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Interaction Between Hoop Stresses and Passive Earth Resistance in Single and Multiple Geocell Structures

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ABSTRACT
Geocell structures consist of a series of interconnected single cells, made from different polymer materials. The cell walls completely encase the infill material and provide an all-around confinement to the soil. The confinement effect is based on three main mechanisms: active earth pressure within loaded cell, passive earth resistance in the adjacent cells and hoop stresses in the cell walls. To evaluate the interaction between hoop stresses and passive earth resistance radial load tests on single and multiple geocell structures were carried out. Geocell materials with different stiffness and different numbers of interconnected geocells were tested. The tests results have shown that the stiffness of the geocell material and the numbers of adjacent cells are the most important parameters for the confinement effect.

1. INTRODUCTION

Geocell structures consist of a series of interconnected single cells, made from different polymer materials. The geocells are delivered to the construction site, expanded and are filled with soil. The cell walls completely encase the infill material and provide an all-around confinement to the soil. If a vertical load is applied on a geocell structure horizontal active earth pressure is mobilized within the loaded cell. The magnitude of active earth pressure is depending on the friction between the infill material and the cell walls. Due to active earth pressure, hoop stresses within the cell walls and earth resistance in the adjacent cells are mobilized which increases the stiffness and the load-deformation behavior of the soil. Different large scale model tests have shown that geocell reinforcements reduce the vertical and horizontal deformation of the soil and the vertical stresses in the subgrade material (Dash et al., 2001, 2003; Emersleben and Meyer 2008a; Meyer and Emersleben, 2005a, 2006).
By the significantly increasing application of geocells for the stabilization of materials with low bearing capacity, especially in regions were qualified material is rarely, a common useable design method for geocells is awfully important for a cost effective solution. For the evaluation of common design method the interaction between hoop stresses, active earth pressure and passive earth resistance in single and multiple geocell structures has to be known very exactly.
Different authors have carried out triaxial tests on single geocells and multiple geocell systems to evaluate the influence of geocell walls and mobilized hoop stresses on the shear strength of different infill materials. Bathurst and Karpurapu (1993) have carried out triaxial tests on aggregate materials (silicia sand and crushed limestone) confined by a single geocell manufactured of polymeric material. The test results show that the geocell-soil composite materials have the same angle of friction as the unreinforced materials but that the geocells mobilize an apparent cohesion to the soil. Depending on the infill material the apparent cohesion varied between 156 to 190 kPa. Madhavi Latha and Murphy (2007) studied the influence of two different geocell membranes on the shear strength of river sand. The geocell membranes were manufactured from a geotextile and a polyester film and were self welded to a cylindrical form. Compared to other reinforcement forms (e.g. eight geotextile layers and discrete fiber forms) the geocell forms were found to be highly effective in improving the strength of the used sand. The geocell membrane made of geotextile showed an improvement in strength of 100 percent at all confining pressures compared to unreinforced sand. Because of the formation of indents the strength of geocells made from polyester was increased by 100 percent compared to the geotextile cells. Both geocell materials mobilized an apparent cohesion to the sand of 78 kPa (geotextile) and 273 kPa (polyester) while the friction angle was nearly the same.
Rajagopal et al. (1999) carried out triaxial tests on multiple geocells to simulate the real conditions in which a number of geocells are interconnected. Four different types of geosynthetics (polypropylene, woven geotextile, nonwoven geotextile and a soft plaster mesh) were used to fabricate circular shapes

