experimental device is located at IUT of Grenoble, in Joseph Fourier University (Chevalier *et al*. 2012). Three sides are made of plywood while the front side is made of Plexiglas, allowing a direct view of the specimen during the test. The vertical walls are reinforced by steel frames to prevent any deformation. The bottom of the box has a length of 1m and a width of 0.4m (Fig. 1). The trap-door section is 0.2m x 0.4m. It can move vertically up and down using a motor with a controlled velocity of 1mm/min. The displacement of the trap-door is measured with a displacement sensor with 50 µm resolution. The trap-door is made of three distinct parts and the load is measured in the central portion of section 0.2m x 0.2m, in order to limit the influence of the walls on the measure, using a 1kN-load sensor, with 1N resolution.

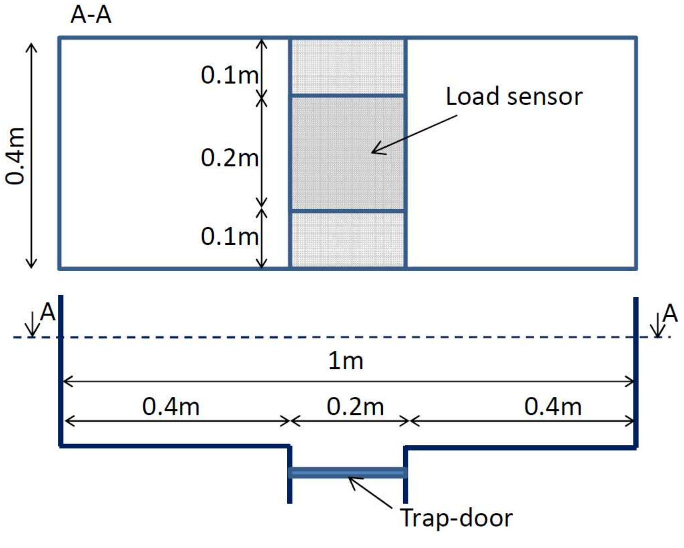

Figure 1. Dimensions of the trap-door apparatus

When cyclic load tests are performed, the trap-door is placed in the lowest position and a foam element is placed between two wooden plates (Fig. 2 and 3). The foam element is cut with a section 0.18m x 0.38m to avoid any contact with the walls and thus avoid friction that could not be measured (the load sensor is still placed under the trap-door, under the foam element).

Figure 2. Picture of the central part of a test under cyclic load (trap-door replaced by foam element)

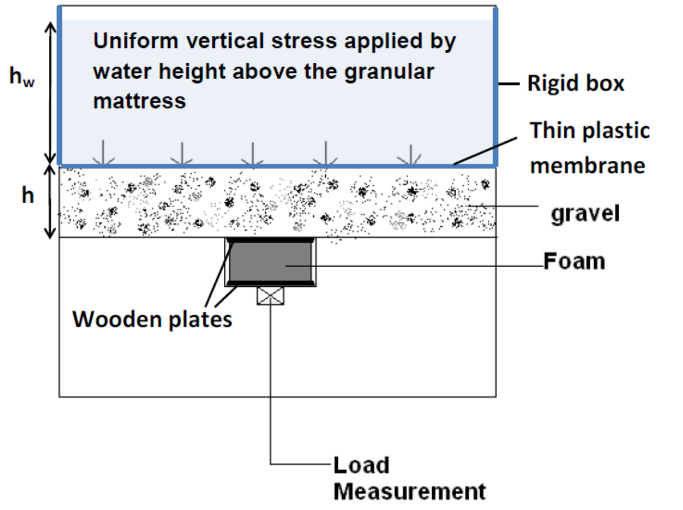

Figure 3. Schematic view of the experimentations under cyclic load

2.2 *Material used and characterization*

The material constituting the granular layer is gravel with grains of random and angular shape, so arching effect can rapidly take place. Grain diameter ranges between 5 and 15mm with d_{50}=10mm. This size of grain was chosen (instead of using sand, for instance), as real soil platforms over soft soil improved by piles are generally made of coarse gravel and gravel will be used on the 3D model test mentioned in introduction.

