Chapter 2

Literature review

2.1 Introduction

The objective of this chapter is to present a literature review on geocell reinforced soil. Research and subsequent literature on the subject is focussed on the behaviour of thin geocell reinforced mattresses, rather than more slender, unconfined support packs. Although the functioning of geocell reinforced support packs differs from that of mattresses, this research does provide valuable information on the subject of cellular reinforcement of soil and an important introduction to the understanding of the functioning of geocell reinforced support packs.

After providing an introduction to the types and common uses of geocell systems, reference is made to a few case studies of less common uses of these systems. This is followed by a discussion on the research performed by laboratory testing of geocell reinforced soil. To assist the reader in developing an appreciation of the diversity of the laboratory testing programmes, an overview of the experimental procedures and setups used by the researchers is given before the conclusions that can be drawn from these studies, are discussed.

This is followed by a discussion of the more fundamental studies, aimed at quantifying the reinforcing action of cellular reinforcement. These studies are discussed in more detail as they are directly related to the objective of the current study.

2.2 Geocell systems and applications

The development of the concept of the reinforcement of soil by cellular confinement is credited to the United States Army Corps of Engineers who developed the concept for the stabilisation of granular materials, such as beach sand, under vehicle loading.

This initial work performed at the U.S. Army Engineer Waterways Experimental Station led to the development of commercially available geocell systems. Two types of geocell systems are referred to in the literature. The first type consists of strips of polymer sheets welded together to form a mattress of interconnected cells (Figure 2.1). These geocell mattresses are generally manufactured with cell widths of between 75 mm and 250 mm and cell heights of the same order. This type of geocell system has mostly been used for the reinforcement of road bases and ballast track, slope protection, channel protection and retaining walls (Bathurst and Crowe, 1994).

Another type of geocell system referred to in literature consists of strips of geogrids connected to form three dimensional cells (Figure 2.2). The geocells formed in this manner are usually about 1 m wide and 1 m high. This type of geocell system has been used successfully in, amongst other things, reinforcing the foundations of embankments over soft soils and forming foundations of marine structures (Bush et al. 1990).

In the last couple of decades the use of geocell reinforcement of soil has seen new and technically challenging applications. Bathurst and Crowe (1994), for example, describe the use of polymer geocell confinement systems to construct flexible gravity structures and to construct facia of geosynthetic-reinforced soil retaining wall structures and steepened slopes (Figures 2.3 and 2.4).

Bush et al. (1990) describe the use of a geocell foundation mattress formed from polymer geogrid reinforcement to support embankments over soft ground. The results of the monitoring of a similar application are presented by Cowland and Wong (1993).

Bush et al. (1990) describe the construction of the geocell foundation mattress consisting of polymer geogrid reinforcement as follows: The contractor fills the cells with granular material, pushing forward his working platform on the cellular mattress which is strong enough to support fully laden stone delivery wagons and heavy earth moving plant for subsequent construction of the embankment. Distortion of the cells is avoided by filling two rows of cells to half their height before filling the first of the two to full height, always ensuring that no cell is filled to full height before its neighbour is at least half filled. The fill in the material is not compacted, except for normal construction traffic.

In the project described by Cowland and Wong (1993) the cells were filled with smaller than 25 mm angular shaped gravel. The geogrids that formed the cell walls, had 16 mm and 28 mm wide holes and interlocking of the gravel and geocells therefore took place, forming an internally reinforced structure.

2.3 Laboratory studies on geocell reinforcement

2.3.1 Laboratory studies on geocell mattresses

Several laboratory studies on the reinforcing effect of geocell mattresses have been performed over the last two to three decades. These studies were aimed at a wide variety of applications and the experimental procedures and setups differ considerably.

Table 2.1 provides a summary of the relevant literature discussed in this section.

Rea and Mitchell (1978) reported on laboratory tests to investigate the reinforcement of sand, using paper grid cells. Their study investigated the influence of the ratio of the diameter of the loading area to cell width, the ratio of cell width to cell height and the subgrade stiffness. A mattress of square paper grid cells with a membrane thickness of 0.2 mm and a cell height of 51 mm was filled with a uniform fine quartz sand at its maximum density of 16.8 kN/m^3. The sand had a mean particle size of 0.36 mm and a coefficient of uniformity (C_u) of 1.45. Failure of the reinforced soil was sudden and well-defined and in some cases the cells burst open from the bottom along glued junctions. Figure 2.5 shows a sketch of the test setup. Tests were performed with the loading centred on the junction (x-test) and with the load centred on the cell (o-test) (Figure 2.6).

Mhaiskar and Mandal (1992, 1996) investigated the efficiency of a geocell mattress over soft clay. The influence of the width and height of the geocells, the strength of the geocell membranes and the relative density of the fill material were investigated. Geocells of needle punched nonwoven and of woven slit film was used in the study. Mumbra sand with a minimum density of 16.05 kN/m^3, a maximum density of 18.1 kN/m^3 and a C_u of 4.6 were used as a fill material. Tests were performed with the fill at a relative density of 15% and at 80%. Figure 2.7 shows a schematic sketch of the experimental setup used by Mhaiskar and Mandal (1992).

Table 2.1 Summary of relevant literature.

Researchers	Geocell type	Application	Parameters investigated
Rea and Mitchell (1978)	Square paper grid		Ratio of load width to cell width, cell aspect ratio, subgrade stiffness
Mhaiskar and Mandal (1992, 1996)	Needle punched woven and nonwoven slit film	Geocell mattress over soft clay	Cell aspect ratio, strength of geocell membrane, density of fill
Bathurst and Crowe (1994)	Soil filled geocell columns	Flexible gravity wall structures and geocell reinforced soil facia	Shear strength of interface between geocell reinforced soil layers, uniaxial strength of columns
Krishnaswamy et al. (2000)	Diamond and chevron patterned geogrid geocells	Embankment on geocell reinforcement over soft clay	Effect of mattress reinforcement
Dash et al. (2001)	Geogrid geocells	Strip footing supported by sand bed reinforced with geocell mattress	Geocell pattern, mattress size and aspect ratio, depth of mattress, tensile strength of geogrids, density of sand
Dash et al. (2003)	Geogrid geocells	Circular footings on geocell reinforced sand over soft clay	Width and height of geocell mattress, and the addition of planar reinforcement layers and geogrids layer underneath geocell mattress.

Bathurst and Crowe (1994) performed uniaxial tests on geocell-sand composite columns and shear tests on the interface between geocell reinforced soil layers. This was done in order to obtain parameters for the design of a flexible gravity wall structure constructed with geocell reinforced soil and a geosynthetic reinforced retaining wall, with a geocell reinforced soil facia. The geocells were filled with a coarse sand with a C_u of 4.0, a D_{60} of 1.7 and a D_{10} of 0.42. Figure 2.10 and Figure 2.11 shows sketches of the test setup used by Bathurst and Crowe (1994).

Krishnaswamy et al. (2000) reported on the laboratory model tests of embankments on a geocell reinforced layer over soft clay (Figure 2.8). Diamond and chevron patterned geocells (Figure 2.9) made of uniaxial and biaxial geogrids were used to construct the embankment foundation over the soft clay. The geocells were filled with a clayey sand and clay. The embankment was loaded until failure occurred.

Dash et al. (2001) reported on laboratory tests of a strip footing supported by a sand bed reinforced with a geocell mattress (Figure 2.12). The parameters varied in this study included the pattern of the geocell formation, the size, the height and width of the geocell mattress, the depth to the top of the geocell mattress, the tensile stiffness of the geogrids used to form the cell walls and the relative density of the sand fill. The geocells were filled with a dry river sand with C_u of 2.32, a C_c of 1.03 and an effective particle size of 0.22 mm. The minimum and maximum dry unit mass were 1450 kg/m^3 and 1760 kg/m^3. The model footing tests were performed at relative densities of 30 to 70%.

