Granular Matter (2009) 11:379–390
DOI 10.1007/s10035-009-0153-3

Ratcheting convective cells of sand grains around offshore piles under cyclic lateral loads

Pablo Cuéllar · Matthias Baeßler · Werner Rücker

Received: 4 March 2009 / Published online: 17 September 2009

Abstract Sand densification around the pile has traditionally been regarded as an explanation for the grain migration and soil subsidence that often occur around cyclic laterally loaded piles embedded in sand. Supported by new empirical evidence, this paper proposes that, additionally to some soil densification around the pile, the main cause for the continuous "steady-state" grain migration is a convective cell flow of sand grains in the vicinities of the pile head. Such convective flow would be caused by a ratcheting mechanism triggered by the cyclic low-frequency lateral displacements of the pile. Furthermore, the experimental results suggest that the limit between the convective cell and the static soil is marked by a distinct direct shear surface. This might shed some light into the complex phenomena related to the pile-soil interaction in the upper layers of the bedding, which are normally the main contributor for the lateral load-bearing capacity of piles.

Keywords Grain migration · Pile foundation · Cyclic lateral load · Ratcheting · Convection · Densification

1 Introduction

The ever-increasing dimensions of wind energy converters lead to the necessity of new foundation systems, especially for the offshore branch. Monopiles of large diameter (up to 8 m in diameter) and tripod foundations are being studied as feasible solutions [1–3], but bring new challenges into scene, as there is little or no experience for systems of such dimensions and expected loads. The effects of extreme loading events (e.g. heavy storms) on these foundations as well as the possible degradation of soil resistance due to the permanent cyclic lateral loads from wind and waves have to be studied.

The current practice in the offshore industry [4–6] provides only general assumptions of limited accuracy for these problems as it mainly focuses on the global behaviour of the foundation (through the use of the so-called *p*–*y* curves of soil lateral resistance versus pile horizontal displacement) and disregards key aspects of cyclic loading as the number and magnitude of the load cycles. Consideration of local aspects of the pile-soil interaction might help improve the definition of the global *p*–*y* curves.

Aiming to gain a better understanding of the complex phenomena related to the pile-soil interaction and improve the safety of future offshore wind-farms, a number of research groups across Germany is currently investigating these issues (a.o. [7–11]).

In the frame of the RAVE project, the research initiative at the first German offshore wind farm [7], the authors have been carrying out model tests for the investigation of the long-term behaviour of pile foundations in saturated sands under lateral cyclic quasi-static loads. During these tests, the authors observed local subsidence on the surface of the surrounding soil and a continuous grain migration towards the pile. While presenting the results of further experiments, this paper investigates the causes of this "steady-state" grain

---

This article contains many references to the colour features of the presented test, which won't be appreciable in the greyscale of the figures. The full colour version of all the figures can be viewed in the on-line version of the paper.

Electronic supplementary material The online version of this article (doi:10.1007/s10035-009-0153-3) contains supplementary material, which is available to authorized users.

P. Cuéllar (✉) · M. Baeßler · W. Rücker
BAM, Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing), Division VII.2 "Buildings and Structures", Unter den Eichen 87, 12205 Berlin, Germany
e-mail: pablo.cuellar@bam.de; pablo.cuellar.moro@gmail.com

migration and proposes a convective model as an explanation for such phenomena.

2 Motivation and scope

The conical soil depression around cyclic laterally loaded piles in saturated sand has been observed and reported in the past, e.g. in [12–14], and soil densification due to the pile-head lateral displacements has also been shown to happen with numerical simulations using a hypoplastic constitutive law [15]. Nevertheless, and despite the abundance of analytical models for the pile-soil interaction under repeated lateral loading (e.g. in [16–18]), the references to subsidence or soil densification near the pile head are scarce in such literature, in part due to the inability of the most commonly used constitutive models to take into account the changes in density of the soil under cyclic solicitation.

In their extensive experimental work with cyclic laterally loaded piles on medium dense sands, Cheang and Matlock consider that this local subsidence might be related to some grain migration towards the pile triggered by the repeated compaction of the soil as the pile moves back and forth, and they acknowledge that after a number of cycles the conical depression is fully developed and remains more or less constant [12].

In a set of long-lasting model tests in a reduced scale (1:100) of a pile under cyclic lateral load (up to 5 million load cycles), the authors were able to observe the same local subsidence (see Fig. 1a), and noticed that within the first thousands of cycles the depression seemed to reach a steady depth and then remain constant. Furthermore, during the whole runtime of each test (two months with load cycles at a frequency of 1 Hz), the grain migration towards the pile never ceased nor seemed to slow down significantly.

Given the natural tendency of dense siliceous sands to dilate under shear at low confining pressures [19], the fact that the tests had been carried out in an already very dense sand (∼90% of the Proctor density) appears to contradict the *densifying* explanation of this continuous grain migration. It seems unlikely that the densification could account for the steady grain migration throughout the whole test since, after all, the soil cyclic densification should have a limit [20,21], especially for such dense sands at low confining stress where particle overriding (and hence dilation) rather than particle crushing might be expected [19].

On the other hand, it is widely accepted that the driving of piles into the soil can also cause fines migration, soil contraction and stress relaxation as a result of particle crushing and rearrangement during the pile-driving [22–25]. However, such phenomena were ruled out in these model tests. In fact, the pile driving did not produce any appreciable local subsidence of the soil surface, in contrast to that one produced by the subsequent cyclic loading.

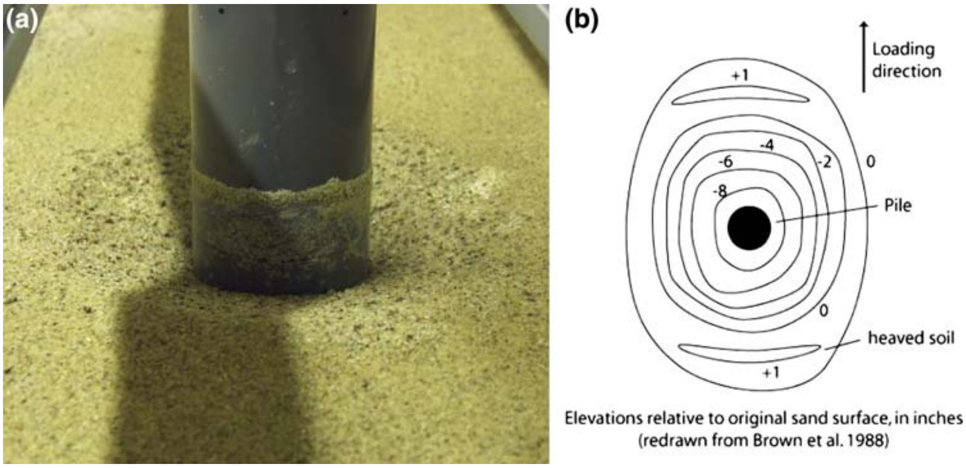
Attempting to find out the final destination of the migrated grains, a further test was devised incorporating bands of coloured sand grains on the soil surface in order to be able to identify them at the end of the loading schedule, upon removal of the upper layers of soil.

