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Influence of structural stiffness on ratcheting convection cells of granular soil under cyclic lateral loading

Gianluca Zorzi[a,*], Matthias Baeßler[a], Fabio Gabrieli[b]

[a]*BAM Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing) - Division 7.2 "Buildings and Structures". Unter den Eichen 87, 12205 Berlin, Germany*

[b]*Department of Civil Environmental and Architectural Engineering, University of Padova, Via Ognissanti 39, 35129 Padova, Italy*

Abstract

In granular soils, long-term cyclically loaded structures can lead to an accumulation of irreversible strain by forming closed convective cells in the upper layer of the bedding. The size of the convective cell, its formation and grain migration inside this closed volume have been studied with reference to different stiffness of the embedded structure and different maximum force amplitudes applied at the head of the structure.

This relation was experimentally investigated by applying a cyclic lateral force to a scaled flexible vertical element embedded in a dry granular soil. The model was monitored with a camera in order to derive the displacement field by means of the PIV technique. Furthermore, the ratcheting convective cell was also simulated with DEM with the aim of extracting some micromechanical information. The main results regarded the different development, shape and size of the convection cell and the surface settlements.

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Keywords: ratcheting convective cell; discrete element method; particle image velocimetry; cyclic loading.

1. Introduction

Offshore monopiles for wind turbines are subjected to more than 10^8 lateral loading cycles due to wave and wind during their lifetime. This long term cyclic loading may change the mechanical response of the structure and of the soil.

* Corresponding author.

E-mail address: gianluca21.zorzi@gmail.com

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In literature some investigations have been made to study the long term structural performance of different physical model piles at several geometrical scales under some millions of lateral cyclic loads [1]. During these tests some interesting phenomena were reported. The soil densified around the pile leading to a reduction of the maximum displacement amplitude (hardening effect). A circular crater appeared around the head of the pile as well as a continuous granular migration at the surface flowing down toward the pile axis. After soil excavation, the presence of two ratcheting convective cells along the loading direction were discovered. The soil grains migrated vertically along the soil-pile interface and then emerged at a certain distance from the pile. The depth of the convective cell was shown to be approximately proportional to one third of the pile's embedded length. These convective cells were limited by a well defined shear band as shown in figure 1.

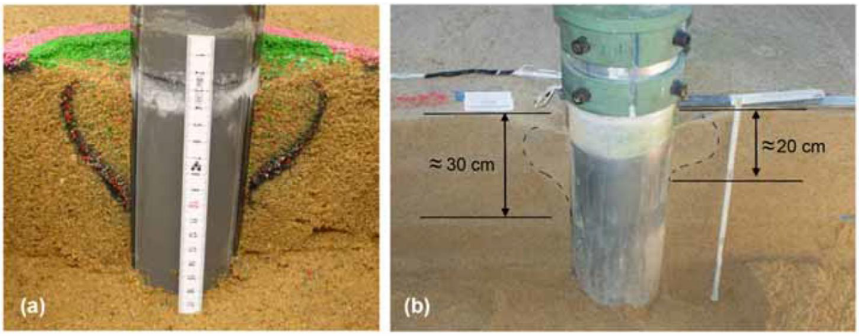


Fig. 1. Convective cells observed at different geometrical scales after the soil excavation. (a) Scale 1:100 and (b) scale 1:30 [1].

Since the convective flow is likely to happen also in the real case it should be important to identify which are the effects of some design parameters such as the maximum force amplitude and the stiffness of the pile on the ratcheting phenomenon. The present work experimentally assesses the evolution of the granular ratcheting convection cell in 2D plane-strain conditions. The laboratory tests were monitored with a camera in order to derive the soil deformation by means of the Particle Image Velocimetry (PIV) technique. Furthermore, the Discrete Element Method (DEM) [2] was used to simulate the 3D grain migration and the formation of the ratcheting convection cell by extracting the position of each particle.