In a subsequent study Dash et al. (2003) performed model studies on a circular footing supported on geocell reinforced sand underlain by soft clay (Figure 2.13). The width and height of the geocell reinforced mattress was varied in the study. The effect of the addition of a geogrids layer underneath the geocell mattress and the effect of planar reinforcement layers were also investigated. A soft natural silty clay with 60% fines passing the 75 μm sieve was used at the base of the test setup. The sand overlaying the clay was a poorly graded sand with a C_u of 2.22, a C_c of 1.05 and an effective particle size (D_{10}) of 0.36 mm. The density of the sand was kept constant at 1703 kg/m^3 corresponding to a relative density of 70%.

2.3.2 Published conclusions drawn from laboratory tests on geocell reinforced mattresses

Rea and Mitchell (1978) observed that the reinforcement resulted in a stiffening of the reinforced layer giving a raft like action to the layer. A raft like action of the geocell reinforced layer is also observed by Cowland and Wong (1993) for geocell reinforced layer under an embankment over soft clay. Other researchers mention the load spreading action of the reinforced layer and a subsequent reduction in the vertical stress in the layer underlying the geocell layer (Mhaiskar and Mandal, 1992; Bush et al., 1990). Dash et al. (2001) showed an increased performance on the footing over a buried geocell layer even with the geocell mattress width equal to the width of the footing. The geocell mattress transfers the footing load to a deeper depth through the geocell layer.

An increase in the bearing capacity of the geocell mattress with an increase in the ratio of cell height to cell width was observed by Rea and Mitchell (1978) and Mhaiskar and Mandal (1992). Dash et al. (2001) found that the load carrying capacity of the foundation bed increases with an increase in the cell height to diameter ratio, up to a ratio of 1.67, beyond which further improvements were marginal. The optimum ratio reported by Rea and Mitchell (1978) is around 2.25. Krishnaswamy et al. (2000) reported an optimum ratio of about 1 for geocell supported embankments constructed over soft clays. Dash et al. (2001) also noted that not only the aspect ratio of the cells but also the cell size (the cross sectional area of the cell compared to the loading area) had an influence on the performance of the geocell system. The increased load carrying capacity with decreasing pocket size is attributed to an overall increase in rigidity of the mattress and an increased confinement per unit volume of soil. A similar influence of the pocket size on the behaviour of the geocell reinforced soil was observed by Rajagopal et al. (1999) when performing triaxial tests on geocell reinforced soil samples. The research of Rajagopal et al. (1999) will be discussed in more detail in the next section.

Increased relative density of the soil increased the strength and stiffness of the reinforced soil (Mhaiskar and Mandal, 1992; Dash et al., 2001; Bathurst and Karpurapu, 1993). Dash et al. (2001) attributed this to an increase in the soil-cell wall friction with a subsequent increase in the resistance to downward penetration of the sand as well as a higher dilation resulting in higher strains in the geocell layer. Higher strains were mobilised in the geocell layers due to the dilation of the sand. It was noted that this only occurred after a settlement of 15% of the footing width. Dash et al. (2001) used a non-dimensional factor, called the bearing capacity improvement factor (I_f) to compare results from different tests. This influence factor was defined as the ratio of footing pressure with the geocell reinforced soil at a given settlement to the pressure on unreinforced soil at the same settlement. It was noted that I_f increased with increase in settlement at a more or less constant rate for soil at lower densities (D_r = 30 - 40%). However, for soil at higher densities, the rate of increase of I_f is higher for higher settlements (Figure 2.14).

Mhaiskar and Mandal (1992) concluded that geotextiles with a high modulus are desirable for use in geocells as they results in a stiffer and stronger composite. A similar response was found by Dash et al. (2001) and Krishnaswamy et al. (2000) and is also shown by the theory proposed by Bathurst and Karpurapu (1993) and Rajagopal et al. (1999), which is discussed later in the chapter. Dash et al. (2001) report an increase in load carrying capacity of the foundation bed when using a chevron pattern compared to a diamond pattern. They contribute this to a higher rigidity of the chevron-patterned geocell resulting from a larger number of joints for the same plan area of geocell. Krishnaswamy et al. (2000), however, concluded that in the reinforcement of an embankment over soft clay, the performance of the chevron and diamond patterned geocells were similar.

Dash et al. (2001) found an improvement in the load bearing capacity of the buried foundation mattresses with an increase in the mattress thickness, up to a geocell height of twice the width of the footing, beyond which the improvement is only marginal due to the local failure of the geocell wall taking place.

Rea and Mitchell (1978) interpreted the mechanism of reinforcement of the sand by the geocells in the following manner. Sand is confined and restricted against large lateral displacements until the tensile strength of the reinforcement is exceeded. The tension in the reinforcement gives a compression in the sand contained within the cell, giving increased strength and stiffness to the sand in the regions beyond the edges of the loaded area. This conclusion is supported by the work of Mhaiskar and Mandal (1992), who stated that their experimental results showed the hoop stress to be a significant factor contributing towards the strength increase in the reinforced layer.

Table 2.2 summarises the relevant conclusions that could be drawn from the literature.

Qualitatively speaking the influence of different parameters on the performance of geocell reinforced soil seem to be similar across the wide variety of applications and geocell geometries. Quantitatively speaking, however, the influence of each parameter is dependent on the specific geometry of the application. This highlights the need for a more fundamental understanding of the interaction between the geocell membrane and fill material.

Table 2.2 Summary of conclusions from literature.

Parameter	Effect of geocell reinforcement	References
Geocell reinforcement	Results in stiffening of reinforced layer	Rea and Mitchell (1978)
	Causes load spreading	Cowland and Wong (1993), Mhaiskar and Mandal (1992), Bush et al. (1990), Dash et al. (2001)
Cell aspect ratio (h/w)	Increased bearing capacity with increased h/w ratio	Rea and Mitchell (1978), Mhaiskar and Mandal (1992), Krishnaswamy et al. (2000), Dash et al. (2001)
Cell size	Smaller cell size - increased stiffness and load carrying capacity	Dash et al. (2001), Rajagopal et al. (1999)*
Relative density of soil	Increased relative density results in increased strength and stiffness of reinforced layer.	Mhaiskar and Mandal (1992), Dash et al. (2001), Bathurst and Karpurapu (1993)*
Membrane modulus	Higher modulus results in stiffer and stronger reinforced layer	Mhaiskar and Mandal (1992), Dash et al. (2001), Krishnaswamy et al. (2000), Bathurst and Karpurapu (1993)*, Rajagopal et al. (1999)*
Pattern	Chevron pattern leads to increased load carrying capacity compared to diamond pattern	Dash et al. (2001)
	Chevron and diamond pattern give similar response	Krishnaswamy et al. (2000)

* This research is discussed in Section 2.3.3.

2.3.3 Studies aimed at the understanding of the membrane-fill interaction

Table 2.3 provides a summary of the relevant literature discussed in this section.

The first study to investigate the strength increase in soil due to lateral confinement resulting from a membrane action was performed by Henkel and Gilbert (1952). This study was concerned with the effect of the rubber membrane on measured triaxial compressive strength of clay in undrained triaxial testing in order to investigate the magnitude and nature of the correction, which must be applied to obtain the true strength of the clay.