3 Experimental study

3.1 Experimental setup

Rather than a quantification of the complex phenomena associated to the pile-soil interaction, the main goal for these experiments was the qualitative understanding of the long-term behaviour of saturated sand around a cyclic laterally loaded pile. Given their simplicity and repeatability, model tests under $1g$ conditions of an offshore monopile at a geometrical scale of 1:100 were performed.

Satisfaction of the scaling laws for a kinematic and constitutive similarity between prototype and model in granular systems is not a trivial matter [26–29] and since the quantification and direct transfer of the results to the prototype



Elevations relative to original sand surface, in inches
(redrawn from Brown et al. 1988)

Fig. 1 Soil subsidence around laterally loaded pile **a** observed by the authors in model test and **b** topographic sketch for in situ tests, after [13] behaviour was not intended, only the pile dimensions and its bending-stiffness were properly scaled. For such purpose, an open-ended hollow PVC pile with 75 mm in external diameter (flexural stiffness EI equal to 2,000 N m^2) and 30 cm of embedded length was used.

Among other technical difficulties of model tests with geomaterials, the 1:100 scaling of the grain dimensions would require clay-size soil particles and hence introduce unwanted cohesive forces into the system. Therefore, a real-size sand from a quarry north of Berlin was used for the experiments. This sand, whose grain size distribution can be seen in Fig. 2, is similar to the siliceous sands present off the German coasts in the North Sea.

A sand container 100 cm long, 80 cm wide and 50 cm deep was used for the experiments. This way, a clearance of 5,75 D between the pile and the container wall was ensured in the loading direction, which was considered enough to disregard disturbing effects from the wall into the pile-soil interaction.

The sand was placed into the container with a 10% water content in layers of 20 cm thickness, and then compacted with a vibrating plate until a density of around 90% of the ASTM standard Proctor density was achieved [30].

Then, the pile was pressed into the soil to a final bedding depth of 30 cm and a pattern of bands with coloured sand grains was placed on the soil surface as displayed in Fig. 3. These coloured bands (2 cm thick) were placed along the loading direction and, since an asymmetric two-way cyclic loading program was scheduled, the bands were wider in the soil's side carrying the highest load, covering a 60 degree circular sector, as shown in Fig. 3. The average size of the coloured grains was about 2 mm.

In order to investigate the grain migration perpendicular to the loading direction, two additional marker lines were placed on the pile's sides. With the additional intent to analyse the influence of grain size and shape on the migration patterns, coarser sand grains (blue markers in Fig. 3, with an average size of 7 mm) and ceramic spherical particles (white markers, in average with 1 mm in diameter) were employed for these lateral marker lines.

Afterwards, the container was progressively flooded with water until a full saturation and a water level of 2 cm above the soil surface were achieved. The introduction of water was done upwards from a drain at the bottom of the container and very slowly to facilitate the expulsion of air occluded

Fig. 2 Grain-size distribution of Berliner sand

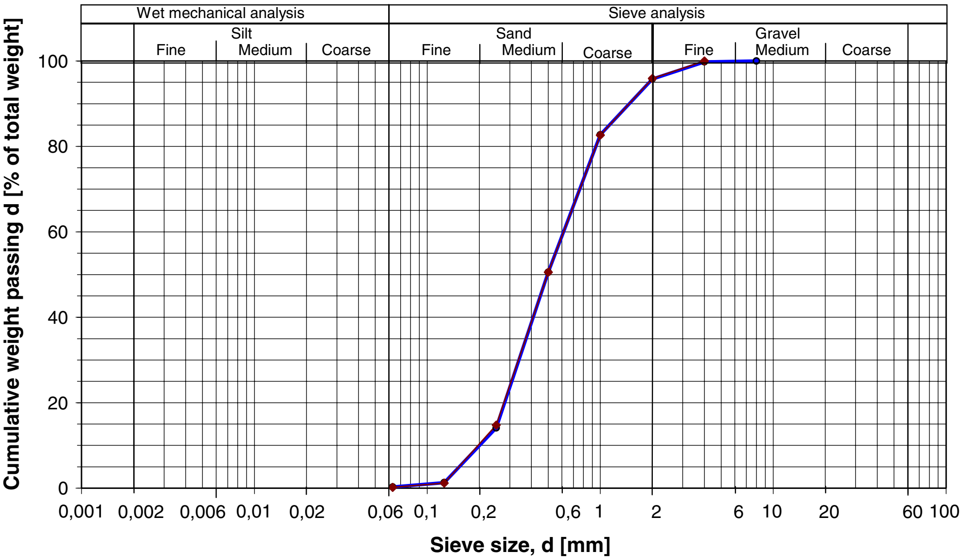
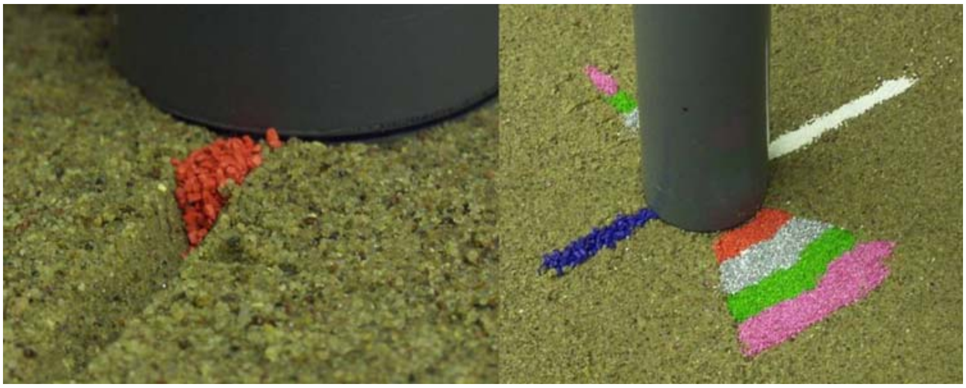


Fig. 3 Pattern of coloured grain markers for the investigation of grain migration



between the grains and avoid the disturbance of the soil skeleton.

Regarding the magnitude of the loads, the common estimations by means of the widely-used Morison equation for extreme events (maximum waves with 50 years return period) assume horizontal loads on the monopiles in the range of a few megaNewtons [31]. For instance, Byrne and Houlsby state that the foundation of a typical 3.5 MW offshore wind turbine could be subject to maximum lateral loads of about 4 MN and overturning moments in the range of 120 MN m, or equivalent to the horizontal load being applied 30 m above the sea-bed level [1]. With reference to the scaling laws for 1g model tests [27] and with a geometrical scaling factor of 1:100, the loads applied to the model should be six orders of magnitude lower, that is, in the range of a few Newtons. Therefore, a two-way asymmetric sinusoidal loading was scheduled, with a frequency of 1 Hz and maximum loads of 20 N in one direction and 10 N in the opposite. These loads range around the 10% of the static ultimate capacity, which would eventually be measured amounting to approximately 150 N at a pile-head displacement of 0.1 D.