2. Laboratory tests

2.1. Model description

The 2D small-scale physical models to study the occurrence of ratcheting convective cells were placed in a box with a transparent vertical wall. In the middle of the box a plate was used as structural element to be tested. The decision to use a plate instead of a half-sectioned pile was made to avoid out-of-plane lateral deflections typical of semi-circular cross-sections.

The plate was made of hard PVC (Vinidur) and was rigidly connected to the bottom of the box. Three springs on the back were attached to ensure the contact between the edge of the plate and the glass wall as show in figure 2b. The development of the ratcheting convective cells was studied with reference to different plate thickness, *b* (i.e. different bending stiffness). In the present work the plate of 1 cm of thickness is called *flexible* plate, while the 1.5 cm thick one is called *rigid* plate. The bending stiffness ratio between the flexible and rigid plate is approximately one third.

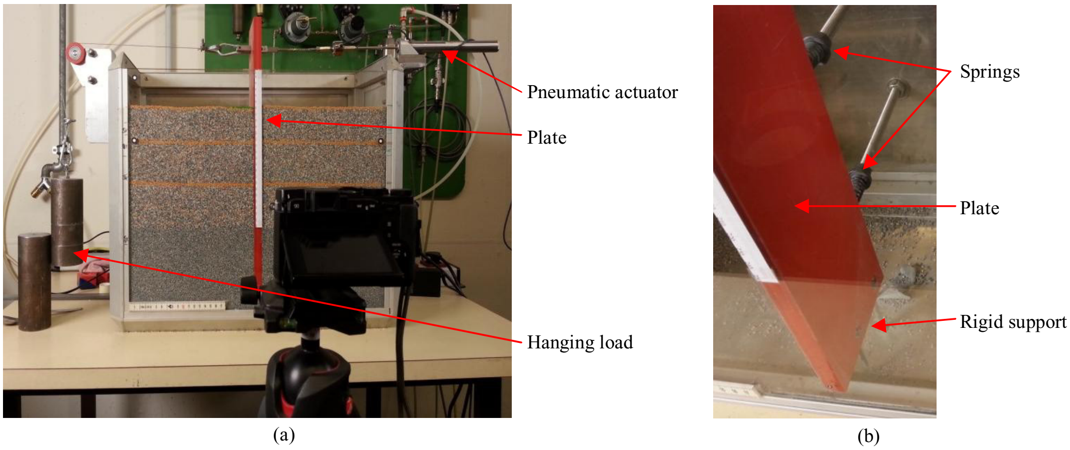


Fig. 2. (a) Layout of the 2D physical model. (b) Connection of the plate to the box.

Dry quartz sand with a median diameter of 1.5 mm was used. The granular material was poured in the box with a irregular succession of coloured horizontal layers in order to visually recognize the granular migration during the test. A cubical volume of the size 52x36x24 cm was filled.

The cyclic loads have been applied by means of a pneumatic actuator on one side and a hanging load on the other (see figure 2a). Both of them were connected to the plate, 12 cm above the soil surface, by a horizontal metal cable monitored with a load cell. Different maximum force amplitudes were applied by changing the hanging load and calibrating the input compressed air in the pneumatic actuator. The force trend was a two-way symmetric harmonic sinusoidal loading with 1 Hz of frequency; 300,000 cycles were performed.

A digital camera (Fujifilm X30) was mounted perpendicular to the box on a stable tripod in order to capture the grain motion behind the transparent wall. The digital pictures were taken whenever the plate was at the zero position after a predefined number of cycles. The sequence of images was analysed with an image analysis module for MATLAB called GeoPIV_RG [3], which applies a digital image correlation algorithm to detect the motion of a grid of patches: in the present work a patch size and a patch interval of 50 pixels were used.

Three tests were performed and reported in Table 1.

Table 1. Laboratory tests.