by stitching. In the case of multiple cells, several single cells were stitched together. Because the diameter of the triaxial test device could not be changed the diameter of the cells had to be changed between the different cell-setups (single, two, three and four connected cells). Due to the confinement effect imparted by the cells an apparent cohesion between 11 kPa and 169 kPa was given to uniformly graded river sand which was used in the tests. The angle of friction was identical for all tests. The cohesion was increasing both with increasing stiffness of the geocell material number of adjacent cells. Rajagopal et al. (1999) observed that if the number of geocells was increased from three to four there was only a marginal improvement in the performance of the samples. The results indicated that the improvement in the performance due to an interaction between the cells is not significant beyond three cells and that the strength behavior of three interconnected cells may represent the mechanism of geocells having a larger number of cells. Referring the results of Rajagopal et al. (1999), it has to be considered that the diameter of the cells changed depending of the cell-setup. Because of that the different test results between single and tow-cell setup can also be attributed to the difference in the cell sizes and the volume of soil which was not encased by the geocells, rather than the interaction of the different cells. Also, the influence of the difference in the cell sizes and the volume of soil outside the geocells in the three- and four-cell tests were not separated from the influence of the cell interaction (Wesseloo, 2004).
The main objective of the triaxial tests which were carried out by the different authors was the evaluation of the influence of a single or multiple geocell structure on the shear strength of soil. No attempt was made to quantify the influence of the geocells other than its influence on the peak strength.
The aim of the investigation reported here is to evaluate the strain-depending interaction between hoop stresses in the cell walls and passive earth resistance. Radial load tests on single and multiple geocell structures were carried out. In the radial load tests a horizontal load is applied in a single or multiple geocell structure, while the strains in the cell walls and the passive earth pressure in different distances to the loaded cell were measured.

2. MATERIALS

2.1 Soil

An uniform dry sand with a maximum grain size of 2 mm was used as confinement material of single geocells and infill material of multiple geocells. The soil is classified as SP according to the Unified Soil Classification System (USCS). The sand was filled in the geocells by hand and was compacted afterwards by a hand tamper to a relative density of at least 80 percent. The relevant soil parameters of the sand are shown in table 1.

Table 1. characteristics of soil

characteristics	sand (SP)
coefficient of uniformity U	2.10
coefficient of curvature C_c	1.00
porosity in loosest state (DIN 18126)	0.45
porosity in densest state (DIN 18126)	0.34
angle of friction φ	38.9°

2.2 Geocells

Three different types of geocells were used in model tests. Geocell “Type 1” was made from high density polyethylene (HDPE) with a density of 0.95 g/cm³. Single cells are 210 mm long and 250 mm width. Single cells with a cell area of 262 cm² were welded together to form a uniform geocell mattress. The cell walls are perforated with 10 mm diameter holes. The total open area is 16 % of the cell wall area. The surface of cell walls is textured. Geocell “Type 3” was made from the same material but was manufactured without perforations. Geocell “Type 2” was made form thermally solidified nonwoven. The height of all geocells was 15 cm.

Table 2: characteristics of geocell material

characteristics	type 1	type 2	type 3
thickness of geocell wall (mm)	1.70	1.70	1.50
height of geocell (mm)	150	150	150
secant modulus at 2 % [N/cm]	1,59 x 10^5	1,85 x 10^5	3,68 x 10^5
secant modulus at 5 % [kN/m]	1,50 x 10^5	1,42 x 10^5	6,95 x 10^5

Two different forms of geocells were tested in the radial load tests (Figure 1). Machine welded geocells were used to evaluate the influence of adjacent cells on the pressure-strain behaviour; circular welded geocells were used to evaluate the influence of different material stiffness on the pressure-strain behaviour. The circular welded geocells were welded from strips with an adhesive. Index tests have shown that the welding points did not influence the pressure-strain behaviour.

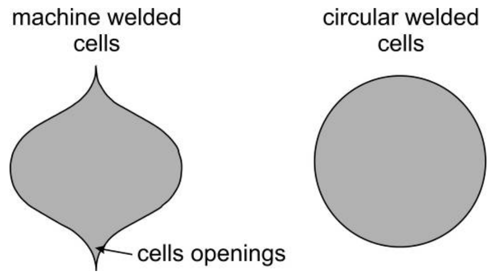


Figure 1: Different forms of tested geocells

3. RADIAL LOAD TESTS

3.1 Test Device

The radial load tests were conducted in a test device in the soil mechanical laboratory of Institute of Geotechnical Engineering and Mine Surveying, Clausthal University of Technology. The test device consists of a test box with inside dimensions of 1.27 m in width, 1.27 m in length and 0.30 m in depth (Figure 2).