Given the relatively high permeability of these clean sands, the loading frequency and magnitude were considered to be low enough to disregard the possibility of a significant long-term pore pressure accumulation within the soil.

As shown in Fig. 4, the loads were transferred to the pile with a pneumatic actuator on one side and a hanging dead load on the other, both connected to the pile through steel cables at a height of 30 cm above the soil surface and controlled with a pair of load cells.

The pile-head displacements were registered with two laser distance-measuring sensors, and the soil movements and grain migration on the surface were captured with a digital camera, which additionally produced a continuous animation with a capture rate of one frame per hour, throughout the whole 2 months of test duration.

3.2 Observations during the test

As evident from the recorded video (see Animations 1 through 5 and Fig. 5), the grain migration towards the pile starts immediately after the beginning of the loading and within the first few hours (the first 100,000 load cycles) the first grain marker band (the red grains) has been totally engulfed and the conical soil depression around the pile reaches a rather constant depth of about 2 cm.

Then, the grain migration decelerates slightly in a progressive manner and by the tenth day of loading (approximately the first million load cycles), the second coloured band (the silver-colour markers) has also disappeared from the soil surface and the grain migration speed seems to stabilise to a constant rate.

By the end of the test after 5 million load cycles, the third band of coloured sand markers (the green sand particles) has also almost completely migrated into the soil-pile interface and the particle migration is still active and at a rather constant speed.

But most remarkably, after ∼2 million cycles, red markers from the first coloured band (which disappeared within the first few hours of loading) started appearing back into the soil surface at some distance from the pile, and then being mixed and drawn back to the pile along with the rest of sand particles affected by the grain migration (see Fig. 6). This evidence clearly suggests a convective nature of the grain migration.

The fourth band of markers (the pink sand grains), at a distance of 6 cm from the pile wall, did not experience any substantial movements, indicating therefore the limits of the observed phenomena.

Additionally to the grain migration along the loading direction, the recorded video also shows a grain migration within the marker lines perpendicular to it. In fact, this pattern of grain movement towards the pile seems to happen

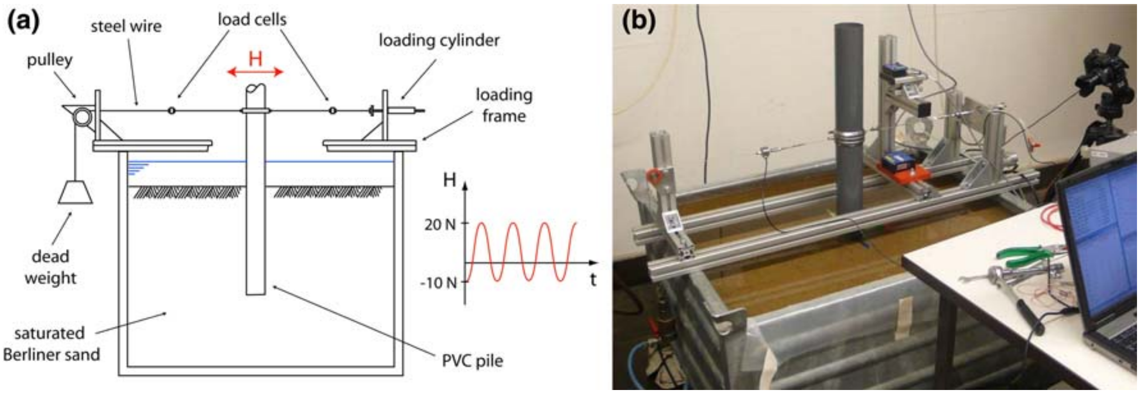


Fig. 4 Experimental setup. **a** Sketch of actuators arrangement and scheduled loads **b** picture of test rig

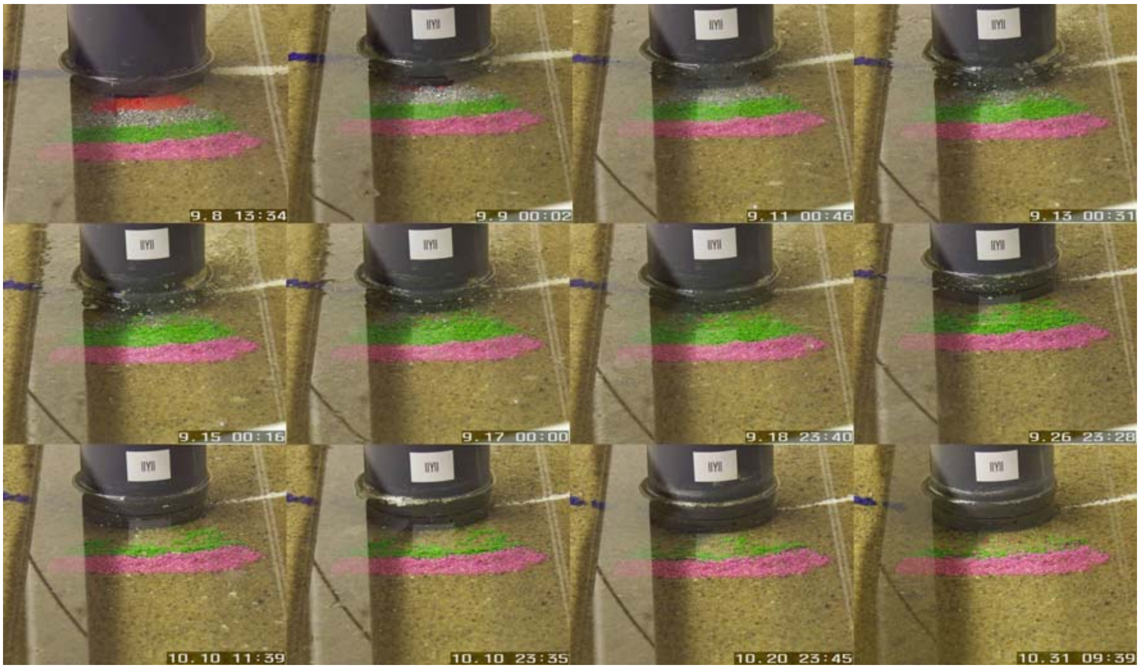


Fig. 5 Photo sequence of progressive grain migration during 5 million load cycles

Fig. 6 Red markers appearing back into the soil surface

radially in every direction of the soil's surface plane, and neither happens to cease during the test's runtime. The average speed of the migrating grains ranges around a millimetre every few hours, as it appears from the video images.

Figure 7 shows the state of the soil's surface at the end of the test, after a concluding static capacity loading and the complete drainage of the soil's water.

A slight ground heave could be appreciated in the outskirts of the conical soil depression, similar to that reported by Brown et al. in their field tests [13] (see Fig. 1b).