Table 2.3 Summary of relevant literature on studies regarding understanding of the membrane-fill interaction.

Researchers	Geocell type	Application	Parameters investigated
Henkel and Gilbert (1952)	Rubber membrane	Triaxial soil specimen	Membrane stiffness, deformation mode
Duncan and Seed (1967)	Rubber membrane	Triaxial soil specimen	Membrane stiffness
La Rochelle et al. (1988)	Rubber membrane	Triaxial soil specimen	Membrane stiffness
Bathurst and Karpurapu (1993)	Single geocell	Fundamental understanding	Confining stress, soil density, soil type
Rajagopal et al. (1999)	Woven and nonwoven geotextiles	Fundamental understanding	Membrane stiffness, number of cells

Henkel and Gilbert (1952) assume that in an undrained constant volume test, the sample deforms as a right cylinder under compression stresses. They proposed that under triaxial conditions buckling of the rubber membrane is unlikely and the rubber membrane may be assumed to act as a reinforcing compression shell outside the sample. As the Poisson's ratio of the clay under undrained conditions and that of the rubber is the same, no circumferential tension will be set up in the rubber provided that the sample deforms as a unit (Henkel and Gilbert, 1952). The component of the vertical stress of the test specimen due to the rubber is given by the following equation:

$$\sigma_r = \frac{\pi \cdot d_0 \cdot M \cdot \varepsilon_a \cdot (1-\varepsilon_a)}{A_0} \tag{2.1}$$

Where:

σ_r = The vertical stress component due to the membrane,

ε_a = The axial strain of the sample,

M = The compression modulus of the rubber membrane (force/unit length),

d_0 = The initial diameter of the sample,

A_0 = The initial cross sectional area of the sample.

However, under conditions where the membrane is not held firmly against the specimen and buckling takes place, a hoop tension will be induced in the rubber membrane as a result of the lateral strain of the specimen. The increase in the confining stress due to hoop stress in the rubber membrane is given by Henkel and Gilbert (1952):

$$\Delta\sigma_{3m} = \frac{2 \cdot M}{d_0} \cdot \left[\frac{1 - \sqrt{1 - \varepsilon_a}}{1 - \varepsilon_a} \right] \tag{2.2}$$

Where:

$\Delta\sigma_{3m}$ = The increase in the confining stress on the soil due to the hoop stress of the confining membrane,

ε_a = The axial strain of the sample,

M = The compression modulus of the rubber membrane (force/unit length),

d_0 = The initial diameter of the sample.

Duncan and Seed (1967) presented the following theoretical expressions for the estimation of the axial and lateral stress resulting from the compression shell action of the membrane around triaxial test specimens which undergo both axial and volumetric strain:

$$\Delta\sigma_a = -\frac{2E_m}{3} \cdot \left(1 + 2 \cdot \varepsilon_{at} - \sqrt{\frac{1 - \varepsilon_v}{1 - \varepsilon_{at}}} \right) \cdot \frac{A_{0m}}{A_{0s} \cdot (1 - \varepsilon_v)} \tag{2.3}$$

$$\Delta\sigma_{3m} = -\frac{2E_m}{3} \cdot \left(2 + \varepsilon_{at} - 2 \cdot \sqrt{\frac{1 - \varepsilon_v}{1 - \varepsilon_{at}}} \right) \cdot \frac{t_{0m}}{r_{0s} \cdot (1 - \varepsilon_v)} \tag{2.4}$$

Where:

$\Delta\sigma_a$, $\Delta\sigma_{3m}$ = Correction to axial and lateral stress,

E_m = The Young's modulus of the membrane,

A_{0m}, A_{0s} = The initial cross-sectional area of the membrane and the sample,

t_{0m} = The initial thickness of the membrane,

r_{0s} = The initial radius of the sample,

ε_{at} = Axial strain due to consolidation and/or undrained deformation,

ε_v = Volumetric strain.

The effect of the membrane on the strength of triaxial test specimens was also investigated by La Rochelle et al. (1988) who performed tests on dummy specimens in order to measure the confining stress resulting from the membrane. They suggested that the membrane applies an initial confining stress due to a small amount of stretching it undergoes as it is placed around the triaxial specimen. Two series of tests were performed. The first consisted of membranes mounted on specimens and air pressure used to inflate the membranes. The second series of tests consisted of triaxial tests on rubber specimens sleeved with rubber membranes. On the grounds of the first series of tests, they proposed the following empirical equation for the confining stress caused by the membrane as a function of the axial strain of the membrane:

$$\Delta\sigma_{3m} = \sigma_{3m0} + 0.75 \cdot \frac{M \cdot \sqrt{\varepsilon_a}}{d_0} \tag{2.5}$$

Where:

$\Delta\sigma_{3m}$ = The increase in the confining stress on the soil due to the membrane action,

σ_{3m0} = The initial confining stress caused by the membrane at placement around the specimen,

ε_a = The axial strain of the sample,

M = The compression modulus of the rubber membrane (force/unit length),

d_0 = The initial diameter of the sample.

From this formula it can be seen that with axial straining, there is an initial contact pressure followed by an initial rapid increase in the contact pressure at small axial strains. This initial rapid increase in the confining stress at small strain is in complete disagreement with the work of both Henkel and Gilbert (1952) and Duncan and Seed (1967). La Rochelle et al. (1988) attribute the difference between their proposal and Henkel and Gilbert's work to the fact that the "hoop stress" theory ignores the variation in the extension modulus of the membrane with strain and "possibly to some other unknown factors". For the rubber membranes tested there is only a moderate variation in the stiffness which cannot account for the significant difference between this theory and those presented by Henkel and Gilbert (1952) and Duncan and Seed (1967) and it is questionable that the significant difference can be contributed to "some other unknown factor".

In 1993, Bathurst and Karpurapu reported on large-scale triaxial compression tests on unreinforced and geocell reinforced granular soil, performed in order to quantify the influence of the geocell membranes. Tests were performed on 200 mm high, 200 mm diameter specimens. Uniformly graded silica sand and crushed limestone aggregate were used in these tests.

The reinforced specimens showed a greater shear strength and axial stiffness as well as greater strain hardening response, compared to the unreinforced specimens. They report that the dilation of the reinforced specimens was noticeably suppressed by the membranes. Bathurst and Karpurapu (1993) suggest that, at large strains, the effect of soil confinement by the geocell wall is to maintain the infill soil in a plastic state while increasing resistance to the vertical deformation due to circumferential expansion of the geocell wall. Some of the test specimens failed at large strains after rupturing of the welded seam occurred.

In the development of a theory to quantify the strength of the geocell-soil composite, Bathurst and Karpurapu (1993) use the "hoop stress" theory developed by Henkel and Gilbert (1952) previously referred to.

The model presented by Bathurst and Karpurapu (1993) to relate the geocell-soil composite Mohr-Coulomb strength envelope to the cohesionless soil infill is shown in Figure 2.15. The effect of the membranes is quantified in terms of an apparent cohesion (c_r), given by:

$$c_r = \frac{\Delta\sigma_3}{2} \cdot \tan\left(45^\circ + \frac{\phi'}{2}\right) \tag{2.6}$$

Where:

c_r = An equivalent cohesion describing the strength increase of the soil due to the hoop stress action of the confining membrane,

$\Delta\sigma_3$ = The increase in the confining stress on the soil given in Equation (2.2),

ϕ' = The internal angle of friction of the sand.

Bathurst and Karpurapu (1993) believed that interaction between connected geocell units in the field will occur and that this will further increase the stiffness and strength of the geocell-soil composite.