Test	A(flexible)	B(flexible)	C(rigid)
Plate thickness, b [cm]	1.0	1.0	1.5
Maximum force amplitude, F_{max} [N]	10	30	30
Total n. of images	2117	3165	8634

2.2. Experimental results

Figure 3 shows the comparison of the three tests after 300,000 cycles. The first observation is that all the tests experienced a ratchet-like grain flow. The flowing domain is separated from the surrounding soil by a well-defined shear band. The two-way symmetric load leads to an almost perfect symmetric cell on both sides of the plate. In addition, all the experiments experienced a subsidence of the soil close to the plate. The first two tests (figure 3a and 3b) with the same plate thickness (flexible plate) and a different maximum force amplitude are characterized by a build up of sand at a certain distance from the pile. In the third test (figure 3c) a regular decreasing ground profile is obtained. The figures 3d-f show the total cumulative displacement map (blue indicates small displacements while red is the maximum displacement) at the end of the test (cycle 300,000). Most of irreversible strains are localized in the upper part of the soil for the flexible plate while the stiffer plate mobilizes also deeper soil strata.

Test A (flexible)

b = 1.0 cm

F_{max} =10 N

Test B (flexible)

b = 1.0 cm

F_{max} =30 N

Test C (rigid)

b = 1.5 cm

F_{max} =30 N

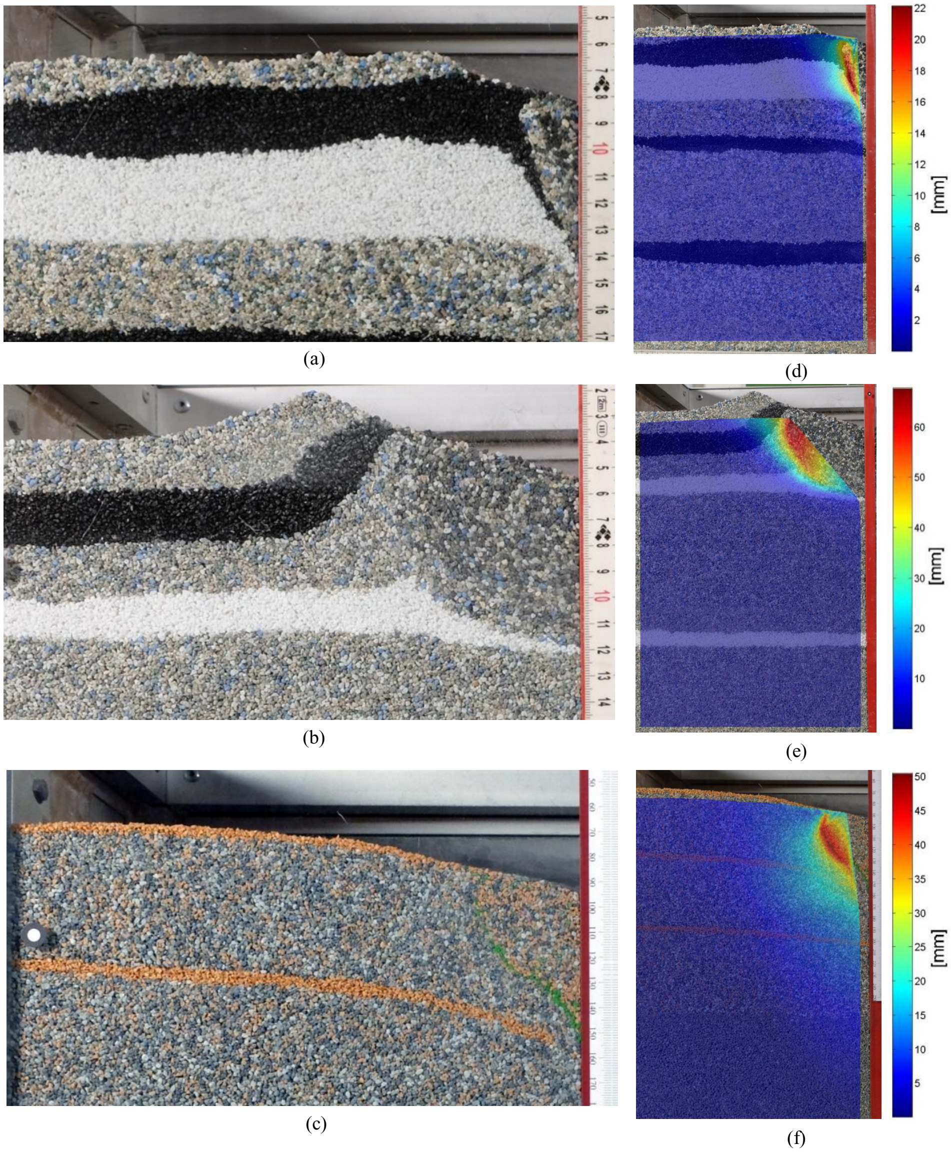


Fig. 3. (a),(b),(c) zoomed view of the soil near the plate after 300,000 cycles for tests A, B and C respectively; (d),(e),(f) the corresponding total cumulative displacement map obtained with PIV.