Figure 8 portrays the evolution of the extremes of the cyclic pile displacements (i.e. the local maxima and minima) as measured 20 cm above the soil level. Within the first hundred thousand cycles (the first day of loading) the amplitude of the pile head cyclic lateral displacements reduces almost a 27% (from 0.812 to 0.595 mm) and then remains rather constant for the rest of the loading program with a marginal decrease of a further 4% in the displacement amplitude by the end of the test. This hints towards a rapid densification (and therefore improvement) of the surrounding soil during the first day of loading, causing the decrease in the displacement amplitude, and then a steady state where the displacement amplitude remains constant and only a slow steady drift of the foundation towards the direction of higher loads can be observed. This drift of the pile slows down progressively to a rather stable rate, insinuating an incremental collapse evolution (in the sense that the permanent pile displacements increase constantly with every cycle).

A plot of the pile-head displacements in a logarithmic scale suggests the existence of two distinct phases during the cyclic loading (see Fig. 9). It shows two rather linear consecutive domains: the first one lasting until the first hundred thousand cycles (incidentally, this is the moment when the soil depression seems to stabilise) and then a second phase, lasting until the end of the test, where the cyclic amplitude seems to stabilise.

3.3 Convective cell

Conclusive evidence supporting the existence of a convective cell around the pile-head was observed upon drainage of the water and careful removal of a part of the upper layers of sand. A vertical cut of the soil along the direction of loading exposed two clearly differentiated domains of soil and, most

Fig. 7 Soil surface at the end of the test, upon drainage of the water

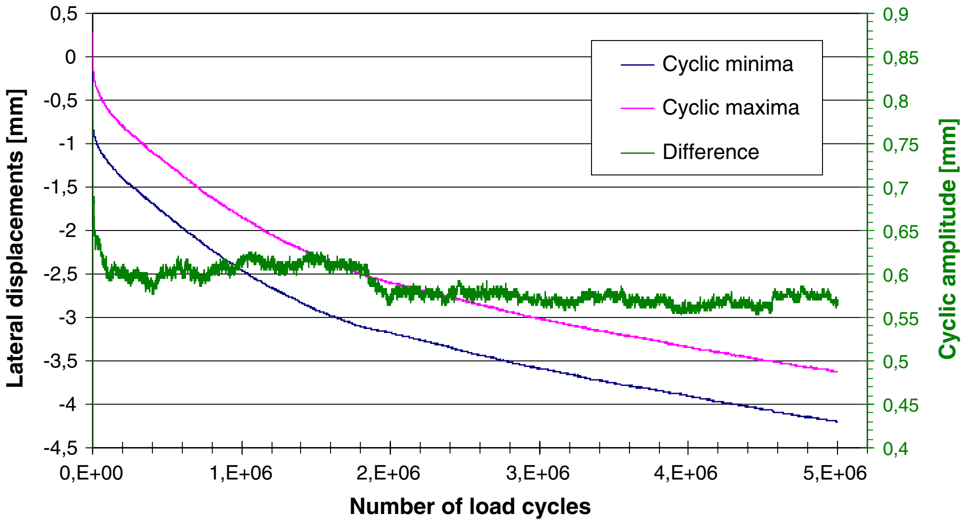


Fig. 8 Evolution of pile lateral displacements and cyclic amplitude

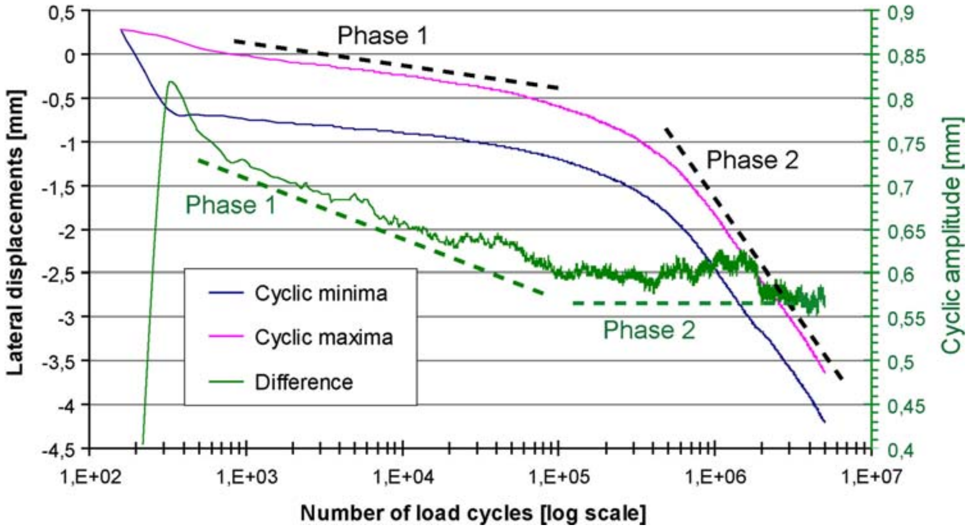


Fig. 9 Measured lateral pile-head displacements in logarithmic scale

notably, a dark transition band marking the limit between these two domains (see Fig. 10).

The first soil domain, which we shall term the *convected domain*, could be observed beside the pile-head and right under the soil depression. All over this domain, it is possible to see a heterogeneous mixture of sand grains and coloured particles from the different marker bands. It reaches a depth of 10 cm along the pile-soil interface, as measured from the apex of the conical soil depression, and its depth decreases rapidly with the distance from the pile wall. Besides, the domain's most distant point from the pile (the domain's maximum extension) happens to be right below the beginning of the pink marker band at the soil surface, which, as mentioned before, was observed to be practically unaffected by the grain migration, indicating therefore the limit of this hypothetical convective cell.

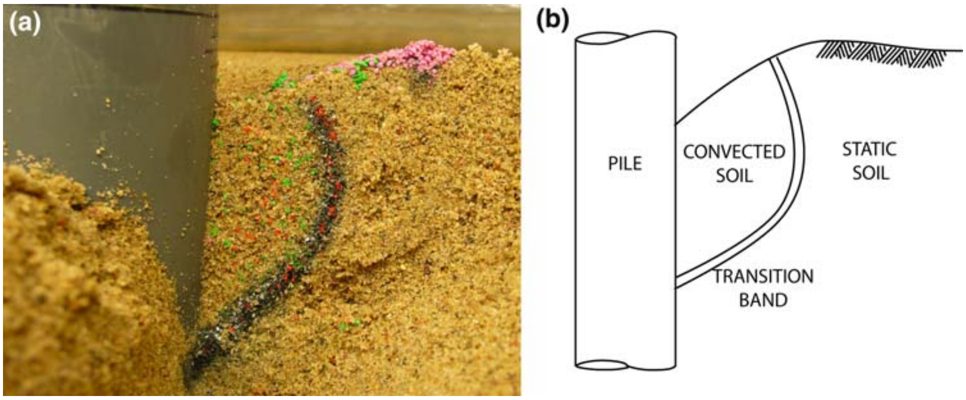


Fig. 10 **a** Vertical cut of the soil, along the loading direction. **b** Sketch of soil domains

On the other hand, the second soil domain, henceforth referred to as the *static domain* (noting that it is not implied that it does not actually move), covers the rest of the soil, from the undisturbed regions at the boundary with the soil container right up to the limits of the transition band (or, more appropriately, transition *surface*, as will be explained below). Remarkably, this static soil domain is characterised by a complete absence of coloured sand markers, with the mere exception of a few coloured grains unavoidably pressed into it during the cut and removal of the soil after the loading program.