Rajagopal et al. (1999) studied the influence of geocell confinement on the strength and stiffness behaviour of granular soils by performing triaxial tests on single and multiple geocells fabricated by hand from woven and nonwoven geotextiles. The geometries of the test cells are shown in Figure 2.16 and Figure 2.17. It was observed that the geocell reinforcement had a considerable effect on the apparent cohesion and the stiffness of the geocell reinforced samples.

Failure of both the single and multiple geocells were observed to be by bursting of the seams at the mid-height of the samples. In the case of samples with multiple geocells, the bursting started from the seams of the outer cells and slowly propagated towards the inner cells. The seams of the outer cells showed clear ruptures while the seams of the inner cells were damaged to a lesser extent.

Reinforced samples exhibited a friction angle similar to that of unreinforced samples, but showed an increase in the apparent cohesion. Samples with stiffer geocells developed higher cohesive strengths.

They found that the value of the apparent cohesion and the stiffness increased with an increase in the number of cells in their tests. No significant difference was, however, observed between 3 and 4 cell tests, and the conclusion was made that the strength of three interconnected cells may represent the mechanism of geocells having a large number of interconnected cells.

Rajagopal et al. (1999) proposed that the increase in the cohesion of the reinforced soil is due to the confining stresses generated in the soil, caused by the membrane stresses in the walls of the geocells. Similar to Bathurst and Karpurapu (1993), the authors proposed the use of the "hoop stress" theory to calculate the apparent cohesion for the geocell-soil composite using Equations (2.2) and (2.6).

A critical examination of the results of the more fundamental research on the contribution of the membranes on the strength of geocell systems and the interaction of the membranes and soil presented above, reveals the following:

Two important assumptions have been made by Henkel and Gilbert (1952) in the derivation of their "hoop stress" theory. These assumptions being that the volume of the soil remains constant and that the soil specimen deforms as a right cylinder. The first assumption is acceptable for undrained triaxial tests for which the theory was originally proposed. The second assumption seems to be acceptable for the purpose of estimating the influence on the membranes on the tested strength of clay triaxial test specimens. Having said this, it is interesting to note that according to their data, the "hoop stress" theory underestimate the confining stress caused by the straining of the membrane. This may be attributed to the fact that the bulging of the sample is not accounted for, with a subsequent underestimation of the membrane strain, and therefore membrane stress, in the middle portion of the specimen.

This is also the case for the theories proposed by Bathurst and Karpurapu (1993) and Rajagopal et al. (1999), being largely based on the "hoop stress" theory of Henkel and Gilbert. In addition, the constant volume assumption is not applicable to undrained shearing of granular material. This fact is ignored by the proposed theories. A critical examination of the data presented by Bathurst and Karpurapu (1993) shows that their proposed theory underestimates the apparent cohesion by 18% for medium dense sand specimens and overestimates the apparent cohesion by 12% for loose sand specimens. Bathurst and Karpurapu (1993) proposed that the underestimation of the apparent cohesion for the dense specimens might be due to frictional resistance between the soil and geocell wall materials, which is not accounted for in the membrane model.

However, coupled with the fact that the apparent cohesion for the loose specimen was overestimated, this could more likely be attributed to the volume change in the soil. For dense soil the volume will increase upon shearing, resulting in a greater confining stress generated by the membrane than that predicted for a constant volume material. Very loose sand, as was used in the study by Bathurst and Karpurapu (1993), will contract upon shearing, resulting in a lower confining stress generated by the membrane than that predicted for a constant volume material.

The theories presented by Bathurst and Karpurapu (1993) and Rajagopal et al. (1999) are aimed at predicting the ultimate strength of the geocell-soil composite structures. Although the researchers mention the increase in the stiffness of the composite structure compared to the unreinforced soil, no attempt was made to quantify the influence of the membrane, other than its influence on the peak strength.

Rajagopal et al. (1999) also concluded that a configuration of three interconnected cells may represent the mechanism of geocells having a large number of interconnected cells and recommend that for experimental purposes, a test configuration with at least three interconnected cells should be used to simulate the performance of soil encased by many interconnected cells.

They base their conclusion on the fact that the strength increase between the three-cell and four-cell tests is marginal compared to the increase in the strength between the single and the two-cell and the two- and three-cell tests.

Referring to Figure 2.16 it can be seen that the two-cell setup used by Rajagopal et al. (1999) were only connected at a single line and the two cells therefore effectively acted independently. The difference between the single and two-cell tests can therefore be attributed to the difference in the cell sizes and the volume of soil not encased by the geocells, rather than the interaction of the two 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.

2.4 Conclusions drawn from the literature review

Although the research that has been performed on geocell reinforced soil encompass a wide variety of geometries and loading mechanisms, there seems to be consensus on several issues from which the following qualitative conclusions can be drawn:

- A geocell reinforced soil composite is stronger and stiffer than the equivalent soil without the geocell reinforcement.
- The strength of the geocell-soil composite seem to increase due to the soil being confined by the membranes. The tension in the membranes of the geocells gives rise to a compression stress in the soil, resulting in an increased strength and stiffness behaviour of the composite.
- The strengthening and stiffening effect of the cellular reinforcement increases with a decrease in the cell sizes and with a decrease in the width to height ratio of the cells. The optimum width to height ratio of the cells seems to be dependent on the specific geometry of the geocell system used in an application.
- The effectiveness of the geocell reinforcement increase with an increase in the density for a particular soil.
- The strength and stiffness of the geocell reinforced composite increase with an increase in the stiffness of the geocell membranes.

However, little attention has been given to the understanding of the interaction of the soil and the membranes, and the constitutive behaviour of the geocell-soil composite as a function of the constitutive behaviour of the soil and the membranes.

Current theories for the prediction of geocell-soil composite structures are aimed at predicting only the ultimate shear strength of the composite structure. These theories ignore the deformation profile of the structure and the volume change of the soil resulting in an underestimation of the strength for soil at high densities and an over prediction for soil at low densities.

Little attention in literature has been given to the influence of the interaction of multiple cells on the behaviour of the geocell-soil composite structure. The conclusion made by Rajagopal et al. (1999) that the behaviour of a four cell assembly is representative of a geocell/soil structure consisting of a larger number of cells is questionable and the issue, therefore, needs further attention.

2.5 Specific issues addressed in the thesis

This study aims to investigate the peak, as well as the pre-peak behaviour of geocell-soil composite structures to further the understanding of the constitutive behaviour of geocell-soil composite structures.

In order to achieve this goal, the constitutive behaviour of the fill and membrane material and the composite structures are investigated. Models are developed to describe the behaviour of the fill and membrane materials for the purpose of facilitating the understanding of the interaction of the components of the geocell-soil composite.

In the investigation of the constitutive behaviour of the geocell-fill composite, consideration is first given to the behaviour of a single geocell composite structure after which the insights gained, are applied to multiple geocell structures. Due consideration is given to the volumetric behaviour of the fill and the non-uniform straining of the composite. This work advances the state of the art by addressing some of the shortcomings of the theories of Bathurst and Karpurapu (1993) and Rajagopal et al. (1999).

A calculation procedure is developed to enable the calculation of the stress strain curve of a single cell geocell-soil structure, which facilitates the understanding of the interaction between the constituting components of the composite. This procedure incorporates the developed material models. This work for the first time presents a method for estimating the stress-strain behaviour of a granular soil reinforced by a single geocell.

Interaction between connected geocell units influences the behaviour of the composite structure. As part of this study, the influence of the cell interaction is investigated and, for the first time, a rational method for evaluating and quantifying the influence of the interconnection of geocells on the performance of the composite structure, developed.