A drained triaxial tests at confinement pressure equal to 25kPa was performed on this soil (unit weight 11,8kN/m^3) and a peak friction angle of 48° was determined (the soil is cohesionless). The residual friction angle is about 40°. This value was confirmed by the measurement of the natural slope angle of this material.

Foam elements with various compressibility values were tested and the results presented here are obtained using one type of polyurethane foam. The choice of using foam elements instead of real soil was made as:

- it permits having an independent element without any friction along the walls (lateral and facial),

- there is no problem of soil installation that would lead to varying initial conditions and/or varying mechanical properties, as foam elements are homogeneous and identical from one test to the other.

The behavior of the foam elements was investigated under cyclic simple compression tests: the behavior is almost elastic and the compressibility increases slightly during the loading-unloading cycles.

2.3 *Experimental procedure*

Two types of tests have been performed: monotonic and cyclic tests. For both type of tests, the granular material was placed in the box always with the same procedure: by filling 2cm thick layers, very carefully and slowly, always in the same direction, in order to reach a constant density for all of the tests. During soil installation, the load applied on the trap door was measured. For 'classical' trap door tests, the load measured should correspond to the weight of the soil column above the trap-door (no basal displacement, thus no arching effect). Nevertheless, arching effect was observed (probably between the lateral walls, due to the shape of the grains, or due to small downward movement of the trap door when pouring the gravel). During soil installation, the dust generated must be cleaned along the Plexiglas, in order to have clean pictures to perform DIC analysis.

For the picture acquisition (to perform DIC analysis), a 12 M pixels camera is used, fixed on a tripod, connected to a laptop with dedicated software to shoot (without touching the camera) and store the pictures. Two 1000W lights were used to have a uniform lighting throughout the whole test (which can last one full day). The camera should be placed horizontally and along the axis perpendicular to the front face of the box, in order to assure good quality pictures.

During 'classical' trap-door tests (monotonic conditions) the trap-door moves downwards with a constant speed of 1mm/min (quasi-static conditions). Pictures are taken every 15 seconds and acquisition of the load is made every 5 seconds.

For the cyclic load tests, after filling the box with the granular soil, the upper part of the box was filled with water (the waterproofness with the lower part was assured using a thin plastic membrane) using a water pump with a constant flow of 16ℓ/min. A maximum height of water of 0.8m is reached, applying a uniform and vertical stress of 8kPa on the granular layer surface. During filling of the box with water (20min duration, to fill 320ℓ of water), pictures were taken every 15 seconds. Unloading was performed 20 minutes after the end of filling; also using the pump to empty the box, with constant flow (20min duration) and pictures were taken every 15 seconds. A complete cycle lasts 1 hour and 6 successive cycles are executed. The variation of water level according to time is given on Fig. 4.

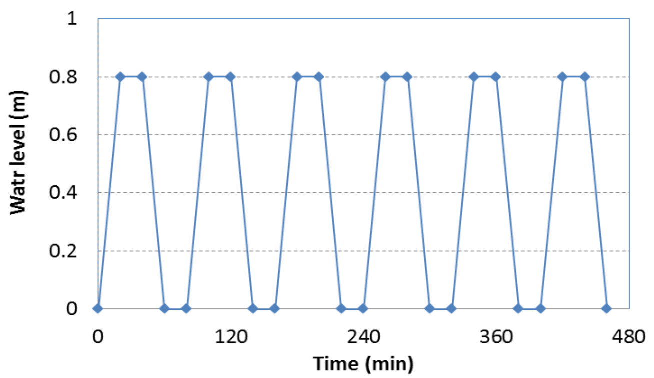

Figure 4. Cycles of loading-unloading using water level

2.4 *Tests performed*

Three 'classical' trap-door tests are presented, with granular layer thickness of 0.1, 0.2 and 0.4m (Table 1.

Table 1. Geometrical parameters of the classical trap door tests

Test name	Test type	Granular layer thickness h (m)
Trap 1	trap door	0.1
Trap 2	trap door	0.2
Trap 3	trap door	0.4

Concerning the behavior under cyclic loading, the case of low thickness mattress is considered. Granular layers of thickness 0.1m are subjected to 6 cycles of loading and unloading. The test is performed twice to analyze repeatability (Table 2).