Noteworthily, the transition region between the convected and static domains features a high population of coloured markers and, especially, the striking presence of very fine dark particles, previously unaccounted for (see Fig. 11, magnification of the Fig. 10). These dark particles where later identified as coming from the silver-colour coating of the grains of the third marker band. It appears that upon shear under water, the abrasion occurring at the contact between sliding grains wears off the paint-coating of the silver-coloured sand grains, generating the dark dust-size particles. The authors believe that this fact strongly supports the idea of two distinct soil domains, a static and a moving one, and the existence of a direct shear surface between them, where the weak coating of the silver markers is worn off.

To further reinforce this hypothesis, it can be observed that within the lower parts of the transition surface, where the abrasion of the silver-coloured particles would be just only beginning, there is a much higher population of silver particles than in the upper parts of the limit surface, in which the silver markers would have experienced the abrasion all the way up during their convective migration and thus would have lost most of their colour coating.

The paint-coatings of the other migrated coloured markers (the red and green ones) do not appear to be susceptible to such abrasion under water, at least at the low confining stresses present during the experiment, and thus these markers can be clearly seen all over the convected domain and delimiting surface.

The subsequent removal of the pile exposed the three dimensional nature of the convected domain (see Fig. 12). It can be observed that the transition band is also present in vertical planes along directions other than the loading line, although only reaching shallower depths. A difference of about 3 cm in the maximum depths of the convected domain was measured between the loading direction, where

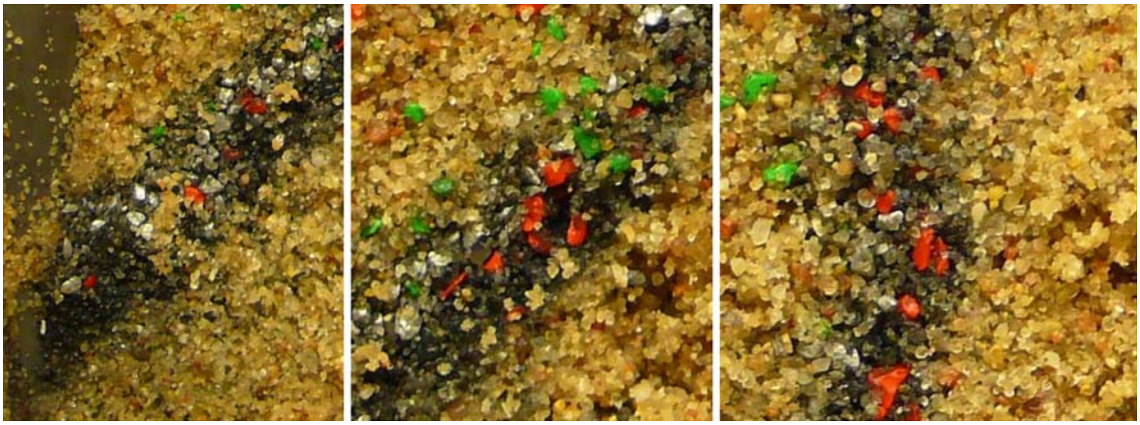


Fig. 11 Close-up images of the transition band

Fig. 12 3D nature of convective cell (images upon removal of pile)

the convection cell reaches its deepest point, and the furthest radial direction within the marker circular sector, which is about 30 degrees off the loading line in the soil surface plane.

Also worth mentioning is the pattern of grain displacement in the direction transversal to the loading line, which, as mentioned earlier, was traced with the white ceramic spheres and blue coarse sand particles. As shown in Fig. 13, the flow of grains in this transversal direction moves out of the vertical plane and deviates clearly towards the less loaded side of the loading direction (the side where the pile is only loaded with a maximum 10 N). As evidenced by the video images, both ceramic spheres and coarse sand markers first migrate radially towards the pile, that is, moving within their vertical plane transversal to the loading direction. But once they reach the pile and penetrate into the soil at the pile-soil interface, they seem to experience an out-of-plane convection that takes them towards the side where the cyclic stresses are lower.

Interestingly, the convected coarse blue particles reach a much shallower depth (around 2 cm under the soil surface) than any other markers, especially than the ceramic markers placed on the opposite side of the pile, which points out to a significant influence of the grain size in the magnitudes of the observed phenomena.

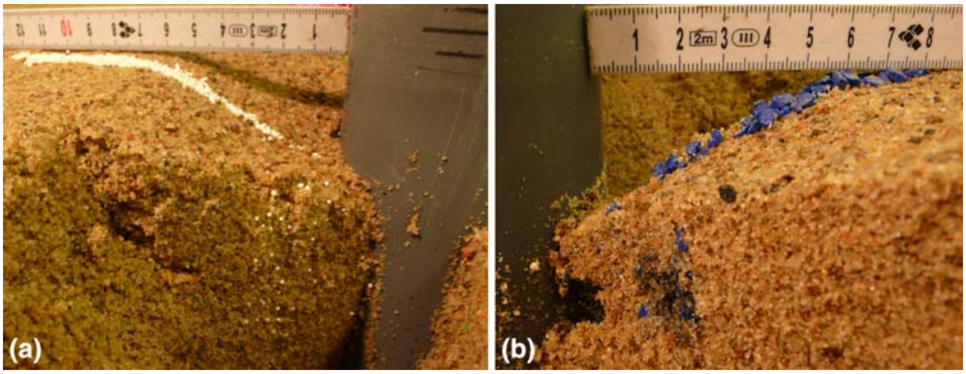
4 Discussion

4.1 On the phases of pile-soil interaction

The empirical evidence shown in this paper suggests a two-phase scenario of pile-soil interaction that, to the knowledge of the authors, has not been described or reported before. Such hypothetical scenario could be outlined as follows: The saturated sand surrounding a flexible pile foundation, subject to a two-way cyclic horizontal loading on the pile-head, undergoes two main distinct phases of deformation and grain displacement: a densification-dominated phase and a convection-dominated phase.

The first phase, the *densification phase* (or simply *rearrangement phase*, if the sand is dense enough), starts immediately after the first cycle of loading and is characterised by a progressive subsidence of the soil surface surrounding the pile. During this phase, the cyclic compaction of the soil due

Fig. 13 Out-of-plane convection and deviation of the transversal convective grain flow towards the “unloaded” side of the pile. **a** White ceramic spheres **b** coarse sand blue markers



to the pile displacements causes a grain rearrangement and, in general, a reduction of inter-granular voids.

The duration of this phase would be influenced, among others, by the magnitude of the pile displacements and relative density of the soil, and it would occur even in absence of particle-crushing or significant pore-pressure accumulations, which do not seem to have happened in the presented tests. As Hettler reckons, grain-crushing and elastic compression of the single grains may be disregarded at low levels of stress (up to 1 MPa) for such sands [32].