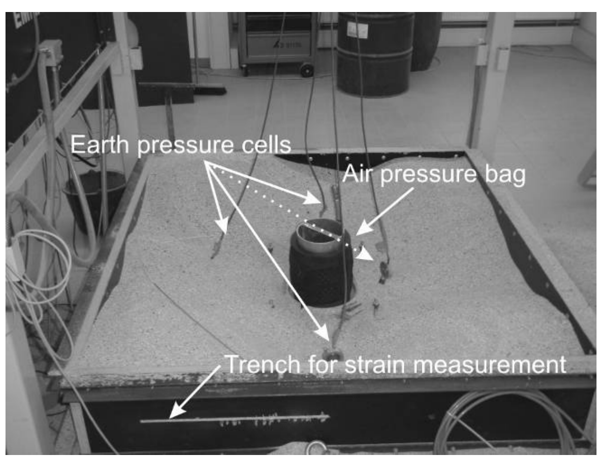


Figure 2: Radial load test (RLT) device

Radial load is applied over an air pressure bag with a diameter of 210 mm and a height of 300 mm which is placed in the centre of the test box (Chapter 3.3). Maximum static loads ranging up to 600 kN can be applied. Dynamic loads with varying frequency between 0.2 and 4 Hz and varying load amplitudes can be applied also. The air pressure bag is placed directly within a single geocell to simulate the horizontal static or dynamic traffic loads which are transferred to the geocells walls due to vertical loads.

3.2 Measurement Equipment

During each test the applied horizontal loads, the deformation of the geocell walls and the horizontal pressure in the surrounding soil are measured. The deformations of cell walls are measured by an electrical potentiometer which is placed outside the test box. The potentiometer is connected to the geocells by a wire. The wire is passed through a trench into the test box. The strains within the cell walls are back calculated from the measured deformation on basis of mathematical coherences. The horizontal pressure in the surrounding soil is measured by four earth pressure cells in distances of 10 cm, 20 cm, 30 cm and 40 cm to the air pressure bag (Figure 2). The earth pressure cells (EPC) have a diameter of 5 cm and a maximum pressure capacity of 500 kN/m². The electrical potentiometer and the earth pressure cells were calibrated in index tests. To minimize stress concentrations in front of the earth pressure cells, especially if large soil deformations occur, the pressure cells are installed in clamps which are connected by elastic plumes to the bottom of the test box.

3.3 Test Preparation

First of all the air pressure bag was placed in the centre of the test box. In case of a multiple geocell system the centre geocell of the structure was placed on the air bag as shown in figure 2.
After a strain wire was connected to the centre geocell, the wire was connected to an electrical potentiometer on the other side. Because the diameter of the self welded cells was slightly different between single tests, an initial load was applied on the air pressure bag to make sure that the geocells are in direct contact with the air pressure bag. For the tests with multiple, machine welded geocells an initial load was chosen to make sure that the opening angle at the connection points was approximately 90 degree in all tests. After the preparation of the geocells the earth pressure cells were installed in different distances to the load plate. To make sure that the distance between the earth pressure cells and the load device was the same in every test, the earth pressure cells were installed in mountings with were connected to the test box. After installation of earth pressure cells dry sand was poured into the tests box by hand in different layers and compacted by a tamper afterwards. The infill density was controlled by the infill weight of the sand and the volume of the test box. After the test preparation was finished the tests were started. Static tests were carried out deformation controlled until a failure of the tests samples was observed.

3.4 Test Program

Three different tests were carried out to evaluate the influence of the material stiffness, the soil confinement and the number of adjacent cells on the pressure-strain behaviour of geocells. Table 3 gives an overview over the tests which were carried out and the material which were used for those tests.

Table 3: test program and used geocell materials

test program:	type 1	type 2	type 3
influence of material stiffness	circular welded	circular welded	circular welded
influence of soil confinement	---	---	circular welded
influence of adjacent cells	9 and 25 cells machine welded	---	---

4. TEST RESULTS

Each single test was carried out at least three times to control the reproducibility of the test results. The tests results have shown an excellent reproducibility of the measured strains independent of the test parameters. The reproducibility of horizontal earth pressure which was measured in different distances to the air pressure bag was not as excellent as the strain measurement because of small differences during the preparation of the infill material. Nevertheless the reproducibility was quite well. Because of the good reproducibility the average values of three test results were taken for further analysis.