Table 2. Geometrical parameters of the cyclic tests

Test name	Test type	Granular layer thickness (m)
Cycl 1	cyclic	0.1
Cycl 2	cyclic	0.1

3 DIGITAL IMAGE CORRELATION METHOD

Digital pictures are taken at several stages of the experiment for application of the Digital Image Correlation (DIC) method. DIC methods are mathematical tools for measuring spatial transformations between two digital pictures. Several methods exist. In this study, a two-dimensional method is used (2D-DIC), treating grey-level images. The program is called "Photowarp" and was developed at 3SR laboratory by Hall *et al.* (2010). The NCC (Normalized Correlation Coefficient) is used, given in Eq. 1, where I_1 and I_2 are grey-level function before and after deformation, (x, y) are the local spatial coordinates and (u, v) are the local displacement coordinates, $\overline{I_1}$ (or $\overline{I_2}$) is the mean grey level computed over the corresponding pixel subsets:

$$NCC(u,v) = \frac{\sum_{x,y}\left(\left(I_1(x,y)-\overline{I_1}\right)\left(I_2(x+u,y+v)-\overline{I_2}\right)\right)}{\sqrt{\sum_{x,y}\left[I_1(x,y)-\overline{I_1}\right]^2 \sum_{x,y}\left[I_2(x+u,y+v)-\overline{I_2}\right]^2}} \quad (1)$$

A correlation pattern is defined in the program, represented by a grey-level function $I_1(x,y)$ in the correlation window. A comparison is made between the two pictures and the program searches the best correlation between the two patterns, within an area (the search window) using the NCC, and thus the displacement (u, v). Obtaining the displacement for each pattern enables the calculation of the full displacement field, from which a deformation field can also be obtained. The discrete displacements obtained are integer numbers of pixels. If the correlation is perfect, the NCC is equal to 1. Then the sub-pixel approach through interpolation of the NCC permits to assess the non-integer values of displacement.

Figure 5 shows an example of correlation windows (30 pixels x 30 pixels or about 5mm x 5mm) on an original and a deformed picture. Pictures should be contrasted in order the method is efficient.

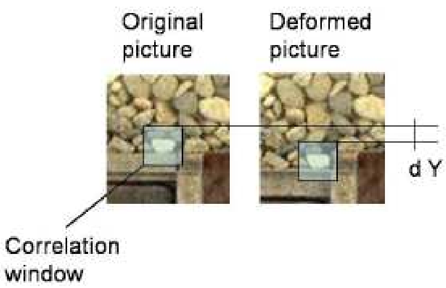

Figure 5. Correlation windows in the original and deformed pictures

In this work, the correlation is made on a regular grid of nodes. A correlation window is defined around each node. The method can also be applied on nodes located at grain centers and then grain displacements can be obtained.

4 RESULTS UNDER MONOTONIC LOAD

The list of the 'classical' trap-door tests is given on table 1. During each test, the load applied on the central part of the trap-door is recorded and is given in terms of average vertical stress on the trap-door (p) according to the vertical displacement of the trap-door. The result for tests 'Trap 1' (h = 0.1m) and 'Trap 3' (h = 0.4m) are given on the following figures. One should note that the granular layer thickness of 'Trap 1' test is the thickness tested for the cyclic tests (see table 2).

From the stress-displacement curves of figures 6 and 7, three phases are distinguished:

- Phase (a): where the maximum load is transferred (minimum load on the trap door). It starts from the beginning of the test up to a trap-door displacement of approximately 5mm. This phase corresponds to the decompression of the granular material close to the trap door. p has a minimum value of 1.1kPa for h = 0.1m and 1.3kPa for h = 0.4m : it is noticeable that these minimum values are similar whatever the mattress thickness.
- Phase (b): transitory phase where the load is increasing with the vertical displacement
- Phase (c): critical phase, with a slower increase of the load with the vertical displacement. This phase corresponds to the classical kinematic scheme generally used for the description of the trap-door problem.

These observations are similar to those of Chevalier *et al.* 2012. The various phases are more noticeable for higher thickness of granular layer (Fig. 7 vs Fig. 6).