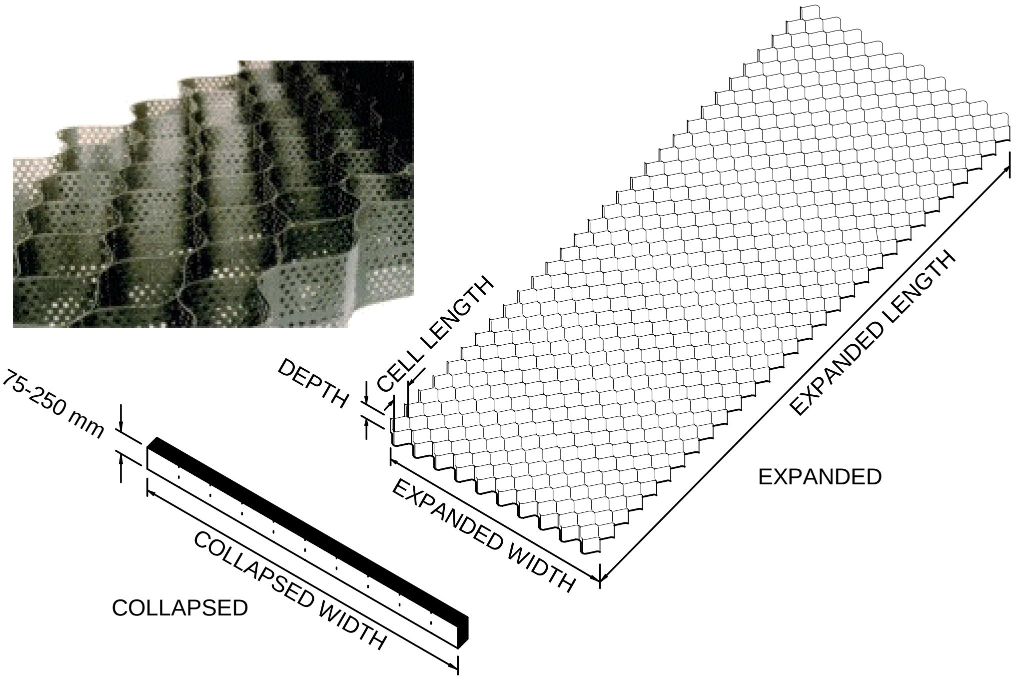
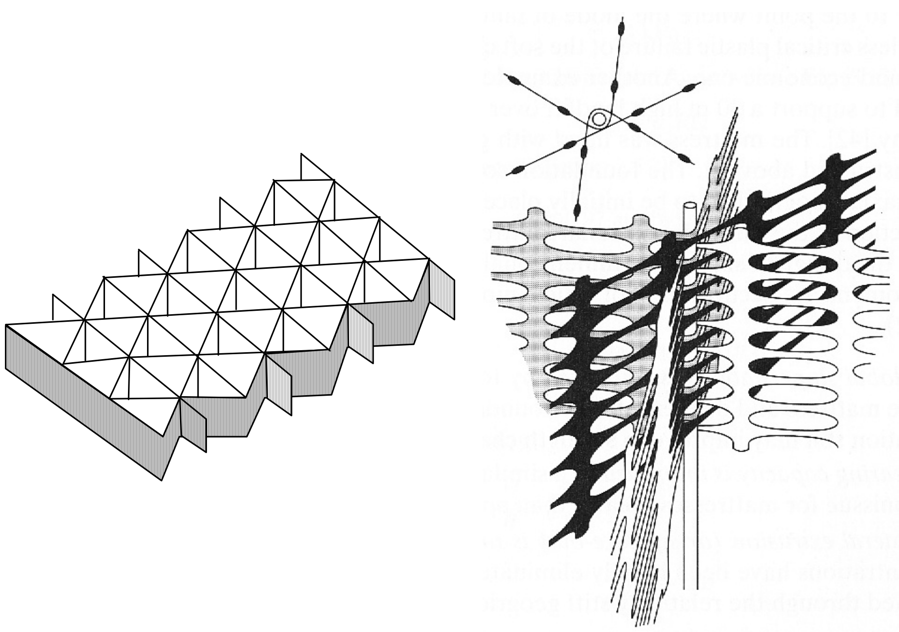


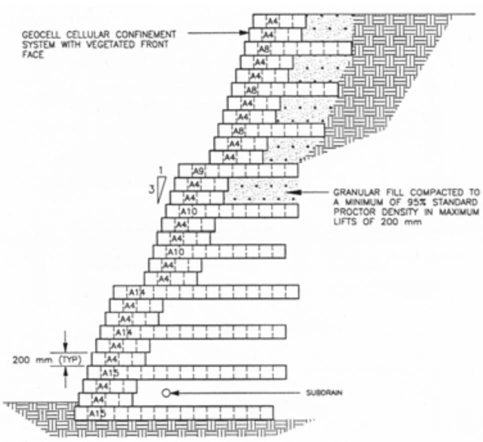
Figure 2.1 *Geocell system manufactured from strips of polymer sheets welded together.*



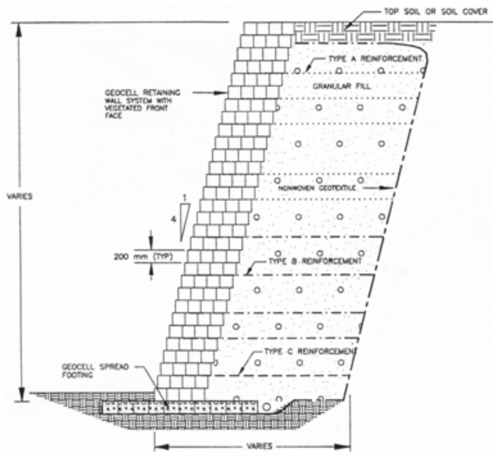
a) Typical mattress layout b) Coupling of geogrids

Figure 2.2 *Geocell system constructed from geogrids (Koerner, 1997).*

Figure 2.3 *Geocell applications in retaining structures (with courtesy from Geoweb cellular confinement systems).*



a) Geocell gravity retaining wall structure



b) Geosynthetic reinforced soil wall with geocell facia system

Figure 2.4 *Cross section through geocell retaining structures (Bathurst and Crow, 1994).*

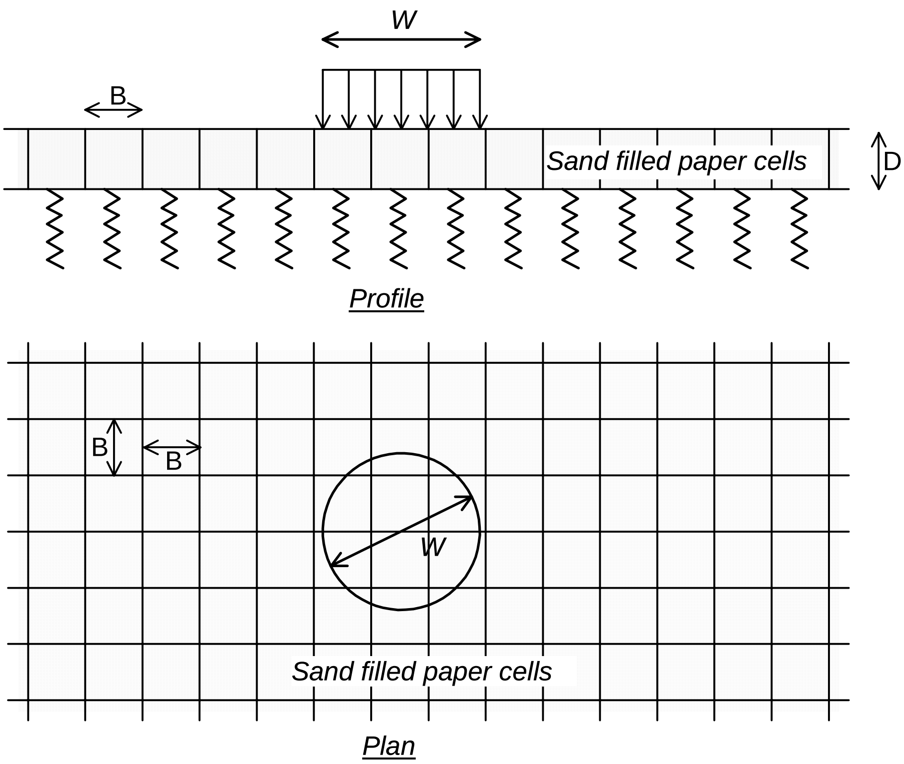


Figure 2.5 Schematic diagram of the test configuration used by Rea and Mitchell (1978).