4.1 Influence of material stiffness and cell openings

To evaluate the pressure-strain behaviour of different geocell materials under horizontal loads, radial load tests were carried out on single circular and machine welded geocells without soil confinement. Figure 3 presents the results of circular welded geocell samples type 1, type 2 and type 3.
The results show an increase of the measured strains with decreasing material stiffness. For the same pressure the smallest strains were measured in the non perforated type 3 geocell while the largest strains were measured for the perforated type 1 geocells. It could be observed that at an applied load of 80 kN/m² the perforated type 1 geocell material began to creep and rupture takes place between the perforations. The non-perforated materials type 2 and type 3 did not show any kind of creep behaviour. An abrupt failure occurred for type 2 material at an applied pressure of about 140 kN/m² and for type 3 material at an applied pressure of about 180 kN/m². The observations made in the radial load tests could also be observed in tensile tests, which were carried out to determine the secant modulus of the materials. The calculated hoop strength on basis of the results of radial load tests were in good agreement with the strength which was measured in tensile tests.

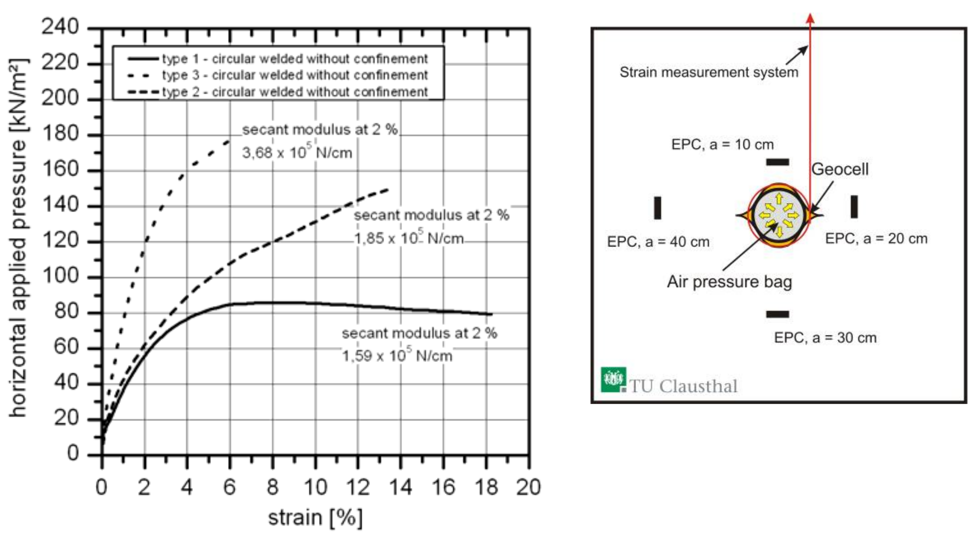


Figure 2: pressure-strain curves for different geocell materials without soil confinement

Same tests were also carried out with machine welded type 1 geocells to evaluate the influence of the geocell openings according to figure 1 on the measured strains. Figure 3 presents a comparison of the measured pressure-strain curves of machine welded and circular welded geocells. Due to the geocell openings at the same applied pressure the measured strains were significantly larger for the machine welded samples. This is because at the beginning of the test first of all the geocell openings of the machine welded geocells are opened. Because these deformations do not induce strains in the cell walls, the calculated strains of the machine welded samples had to be corrected on basis of the measured strains in circular welded test samples. Nevertheless the maximum horizontal pressure was nearly the same for both circular and machine welded samples.