Then, once the soil depression reaches a rather constant depth, a second phase starts, namely the *convection-dominated phase*. During such phase, rather than producing further densification of the soil, the cyclic lateral movements of the pile would mainly cause a convective ratcheting displacement of the sand particles. This way, every time the pile moves back after a loading peak, a small gap opens at the pile-soil interface allowing the sand grains adjacent to the pile-head to move downwards along the interface. Once they reach a critical depth where the gap is not big enough and they cannot move further down, the sand particles would then be pressed into the soil, moving a little bit further with every load cycle, in a ratchet-like fashion.

Along their way through the soil mass, the migrated grains would be pushed forward by the following grains, and also move towards areas of lower confining stresses, i.e. upwards, setting in motion a whole ratcheting convective cell within the pile-head vicinities.

Such a convective phenomenon would imply that, after a large enough number of load cycles, and despite the constant grain migration and inflow of material into the pile-soil interface, no more significant soil densification is taking place.

At the limit where the sand grains are no longer directly affected by the pile-head displacements (and hence rather static), the migrating grains would have to override the standing particles in order to move forward, triggering a direct shear between the convected and the static material.

It is important to stress that these two phenomena, densification and convection, need not be necessarily decoupled. In fact, it is possible that some convective grain migration already takes place simultaneously with the densification during the first loading cycles and, reciprocally, some degree of further densification might also occur during the convection-dominated phase.

It must be noted that not all sands have a tendency to densify and, in some circumstances, part of the local subsidence might be also caused by a mere plastic deformation of the soil without reduction in volume, meaning that the subsided volume *emerges* somewhere else. This might have happened to some extent in the presented test, where the sand was already quite dense and some slight local heave was observed right outside the subsided area. In any case, it did not appear that the heaved volume of soil could account for the whole subsidence, so it seems that some densification happened indeed.

On the other hand, a significant decrease in the amplitude of the pile-head displacements was observed during the first day of loading, which also supports the hypothesis of some densification taking place even with such dense sands, and reinforces the idea of an initial densification-dominated phase. Brown et al. report a similar “surprising” densification of an already well compacted sand as a result of the two-way cyclic lateral load on a pile [13].

Since in this investigation it was not intended to study the relationship between the local heave, subsidence and the resulting degree of densification, for the moment it will suffice to term the first phase simply as densifying, noting that the shallow (upper) layers of most natural sand deposits might not be so dense to exclude the possibility of further densification.

At this point it is also interesting to note the similarities with the experimental results of Bobryakov et al. [33]. Although carried out on a different system (a retaining wall and a raking slope of confined sand, one way loading and plane strain conditions), they also report two stages of soil deformation in their system, namely an initial non-stationary phase with densifying character during the first few load cycles and a subsequent stationary stage “with steady state material density and unchanging specimen surface”. The authors believe that such correspondence with the two-phase scenario described here strongly supports the model of pile-soil cyclic interaction proposed in this paper.

4.2 On granular convection and ratcheting

It is also important to emphasise that, in contrast to the usual *vibratory* granular convection that has been broadly mentioned and studied since its discovery in 1831 by Faraday, e.g. in [34–40], where the granular matter is subjected to vibrations and relatively high accelerations, the convective flow presented in this paper has instead a *quasi-static ratcheting* nature. During the test, both the loading frequency and pile-head displacements were so low that the induced accelerations of the soil particles must have been negligible compared to the earth’s gravity.

The idea of ratcheting behaviour has already been used in the field of soil mechanics to explain the progressive accumulation of plastic deformations of granular materials under cyclic loads, e.g., in [41–44], and numerical studies of granular micromechanics have shown that, even under very small loading, a large number of particle contacts can reach the sliding condition and produce irreversible deformations [45,46].

In a recent paper, Alonso-Marroquin et al. analyse the formation of convective vorticity caused by granular ratchets and report, at a micro-mechanical level (a packing of 400 polygons), the existence of two kinds of deformation regimes: short time regimes featuring a fast accumulation of plastic deformation, and long time ratcheting regimes with slow rates of plastic deformation [47]. In a sense, the experimental evidence and the two-phase model of pile-soil interaction proposed in this paper could be interpreted as the macro-mechanical translation of the micro-mechanical effects discussed therein.

4.3 On localised failure and pile behaviour

It must also be noted that, despite the striking presence of the shear surface as shown in the pictures, this is not a localised failure of the foundation in the traditional sense. The term "shear surface" is employed here, instead of the more common "shear band", with a double intention: firstly, it stresses the 3-dimensional character of this phenomenon, since this surface seems to surround a heart-shaped volume of soil all around the pile (the term "band" seems more appropriate for a 2D plane strain case). Additionally, it is also meant to avoid confusion with the more common sense of "shear band" as localised failure of the foundation. The sliding of a whole block of soil along a shear band, as reported for instance by Bobryakov et al. for their experiments [33], was never observed in this case, and during the whole runtime of the test, the soil seems to have kept most of its strength. Instead of a localised abrupt failure of the structure, the measured pile-head displacements rather suggest some shake-down effect or attenuation of the displacement rate during the first 2 million load cycles, and then an incremental collapse in the sense of an almost linear growth of displacements with the number of cycles (see Fig. 8).

At this point it is convenient to stress that the above mentioned attenuation and incremental collapse phases do not need necessarily to match chronologically the previously mentioned densification-dominated and convection-dominated phases. Although their causes are probably closely related, the former are just the global description of pile-head behaviour, while the latter refer to the micro-mechanical processes inside the soil, namely the reduction of inter-granular voids and the ratcheting regime. The beginning and end of all these phases need not be necessarily coupled.

4.4 On the factors responsible for the observed phenomena

It is likely that the opening of a gap at the pile-soil interface is a key element for the appearance of such grain migration and convective cell, because it facilitates the downwards movement of the grains adjacent to the pile-head.

Moreover, the depth of the convection cell is probably strongly influenced by the magnitude of the opening gap and the relative size of the migrating grains. As proposed before, the grains would only migrate downwards at the interface up to the depth where the gap is not big enough to let them through.

This all means that, for a same level of loading, a two-way cyclic load would produce a greater subsidence and grain migration (and thus a deeper convective cell) than a one-way cyclic lateral loading, since the two-way loading would cause a greater aperture of the pile-soil interface. It should be possible to empirically verify the validity of this hypothesis with further tests.

Similar conclusions are drawn by Brown et al. who consider that the sand densification due to lateral pile loading appears to be related to the compaction of the sand falling into the gap behind the pile, and conclude that one-way cyclic lateral load would "undoubtedly" produce less densification than a two-way loading [13].

Numerical simulations with a hypoplastic constitutive law have already shown how, in contrast to a one-way cyclic lateral load causing a progressive collapse, the two-way loading can produce some hardening of the surrounding soil and thus reduce the pile-head displacements [48]. The authors of the simulations interpreted such cyclic hardening as being conditioned by the slippage of soil at the interface after each loading peak, and in this respect it could correspond to the densification phase described in this paper.

Another issue that needs to be clarified is the role of water in the observed phenomena. It seems clear that, despite their obvious resemblance, the conical soil depression reported here is not related to the scour that often occurs in under-water foundations. Local scour is solely caused by the sediment transportation due to the turbulence produced by any foundation that poses an obstacle to the flow of water currents. Given the small dimensions of the confining container and the quasi-static character of the loading, it appears that no water currents strong enough to erode the soil surface did happen during the test.