In figure 4, the comparison of the domain of the convective cells shows that an increase of the maximum loading force leads to an increase of the cell area and thus an extension of the local failure surface which is more horizontal than vertical (dash-dot blue and dashed magenta line). With the raise of the maximum force amplitude from 10 to 30

N the width of the cell triples while just a slight increase of the depth is noticed. Table 2 provides the measures of the soil subsidence near the pile and the size of the convective cell at the end of the tests.

Regarding the influence of the stiffness, test C with the rigid plate (solid red line in figure 4) shows a smaller convective cell compared to the flexible one (dash-dot blue line in figure 4). The deflection of a structural flexible element embedded in soil, mainly influences the upper soil layers. Stiffer structures have a more rigid response with less displacements, but they tends to rotate involving all the soil along the embedment length and thus a higher degree of densification compared to flexible structures. These different mechanisms to transfer the loads to the soil have an impact on the settlement of the ground surface and its shape. The stiffer plate causes a major particle rearrangement at deeper soil and thus it has a bigger soil settlement. Moreover, this higher densification prevents the formation of the built up of sand observed in the tests with the flexible plate.

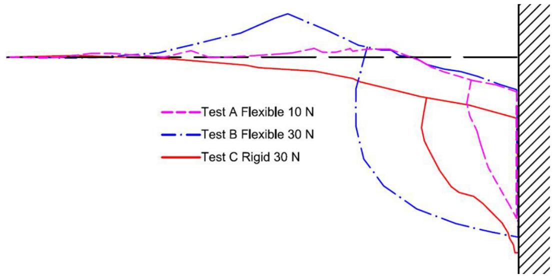
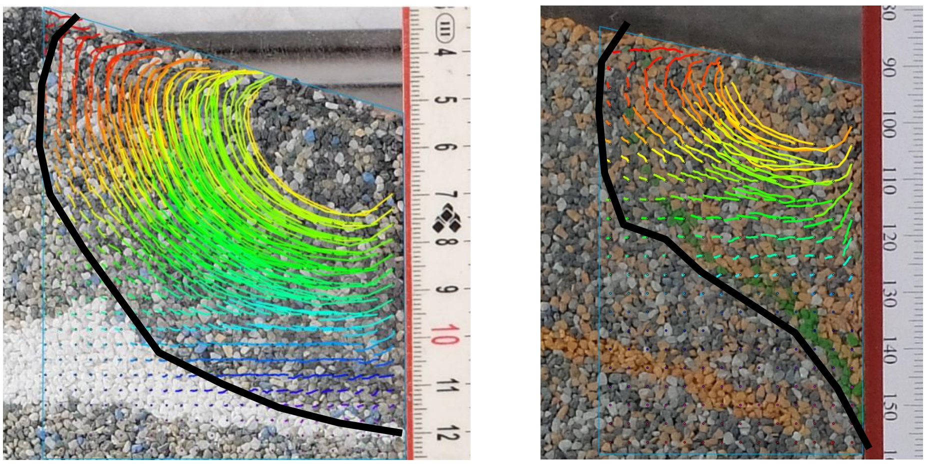


Fig. 4. Convective cell and ground level at the end of the tests.