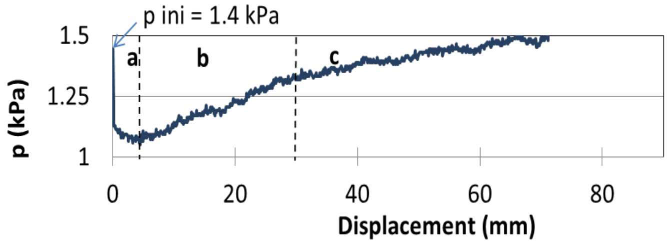

Figure 6. Average vertical stress on the trap door (p) according to the trap vertical displacement, for test Trap 1 (h = 0.1m)

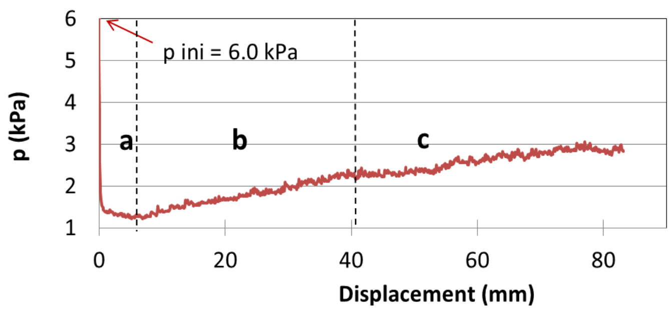

Figure 7. Average vertical stress on the trap door according to the trap vertical displacement for test Trap 3 (h = 0.4m)

The DIC analysis made on a regular grid of points placed over the pictures of the specimen shows a localized deformation in a restricted zone above the trap-door (Fig. 8). It shows how the triangular shape of the moving soil zone over the trap door, observed during phase (a) (first row of pictures), changes into a rectangular shape during phase (c) (second row of pictures). This mechanism is illustrated by Figure 9.

Figure 10 gives the evolution of the vertical stress on the trap-door p, normalized by the average vertical stress at the layer base p^0 (equal to $\gamma.h$), for the three trap-door test configurations. $p/ p^0 = 1$ means that no arching effect takes place. As expected, the larger the granular layer thickness, the less the normalized stress on the trap-door so the more the load transfer on adjacent parts. For test 'Trap 1', with the lowest granular thickness (h = 0.1m), the arching effect totally disappears for a vertical displacement of the trap-door equal to 50mm (= 0.5h).

Table 3 summarizes the values of the initial stress ($p_{ini} \approx p^0$), the minimal stress (obtained for a displacement of about 5mm) and the minimum normalized stress measured on the trap-door. Whereas the initial values are different from one test to the other (corresponds to the material weight), the minimum value is equivalent whatever the mattress thickness, so the higher the thickness, the higher the maximum load transfer.