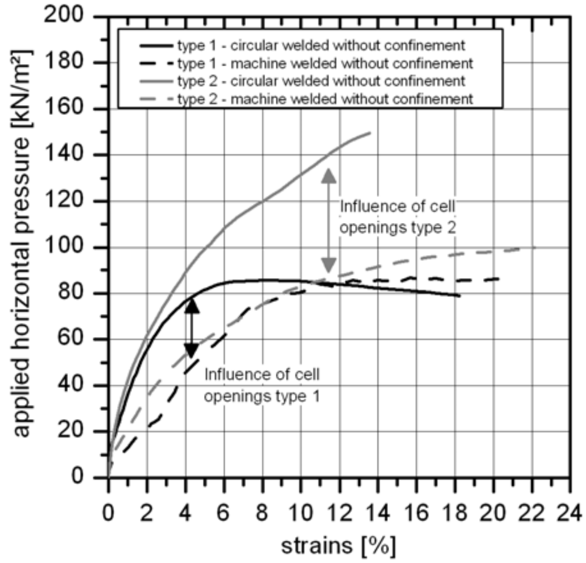
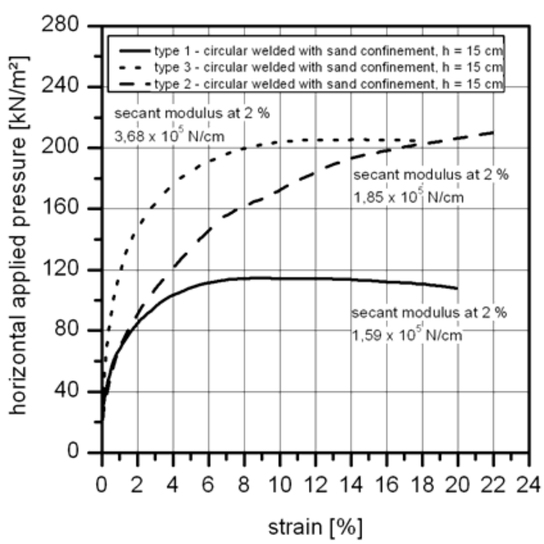


Figure 3: comparison between circular and machine welded geocells

To evaluate the influence of the sand confinement on the pressure-strain behaviour of the different geocell materials, radial load test were carried out on 15 cm height geocells confined by a 15 cm thick sand layer with relative infill density of 80 percent. The pressure-strain curves showed a similar trend to that of the unconfined tests (Figure 4). At the same applied pressure the smallest strains were measured for the type 3 geocells, while the type 1 geocells showed the largest strains. Compared to the results of unconfined tests, the applied pressures at the same strain level were about 40 kN/m² larger for all geocell materials. The pressure-strain curves of type 1 and type 2 geocell material was nearly similar up to strains of 2 percent. After that the geocell type 1 material began to creep and the soil could not give further confinement.



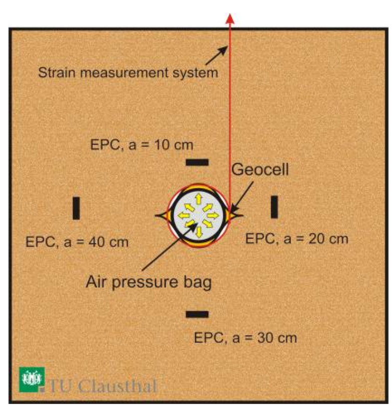


Figure 4: pressure-strain curves for different geocell materials with soil confinement

During the tests the horizontal pressure in the surrounding soil in different distances to the air pressure bag was measured by four earth pressure cells. The results have shown that at the same strain level the measured horizontal pressure at the same distance to the air pressure bag within the surrounding soil was nearly the same independent of the geocell material. That means that at the same strain-level the mobilized earth resistance in the surrounding soil is nearly the same for all materials. These observations were in good agreement which the earth pressure theory. In contrast, the measured horizontal pressures in the soil at the same applied horizontal pressure were different depending on the stiffness of the geocell material. Figure 5 shows the horizontal pressure distribution in the surrounding soil for different geocell materials at a applied pressure of 60 kN/m². The same trend was observed for other pressure levels.