Table 2. Soil subsidence and size of the convective cell after 300,000 cycles.

Test	A(flexible)	B(flexible)	C(rigid)
Soil subsidence [mm]	15	14	26
Maximum depth of the cell [mm]	60	64	58
Maximum width of the cell [mm]	20	63	38

The PIV technique was used to analyse the grain migration inside the convective cell during the last 50,000 cycles. In figure 5 the coloured lines represent the paths of portions of soil.



(a) (b)

Fig. 5. (a) Streamlines after 50,000 cycles obtained with PIV of test B (flexible plate) and (b) Test C (rigid plate).

The grains outside the failure surface do not have a significant accumulation of plastic deformation. The local shear surface (thick black line in figure 5) divides the small displacement domain from the large displacement domain . The last domain is constituted by a fully developed ratcheting convective cell (with circulation due to the succession of an active and passive phase as described by [4]) and a lower part of densified soil. These grains are gradually excluded by the convective motion because of the reduction of the displacement amplitude of the plate in the deeper strata. The lack of streamlines in the central part of the cell is due to the stronger out-of-plane motion of that grains and to the low sampling rate used with the camera.

3. Discrete element simulations

3.1. Model Description

The DEM is the most popular numerical tool suitable to model granular material as an assembly of discontinuous bodies. It offers the possibility to track the particles motion and to investigate the change of stiffness of the soil-structure interaction [4, 5]. This numerical method has been used here to analyze the development of the ratcheting convective cells around the piles by extracting the position of the particles over the cycles. The present work does not aim to simulate any scaled model pile but only to give an insight to the influence of the stiffness of the soil embedded structure and of the maximum force amplitude on the emergence of the ratcheting convective cell.

In the present analysis the open-source code YADE was adopted [6]. The model consists of a pile vertically positioned in the center of a rigid frictionless box (50 cm x 20 cm x 50 cm). The pile has the same length as the box height and it is modeled as a chain of connected cylinders with a prescribed bending stiffness [7]. The calibration of the micromechanical parameters controlling bending between the cylinders was made in order to reproduce an elastic beam-like behavior.

Spherical mono-sized particles were randomly generated in the box with an initial high porosity. Then the gravity was switched on and the particles assembly reached a final stable configuration (figure 6). A final porosity of 0.4 and soil height of 44 cm were obtained for all the numerical tests. The contact constitutive law is the classical linear elasto-plastic law [6]. Table 3 shows the micromechanical parameters for the particles' contact used in the discrete simulation. The stiffness of the embedded pile was varied by using two different pile diameters.

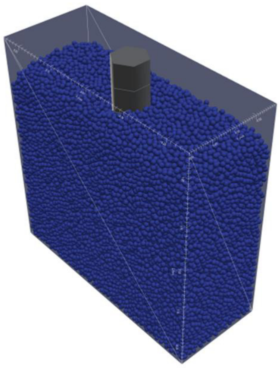


Fig. 6. Perspective view of the initial sample.

Table 3. Micromechanical parameters for the particles contact.

Material properties	Values
Elastic modulus at particles' contact, E_c [Pa]	1e6
Poisson's ratio at particles' contact, v_c [-]	0.2
Friction angle at particles' contact, μ_c [°]	32
Density of the particle, ρ [kg/m^3]	2,300

Table 4. Simulations plan.