On the other hand, the presence of water may have enhanced the soil migration and convective flow, since the effective stresses within the submerged soil matrix are lower than those within a dry material. This, in turn, permits a bigger number of contacts between particles reaching the sliding condition, favouring thus the ratcheting displacements.

In any case, the authors believe that these phenomena might also happen in dry and partially saturated sands, although probably to a minor extent.

The effects of any excess pore water pressure and the possibility of soil liquefaction have in principle been disregarded, but they should be object of further investigations, particularly in relation to the loading frequency.

5 Conclusions and outlook

As discussed in Sect. 2, the phenomena related to the densification phase have already been observed and identified before but, to the knowledge of the authors, the second phase featuring a long-term convective granular flow near the pile has never been reported or described. Furthermore, the existence of two clearly distinct soil domains near the pile, namely the *convected* and *static* soil domains, and the limiting *direct shear* surface between them are also believed to be novel findings.

Despite the qualitative character of these investigations and the special conditions in which they were carried out (a.o. model tests with single frequency, one directional, two-way loading in an homogeneous clean sand), the practical consequences for the pile design might be manifold. If these phenomena are confirmed to take place also at a bigger scale and in real in-situ conditions, the model proposed here could be part of a rational framework for an approximate quantification of the long-term cyclic behaviour of lateral pile-soil interaction.

Depending on the soil conditions and expected loads, it might eventually be possible to define the limits of the densification phase and subsidence cone. On the other hand, it may be possible to relate the depth and extent of the convected soil domain to the different design parameters of the pile (flexural stiffness, service loads, grain size distribution, etc.) so that a clearer picture of the pile bedding emerges. This, in turn, might provide a basis for a further re-examination of the current lateral pile design procedures. Applying the existing and future knowledge on granular ratchets to the lateral pile-soil interaction could lead to better estimations of long-term pile-head displacements and a proper adjustment of the $p-y$ curves. The current practice merely prescribes a 10% reduction of the static $p-y$ curves for all cases of cyclic loading, irrespective of their duration, magnitude and orientation [4].

Another practical consequence that could be drawn for offshore and under-water operations is that, even if scour is not expected to happen or the appropriate counter-measures are adopted, the soil subsidence might still occur due to densification and grain migration.

Regarding the ultimate lateral capacity of the pile, the hypothetical direct shear surface between the convected and static soil domains could lead to the localised damage that eventually might trigger a failure surface. The material and mechanical properties of this limiting surface and its hypothetical connection to localised failure should be investigated in detail.

Numerical analysis might help improve the understanding of these phenomena, but due to the inadequacy of continuum finite element models (FEM) to simulate the grain migration and soil convection, a meshless or a discrete element (DEM) approach might be required for such task.

On the empirical side, on-going and future tests at BAM will address the sensitivity of the proposed model to different factors and design parameters (e.g. the influence of pore water pressure and load frequency, one-way loading versus two-way loading, dry conditions versus wet conditions, influence of pile diameter and flexural stiffness, relationship between deformed pile shape and depth of convected domain, the symmetry of cyclic loads and the deviation of the convection flow, influence of changes in load direction and the coupling of lateral loads with axial loads). On the other hand, a topographic measurement of the soil surface after the tests might provide a simple means to determine whether cyclic densification and soil improvement do effectively occur at some stage during the tests. The differential soil volume between the original and final states shall indicate the *averaged* degree of densification.

As a closure to the paper it could be pointed out that the upper parts of the pile foundations are the most relevant for their lateral bearing capacity [2,13,49], which highlights the potential significance of these findings. A better understanding of processes inside the soil and of the pile-soil interaction at shallow depths might help improve the design and safety of future foundations.

Acknowledgments The authors are particularly indebted to Fred Ziegler, who first suggested the possibility of grain convection near the pile, and Wilfried Wuttke for their assistance with the experiments and insightful discussions about the results. Hans-Joachim Peschke is gratefully acknowledged for his support with the management of sensor-data. The authors enjoyed the support, advice and encouragement of Manuel Pastor and his research group within the Geotechnical Laboratory of CEDEX in Madrid. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) has kindly provided the funding for these investigations, which were carried out in the frame of the RAVE (research at alpha ventus) research program.

References

1. Byrne, B.W., Houlsby, G.T.: Foundations for offshore wind turbines. Philos. Trans. Royal Soc. A **361**(1813), 2909–2930 (2003)
2. Lesny, K.: Gründung von Offshore-Windenergieanlagen—Entscheidungshilfen für Entwurf und Bemessung. Bautechnik **85**(8), 503–511 (2008)
3. Achmus M., Abdel-Rahman K., Kuo Y.-S.: Design of monopile foundations for offshore wind energy converters. Geotechnics in Maritime Engineering. 11th Baltic Sea geotechnical conference, pp. 463–470. Gdansk, Poland (2008)
4. API.: RP-2A-WSD: Recommended practice for planning, designing and constructing fixed offshore platforms—working stress design, (x) 21st edn, Dec. 2000; Errata&Supplement 1, Dec. 2002; Errata&Supplement 2, Sept. 2005; Errata&Supplement 3, Dec. 2007), American Petroleum Institute (2007)
5. Germanischer Lloyd: Guideline for the certification of offshore wind turbines. Germanischer Lloyd Windenergie GmbH (2005)