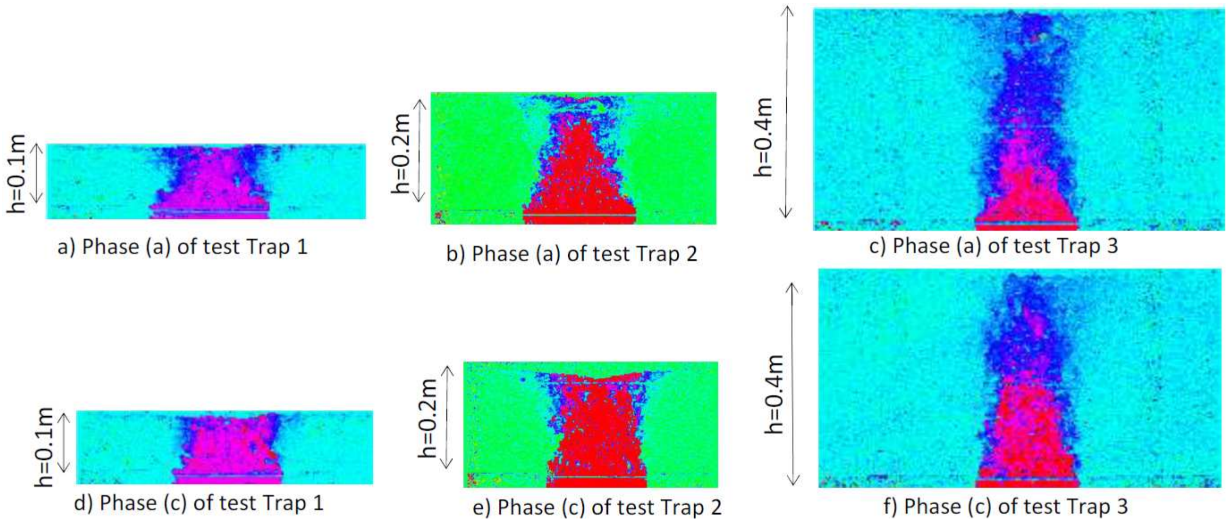

Figure 8. Map of vertical displacements during phase (a) (over) and (c) (below), obtained with the DIC, due to 0.25mm vertical displacement of the trap-door.

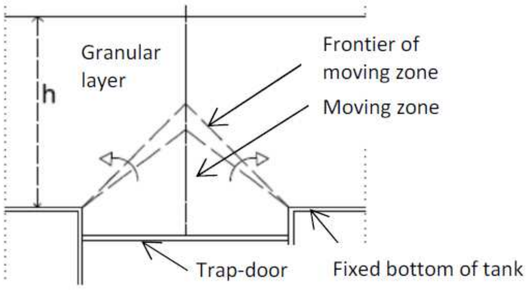

Figure 9. Progressive rotation of the moving zone boundary

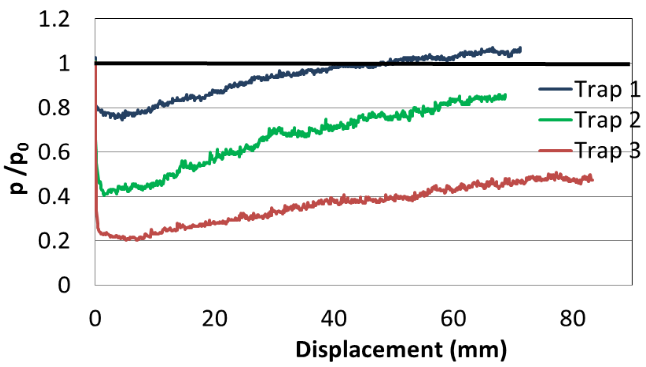

Figure 10. Stress on the trap-door normalized by the average stress due to the weight of the material

Table 3. Average Vertical Stress on the trap deduced from the load measurement.

Test	h	p_{ini}	p_{min}	$p/p^0{}_{min}$
	m	kPa	kPa	-
Trap 1	0.1	1.5	1.1	0.75
Trap 2	0.2	3.0	1.2	0.41
Trap 3	0.4	6.0	1.3	0.20

5 RESULTS OF CYCLIC TESTS

The aim of the study is actually to analyze the evolution of the mechanisms due to a restricted number of cycles, so only 6 cycles of loading and unloading were applied. The same test was performed twice with test conditions and procedure as similar as possible, in order to assess repeatability (see table 2).

The results in terms of the evolution of the stress acting on the foam surface during the cycles are given on figure 11. Both curves show similar results in terms of stress evolution and the following tendencies are observed:

- the initial value acting on the foam is 1.8kPa,
- the maximum value reached at each stage (for an additional stress on surface due to water filling of 8kPa) is constant. It is around 4.5kPa for test ‘Cycl 1’ and around 5kPa for test ‘Cycl 2’,
- the residual value measured for each unloading phase (after water emptying) is much higher than the initial value: it is constant and equal to 3kPa for test ‘Cyc 1’ and is subjected to a small increase from 3 to 3.5kPa for test ‘Cycl 2’.

This means that arching effect is smaller after the first unloading. From an initial value of 1, p/p^0 decreases to a value around 0.5 for a water level of 0.8m ($p^0 = 9.4$kPa) and increases to a value of 2.1 at the end of unloading. During unloading, the foam, which has been subjected to an elastic deformation during loading, tends to apply a vertical ascendant displacement on the granular mattress. During unloading, the mechanisms developing are different from those mobilized during loading. In fact, when loading, the soil mass above the foam element should be in an active earth pressure state. Conversely, during unloading, the soil should be in a passive state, as the foam tends to push the soil upward. This mechanism could be also be named “negative arching effect”.