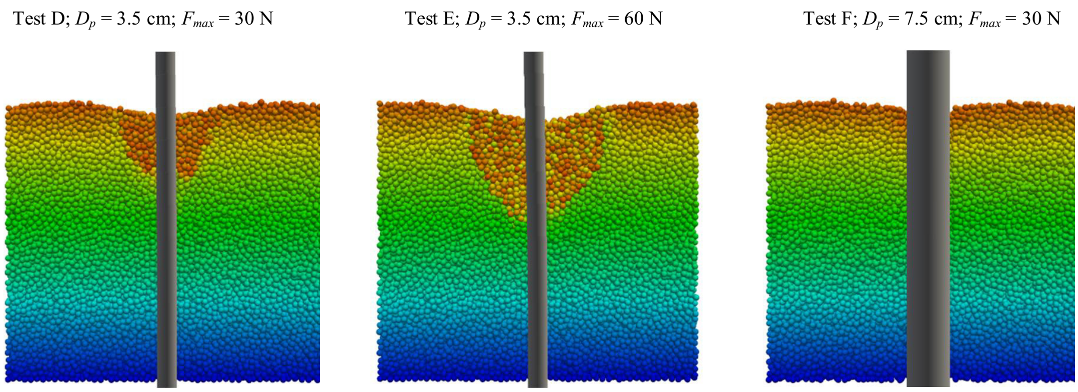
Test	D(flexible)	E(flexible)	F(rigid)
Pile diameter, D_p [cm]	3.5	3.5	7.5
# of spheres	47,334	47,334	44,829
Sphere diameter [cm]	1	1	1
Maximum force amplitude, F_{max} [N]	30	60	30

After the sample had stabilized under gravity, the lateral cyclic load was applied to the pile. The pile was constrained as a cantilever beam with one end fixed at the bottom of the box and it was allowed to translate along the loading direction and rotate just perpendicular to it. The simulation was load-controlled. The horizontal force was applied on the top of the pile with a two-way harmonic sinusoidal loading. The red arrows in figure 6 shows the loading direction. Different maximum force amplitudes were simulated. The number of cycles simulated were 250, lower than the cycles in the experiments, but sufficient enough to show a ratcheting behavior. The Table 4 shows the simulations' plan.

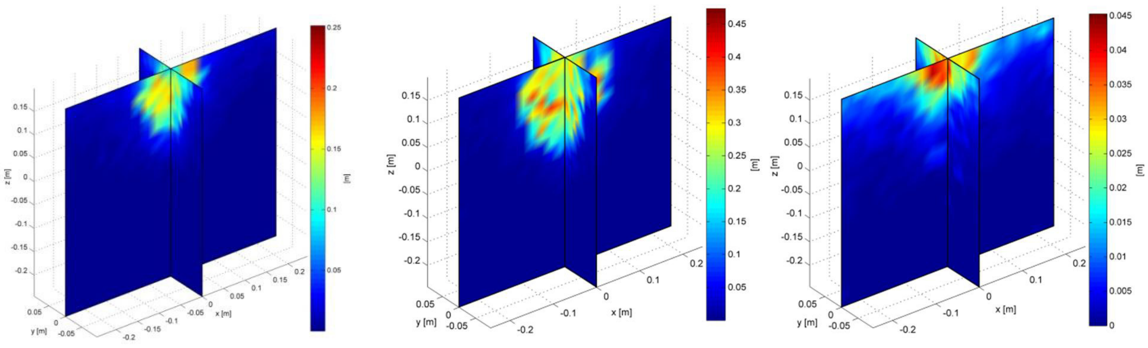
3.2. Numerical results

The figures 7a-b-c show the vertical section of the model along the loading plane at the end of the three tests described in Table 4. In order to enhance the visibility of the ratcheting phenomenon and the closed volume cell, different colors were assigned to the spheres based on the initial vertical coordinate. The first observation is that after 250 cycles, the tests with the flexible pile in figure 7a and 7b show the formation of a convective cell around the pile. Increasing the force and therefore the deflection, the size of the cell is expanding. For the rigid pile in figure 7c a convective cell is not visible. Nevertheless, the particles close to the pile showed a downward movement. It is not clear if a stable condition has been reached or more cycles are needed to develop the convective cell.