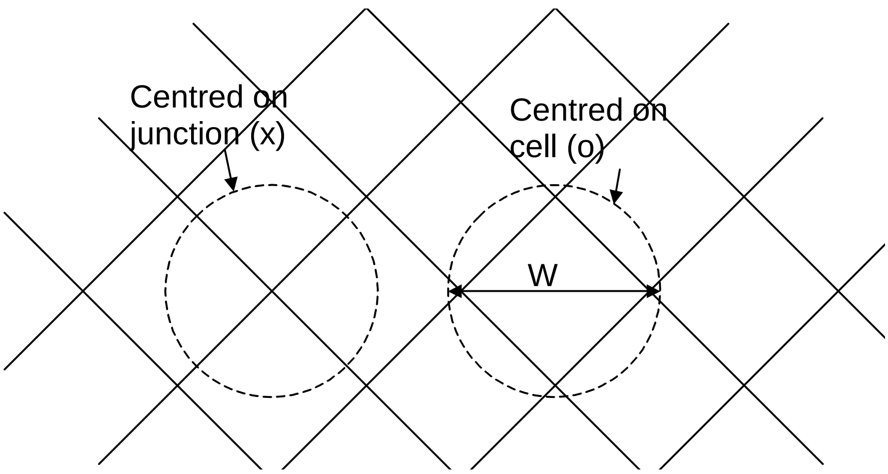


Figure 2.6 Position of the load plate in type "x"- and type "o"- tests performed by Rea and Mitchell (1978).

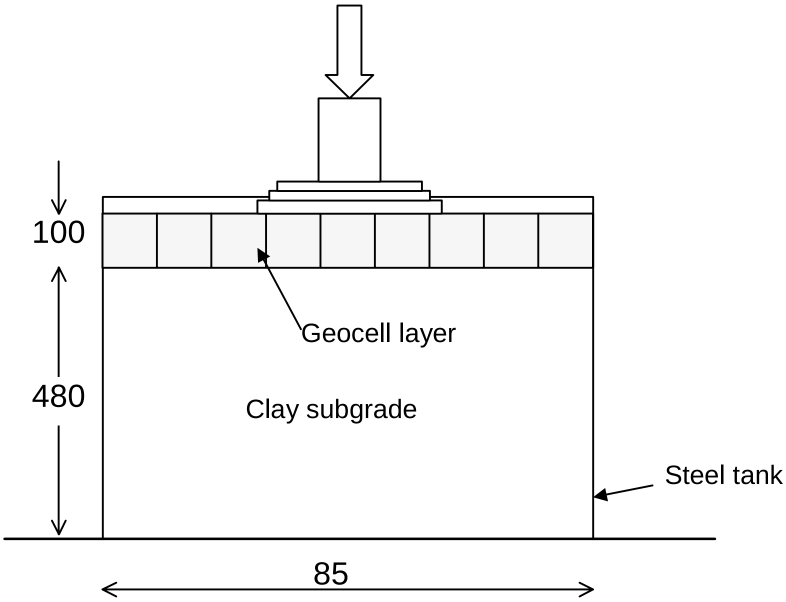


Figure 2.7 *A schematic sketch of the experimental setup used by Mhaiskar and Mandal (1992).*

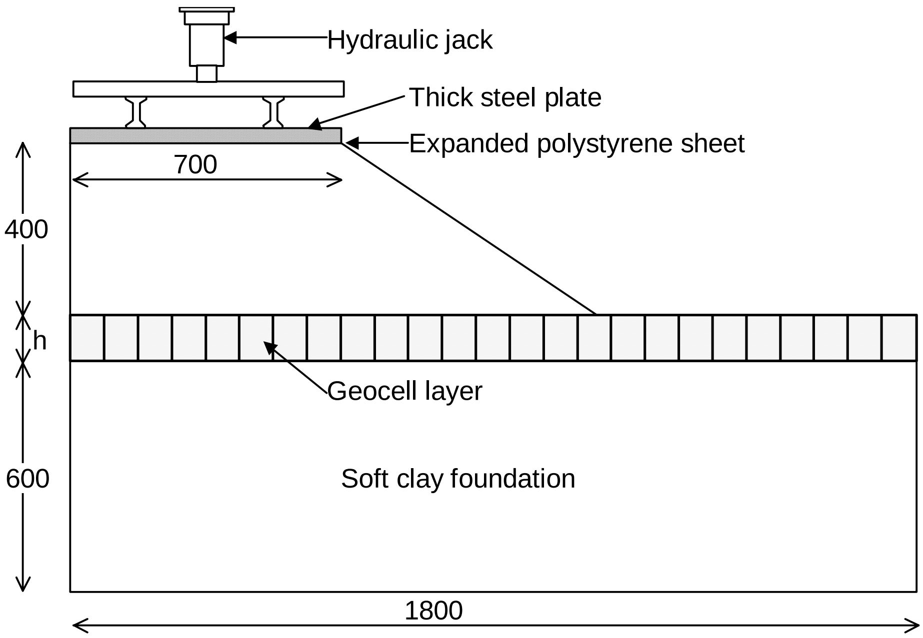


Figure 2.8 *A schematic sketch experimental setup used by Krishnaswamy et al. (2000).*

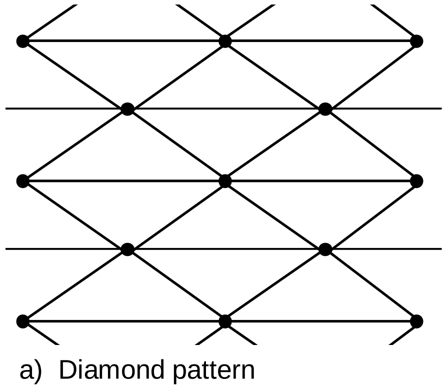


Figure 2.9 *Patterns used in geocells constructed with geogrids.*

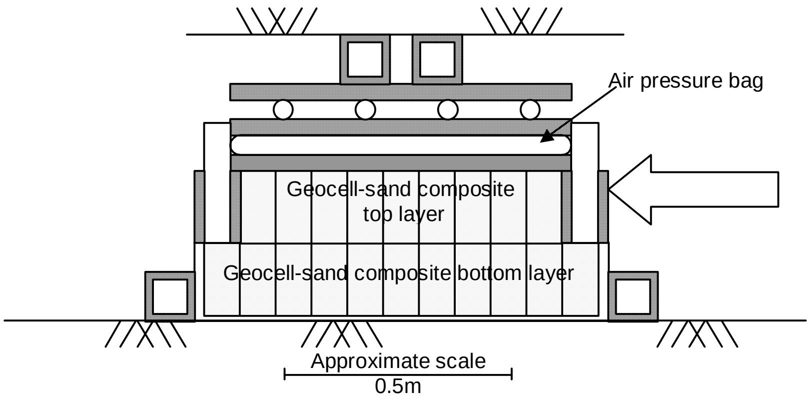


Figure 2.10 *A schematic sketch the experimental setup used by Bathurst and Crowe (1994) for shear strength testing of interface between geocell reinforced layers.*