Figure 12 indicates the average settlement measured at the foam surface, at the end of each loading or unloading stage. This settlement tends to increase slightly during the cycles. We also note that this basal displacement is in the range 0.3-1mm, corresponding to phase (a) described in section 3, where the maximum load transfer takes place (for trap-door lowering).

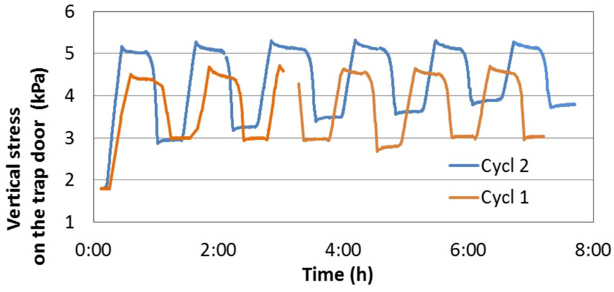

Figure 11. Stress results under cyclic load

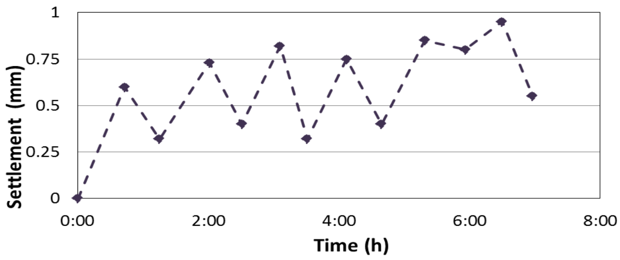

Figure 12. Surface settlement of the foam during test ‘Cycl 1’

Figure 13 shows DIC results (vertical displacement field) between loading and unloading stages, for the 6 cycles. The mechanisms do not significantly change during the cycles. The mattress thickness (h = 0.1m) is relatively small compared to the foam block width (0.2m), so the arching effect is incomplete and differential settlements are obtained on the granular layer surface.

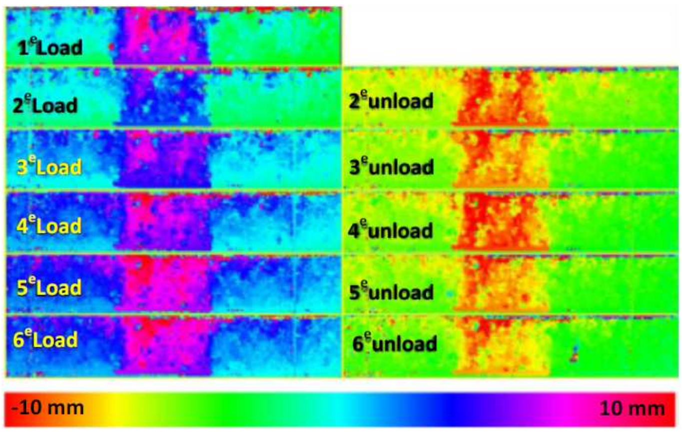

Figure 13. DIC results for test ‘Cycl 1’: vertical displacement field due to loading (left) or unloading (right) stages.

6 CONCLUSIONS AND PERSPECTIVES

This study is a preliminary qualitative analysis of arching effect mechanisms taking place in load transfer platforms over soft soil improved by vertical piles, under monotonic and cyclic load, in terms of both load and displacement field.

Trap-door like tests were achieved and a kinematic analysis was performed applying a Digital Image Correlation (DIC) method. ‘Classical’ trap-door tests were performed. Then an adaptation of the device permitted the analysis under cyclic load. The ‘classical’ trap-door tests showed the influence of the mattress thickness on the arching effect mechanisms and displayed three different phases for the load evolution, as well as for the displacement field (transformation of the corner of soil above the trap-door from a triangular to a rectangular shape). The second part of the work concerned the development of an innovative procedure to study the phenomenon and the mechanisms under loading and unloading cycles, from the classical trap-door test. An important residual stress acting on the foam element simulating the soft soil when unloaded and a slight increase of the basal displacements during the cycles were recorded.

This study also permits the constitution of an experimental database for performing numerical modeling, with a continuum approach or using Discrete Element Modeling (Chevalier *et al.*, 2012) to help the understanding of the precise mechanisms under cyclic load developing in granular mattresses.

7 ACKNOWLEDGMENT

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