In all the tests, the normalized displacement amplitude of the pile tends to decrease up to a steady state value (figure 8). This stabilization of the soil can be partially explained observing the size of the convective cell over the cycles.



(a) (b) (c)



(d) (e) (f)

Fig. 7. (a), (b), (c) section along the loading direction at cycle 250; (d), (e), (f) slice of the tridimensional cumulative displacement map.

The total 3D volume and the geometry of the convective cell was estimated by considering the particles' displacement. For each particle the total absolute cumulative displacement was calculated. These displacement values were interpolated onto a fixed 3D regularly spaced grid at each cycle. The figures 7d-e-f represent the slices along and perpendicular to the loading plain from the 3D displacement interpolation at cycle 250. It was possible to identify two different domains: a small displacement and a large displacement one.

Figure 9 depicts the trend of the volume of the large displacement domain over the cycles. For all the tests, less and less particles were in the large displacement convective domain while they contributed to the quasi-static frictional domain. The stabilization of these curves was related to the number of cycles. The tendency of the volume of the ratcheting domain to stabilize can be seen on the test D which was simulated until 400 cycles.

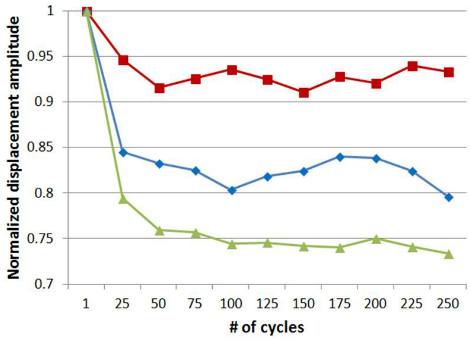


Fig. 8. Normalized displacement amplitude.

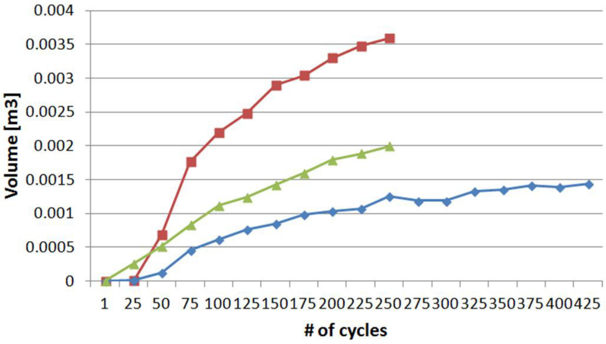


Fig. 9. Estimated volume of the convective cell during the test.

4. Conclusions

The present work shows the result of some experimental and numerical tests to investigate the emergence of a ratcheting convection in different soil-structure interaction problems with cyclic lateral loads. All the tests revealed the presence of an irreversible convective displacement domain close to the structure in the upper part of the soil. These domains differ in size and geometry. The structural stiffness and the maximum force amplitude applied at the head of these structures play an important role in the development of the convective cells as was shown in both numerical and experimental tests. The PIV technique applied to the experimental tests, provides a good insight on tracking grain migration inside the convective cell and permitted to evaluate the geometry of the large displacement domain. Also the numerical tests performed with DEM were successfully used to replicates the ratcheting convective flow for a soil-pile interaction problem and to track the 3D position of each grain.

The stiffer the structure is and the smaller the ratcheting domain results and with a different shape, closer to the soil-structure interface. Conversely, increasing the maximum force amplitude at the head of the structure causes the ratcheting domain to enlarge.

Further experimental and simulation tests are required to study the shape of the large displacement domain in relation to the design parameters of the structure and the soil type. More effort is also required to study countermeasures to avoid or mitigate granular ratcheting convection flow around embedded structures.

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