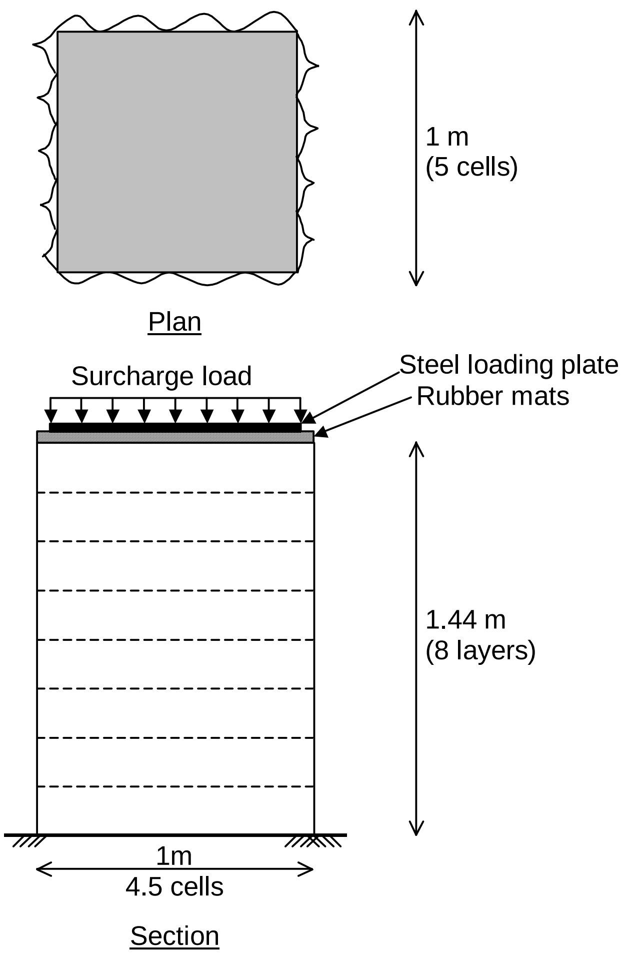


Figure 2.11 *A schematic sketch of the experimental setup used by Bathurst and Crowe (1994) for uniaxial strength of a column of geocell reinforced layers.*

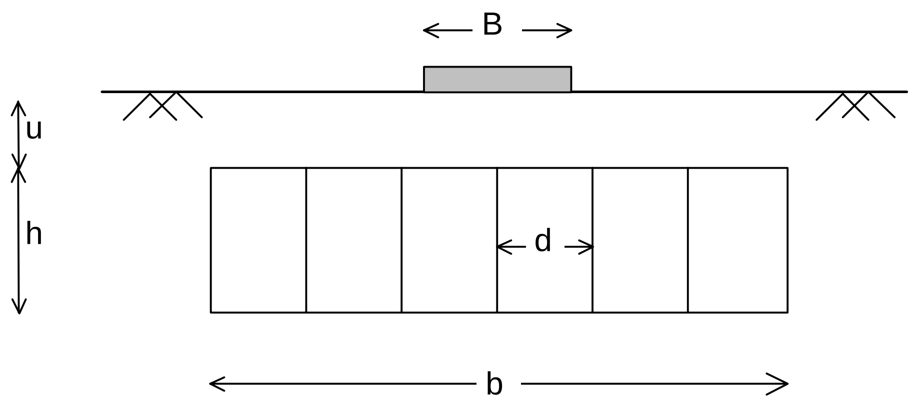


Figure 2.12 *A schematic sketch of the experimental setup used by Dash et al. (2001).*

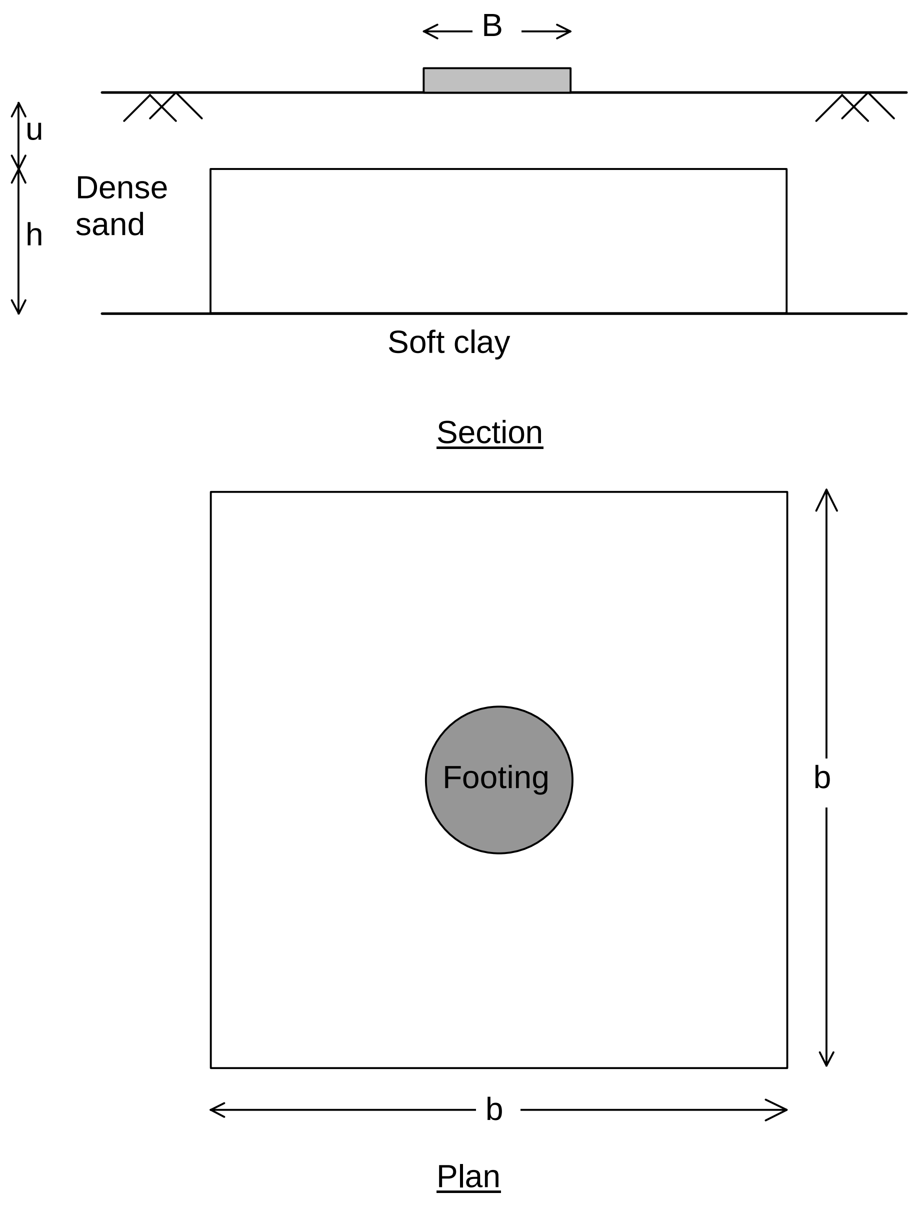


Figure 2.13 A schematic sketch of the experimental setup used by Dash et al. (2003).