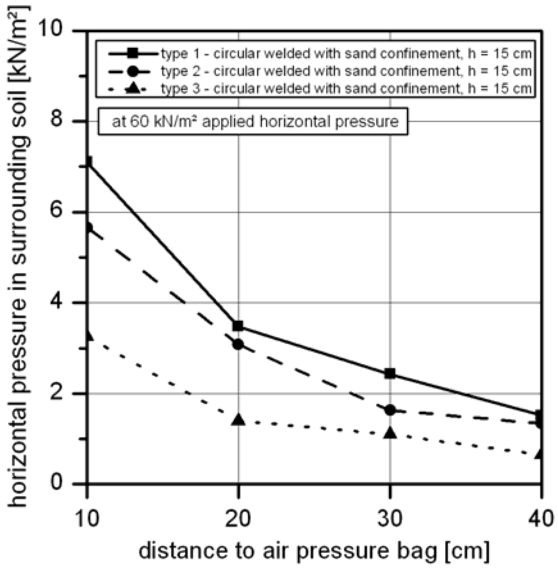


Figure 5: distribution of measured horizontal pressure in the surrounding soil
depending on the stiffness of the geocell material

The horizontal pressure decreases with increasing distance to the air pressure bag and increasing stiffness of the geocell material. The largest earth pressure was measured for the geocell type 1, the smallest horizontal pressure was measured for the type 3 geocell.

4.2 Influence of adjacent cells filled with sand

To evaluate the influence of the adjacent geocells on the pressure - strain behaviour radial load tests with geocells systems were carried out. The tested geocell structures consist of 9 and 25 single, interconnected cells. The results show that there is a large influence on the pressure strain behaviour due to the sand confinement of single cells (Figure 6). Due to the sand confinement of single cells the applied horizontal pressure increases about 30 kN/m² at strains of 8 percent, as explained earlier. The influence of adjacent cells on the pressure-strain behaviour is also large. Due to the installation of a geocell system which consist of nine interconnected single cells the pressure at strain-level of 8 percent was increased about 15 kN/m² compared to the tests on single geocell with sand confinement and about 45 kN/m² compared to the tests with single unconfined geocell. The installation of a geocell system which consists of 25 geocells leads to a further increase in pressure. At a strain level of 8 percent the increase of pressure compared to the unconfined single cell test was about 55 kN/m². A further increase of the numbers of interconnected cells leads only to a marginal increase in horizontal pressure.

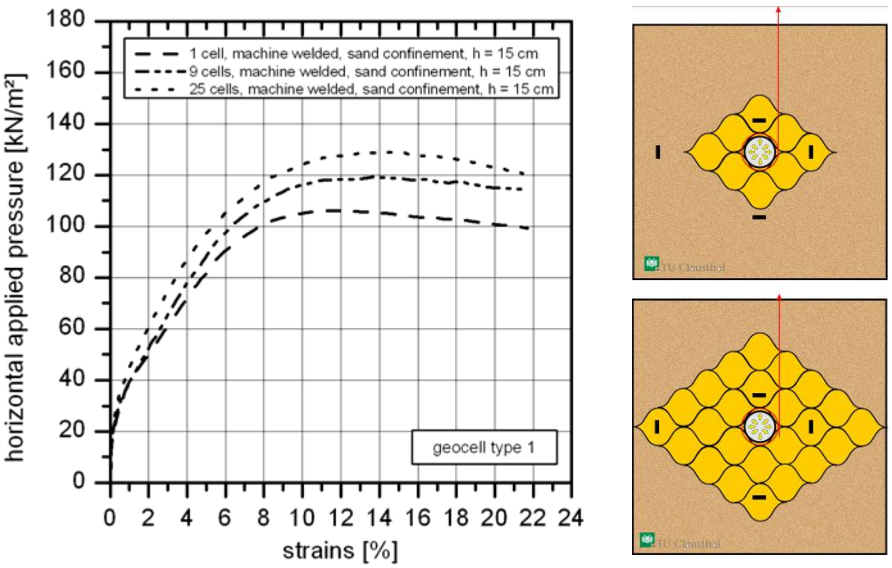


Figure 6: pressure-strain curves depending on the number of adjacent geocells

A comparison of the measured horizontal pressure in the surrounding soil during the tests is presented in figure 7. The results show that the measured pressure increases with increasing number of adjacent cells. The largest horizontal pressure was measured for the 25-geocells-system and the smallest pressure was measured for the single cells. Comparable to the single cell tests with sand confinement, the results show that the measured horizontal pressure decreases with increasing distance to the air pressure bag. The highest pressure was measured at distance of 10 cm form the air pressure bag, the smallest pressure was measured at a distance of 40 cm. In contrast to single cell tests the measured horizontal pressure at a special strain level was not the same for the different tests. For the same strain level as well as for the same pressure level the horizontal pressure increases with increasing number of adjacent cells. With increasing numbers of adjacent cells the applied horizontal pressure is distributed over a wider area of the surrounding soil.