6. ISO.: ISO 19902:2007: Petroleum and natural gas industries—Fixed steel offshore structures. ISO, international organization for standardization (2007)
7. ISET.: RAVE-Research at alpha ventus. The research initiative at the first German offshore wind farm. ISET, Institut für Solare Energieversorgunstechnik, Kassel (2008)
8. Grabe, J.: Pile foundations for nearshore and offshore structures. Geotechnics in Maritime Engineering. 11th Baltic Sea geotechnical conference, pp. 445–462. Gdansk, Poland (2008)
9. Savidis, S., Rackwitz, F., Tasan, H.E.: 1g-Modellversuche mit zyklisch horizontal belasteten Einzelpfählen im wassergesättigten Sand. In: Stahlmann, J. (ed.) Pfahl-Symposium 2007, pp. 115–130. Braunschweig, Germany (2007)
10. Wichtmann, T., Niemunis, A., Triantafyllidis, T.: Predictions of long-term deformations for monopile foundations of offshore wind power plants. Geotechnics in Maritime Engineering. 11th Baltic Sea geotechnical conference, pp. 785-792. Gdansk, Poland (2008)
11. Stahlmann, J., Kluge, K., Gattermann, J.: Theoretische und experimentelle Erkenntnisse zur Bodenverflüssigung bei Offshore-Windenergieanlagen. HTG-Kongress 2005 in Bremen, Germany, Hafenbautechnische Gesellschaft e.V., pp. 265–274 (2005)
12. Cheang, L., Matlock, H.: Static and cyclic lateral load tests on instrumented piles in sand. The Earth Technology Corporation, Long Beach, California (1983)
13. Brown, D.A., Morrison, C., Reese, L.C.: Lateral load behavior of pile group in sand. J. Geotech. Eng. **114**(11), 1261–1276 (1988)
14. Savidis, S., Rackwitz, F., Richter, T., Röhner, J., Schneider, N.: Verhalten von Pfählen in wassergesättigten Sanden unter zyklischen Horizontallasten. Bauingenieur **79**, 383–385 (2004)
15. Grabe, J., Dührkop, J., Mahutka, K.-P.: Monopilegründungen von Offshore-Windenergieanlagen. Zur Bildung von Porenwasserüberdrücken aus zyklischer Belastung. Bauingenieur **79**, 418–423 (2004)
16. Achmus, M., Kuo, Y.-S., Abdel-Rahman, K.: Behaviour of monopile foundations under cyclic lateral load. Comput. Geotech. **36**, 725–735 (2009)
17. Bentley, K.J., El Naggar, M.H.: Numerical analysis of kinematic response of single piles. Can. Geotech. J. **37**, 1368–1382 (2000)
18. Taiebat, H.A.: Three dimensional liquefaction analysis of offshore foundations. Ph.D Thesis, University of Sidney (1999)
19. Bolton, M.D.: The strength and dilatancy of sands. Géotechnique **36**(1), 65–78 (1986)
20. Gudehus, G.: Nichtlineare Bodendynamik in der Geotechnik. Baugrundtagung 2000, Hannover, VGE Verlag GmbH, Essen, pp. 263-270 (2000)
21. Triantafyllidis, T.: Bodenverflüssigung infolge zyklischer Belastung. GEOLEX **2**(2), 5–20 (2003)
22. Randolph, M.F.: Science and empiricism in pile foundation design. Géotechnique **53**(10), 847–875 (2003)
23. White, D.J., Bolton, M.D.: Displacement and strain paths during plane-strain model pile installation in sand. Géotechnique **54**(6), 375–397 (2004)
24. Lobo-Guerrero, S., Vallejo, L.E.: Influence of pile shape and pile interaction on the crushable behavior of granular materials around driven piles: DEM analyses. Granul. Matter **9**, 241–250 (2007)
25. Lobo-Guerrero, S., Vallejo, L.E.: DEM analysis of crushing around driven piles in granular materials. Géotechnique **55**(8), 617–623 (2005)
26. Pöschel, T., Saluena, C., Schwager, T.: Can we scale granular systems?. In: Kishino, Y. (ed.) Powders & Grains'2001, pp. 439–442. Rotterdam, Balkema (2001)
27. Walz, B.: Der 1g-Modellversuch in der Bodenmechanik-Verfahren und Anwendung. Vortrag zum 2. Hans Lorenz Symposium, Grundbauinstitut der Technische Universität Berlin, pp. 13–26 (2006)
28. Holzlöhner, U.: Modellversuchstechnik. Symposium Messtechnik im Erd- und Grundbau, Deutsche Gesellschaft für Erd- und Grundbau e.V., Essen, pp. 119–126 (1983)
29. Altaee, A., Fellenius, B.H.: Physical modeling in sand. Can. Geotech. J. **31**, 420–431 (1994)
30. ASTM.: ASTM D 698:2007e1: Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft3 (600 kN-m/m3)). ASTM International (2007)
31. Achmus, M., Abdel-Rahman, K., Peralta, P.: Untersuchungen zum Tragverhalten von Monopiles für die Gründung von Offshore-Windenergieanlagen. In: Stahlmann, J. (ed.) Pfahl-Symposium, pp. 137–158. Braunschweig, Germany (2005)
32. Hettler, A.: Verschiebungen starrer und elastischer Gründungskörper in Sand bei monotoner und zyklischer Belastung. Institut für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe (1981)
33. Bobryakov A.P., Kosykh V.P., Revuzhenko A.F.: Temporary structures during the deformation of granular media. (Translation from) Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh, vol 2, pp. 29–39. Mining Institute, Siberian Branch, Academy of Sciences of the USSR (1990)
34. Faraday, M.: On a peculiar class of acoustical figures; and on certain forms assumed by groups of particles upon vibrating elastic surfaces. Philos. Trans. Royal Soc. London **121**, 299–340 (1831)
35. Kutzner, C.: Über die Vorgänge in körnigen Schüttungen bei der Rüttelverdichtung. PhD thesis, Technische Hochschule Karlsruhe (1962)
36. Gallas, J.A.C., Herrmann, H.J., Sokolowski, S.: Convection cells in vibrating granular media. Phys. Rev. Lett. **69**(9), 1371–1374 (1992)
37. Herrmann H.J.: Physics of granular media. Chaos, Solitons and Fractals, pp. 203-212. Elsevier Science (1995)
38. Jaeger, H.M., Nagel, S.R., Behringer, R.P.: Granular solids, liquids, and gases. Rev. Mod. Phys. **68**(4), 1259–1273 (1996)
39. Knight, J.B., Ehrichs, E.E., Kuperman, V.Y., Flint, J.K., Jaeger, H.M., Nagel, S.R.: Experimental study of granular convection. Phys. Rev. E **54**(5), 5726–5738 (1996)
40. Ehrichs, E.E., Flint, J.K., Jaeger, H.M., Knight, J.B., Nagel, S.R., Karczmar, G.S., Kuperman, V.Y.: Convection in vertically vibrated granular materials. Philos. Trans. Royal Soc. A **356**, 2561–2567 (1998)
41. Festag, G.: Experimentelle und numerische Untersuchungen zum Verhalten von granularen Materialien unter zyklischer Beanspruchung. Technische Universität Darmstadt (2003)
42. Gudehus, G.: Ratcheting und DIN 1054. 10. Darmstädter Geotechnik-Kolloquium, pp. 159–172 (2003)
43. McNamara, S., García-Rojo, R., Herrmann, H.J.: Microscopic origin of granular ratcheting. Phys. Rev. E, **77** (2008)
44. García-Rojo, R., McNamara, S., Herrmann, H.J.: Discrete element methods for the micro-mechnical investigation of granular ratcheting. Proceedings of the ECCOMAS (2004)
45. Alonso-Marroquin, F., Herrmann, H.J.: Ratcheting of granular materials. Phys. Rev. Lett. **92**(5) (2004)
46. Alonso-Marroquin, F.: Micromechanical investigation of soil deformation: incremental response and granular ratcheting. Universität Stuttgart (2004)
47. Alonso-Marroquin, F., Mühlhaus, H.B., Herrmann, H.J.: Micromechanical investigation of soil plasticity using a discrete model of polygonal particles. Theor. Appl. Mech. **35**, 11–28 (2008)
48. Grabe, J., Mahutka, K.-P., Dührkop, J.: Monopilegründungen von Offshore-Windenergieanlagen—Zum Ansatz der Bettung. Bautechnik **82**(1), 1–10 (2005)
49. Alizadeh, M., Davisson, M.T.: Lateral load tests on piles—Arkansas River project. J. Soil Mech. Found. Div. **96**(5), 1583–1604 (1970)