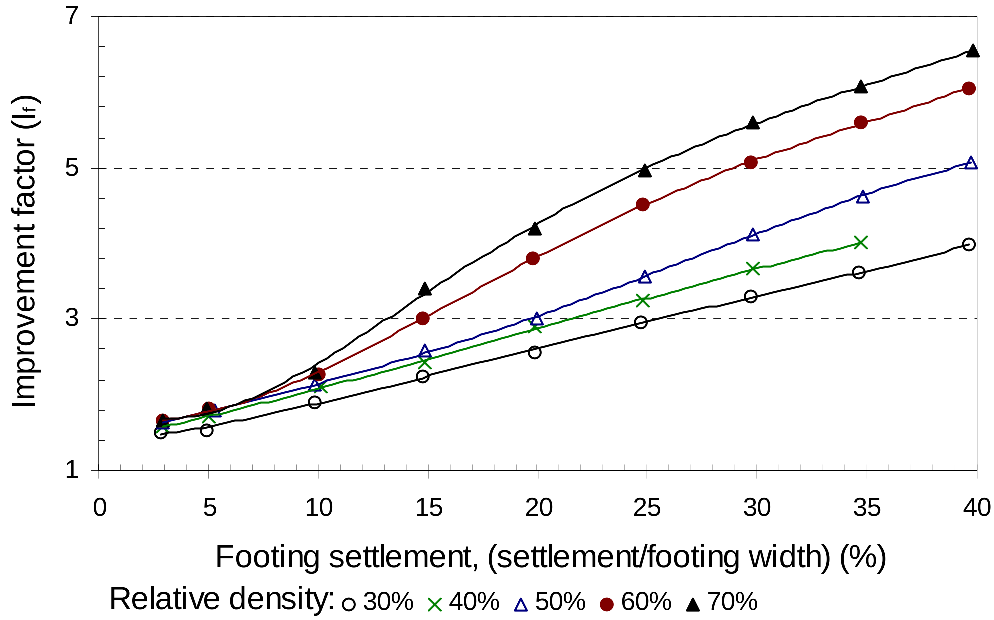


Figure 2.14 *Change of the Improvement factor (I_f) with a change in the relative density of the soil (based on Dash et al. 2001).*

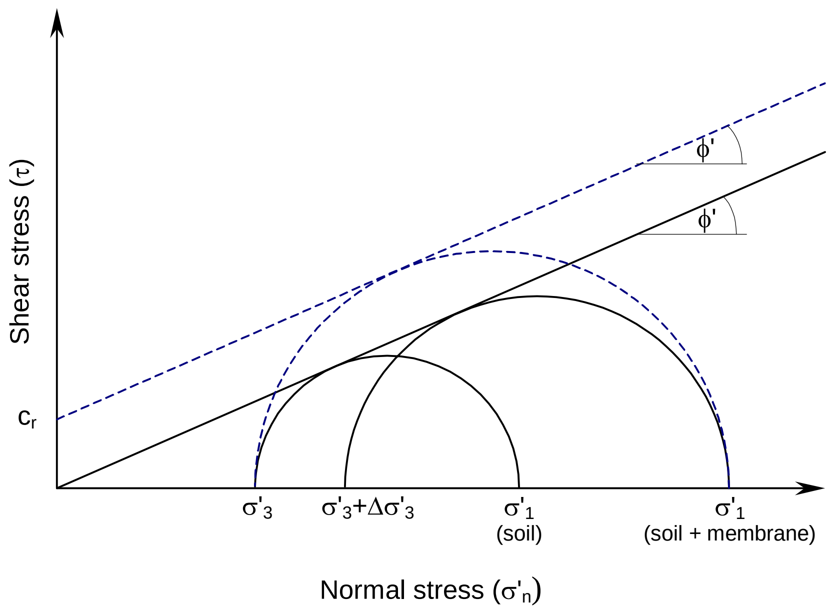


Figure 2.15 *Mohr-Coulomb construction for calculation of equivalent cohesion for geocell-soil composites (Bathurst and Karpurapu (1993)).*

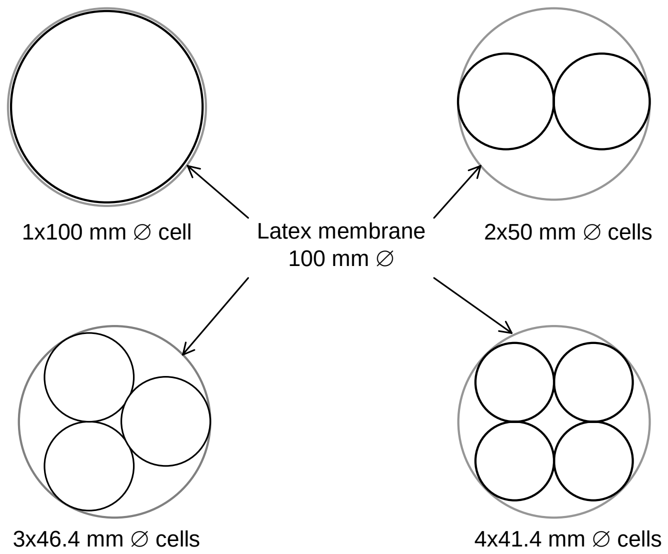


Figure 2.16 Different configuration of cells used in triaxial tests performed by Rajagopal et al. (1999).

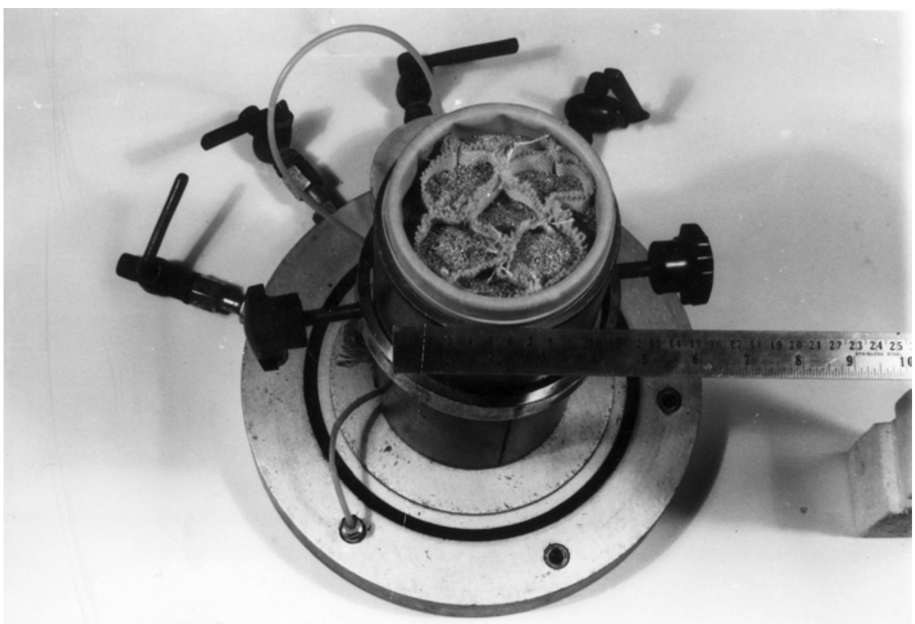


Figure 2.17 Triaxial test sample with four interconnected cells tested by Rajagopal et al. (1999).