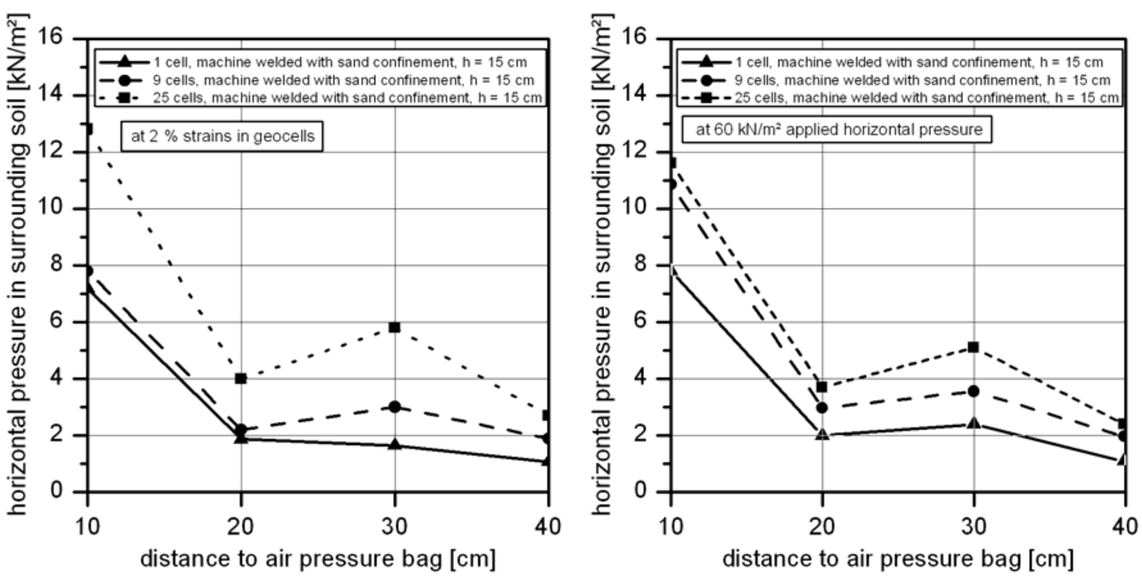


Figure 7: distribution of measured horizontal pressure in soil depending on the number of adjacent cells

There is a small difference between the horizontal pressure cell in a distance of 20 cm and the cell in a distance of 30 cm to the air pressure bag. The measured pressures in a distance of 30 cm to the air pressure bag are slightly higher than those measured at a distance of 20 cm to the air pressure bag. This effect can be explained by the geometry of the machine welded geocells. The seams of the geocells are oriented in the direction of the earth pressure cells at a distance of 20 cm to the air bag while the part of the cell wall without seams are oriented in the direction of the horizontal pressure cell at a distance of 30 cm to the air bag. Because of the seams the stress distribution in the sand layer is different and not radial symmetrical. More loads are transferred due to the cell walls compared to the seams.

5. SUMMARY

To evaluate the influence of the material stiffness, the soil confinement and the number of adjacent geocells on the pressure-strain behaviour of a dry sand, radial load tests were carried out in a test box with inside dimensions of 1.27 m (width) on (1.27 m) on 0.30 m (height). The results have shown that the pressure-strain behaviour increases with increasing stiffness of the geocell material as well as with increasing numbers of adjacent geocells. At the same pressure level the measured horizontal pressure within the surrounding soil was decreasing with increasing geocell stiffness. An increase in the number of adjacent geocells leads to an increase of the horizontal pressure. Compared to single geocells the horizontal applied load was distributed over a wider area in the surrounding soil. These results are in good agreement of vertical load tests which were carried out earlier (Emersleben and Meyer, 2008c)

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