# INFLUENCE OF TRANSVERSE ELEMENTS ON THE PULLOUT CAPACITY OF METAL STRIP REINFORCEMENT IN SANDY SOIL

**By**

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## DECLARATIONS

I declare that this thesis is the results of my own research, that is does not incorporate without acknowledgment any material submitted for a degree or diploma in any university and does not contain any material previously published, written or produced by another person except where due reference is made in the text.

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Date:

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$PRs$= Pull out capacity of skin friction in reinforcement

$PRB$= Pull out capacity of transverse ribs in reinforcement

$\alpha s =$ Fraction of reinforcement surface which is solid

$LR =$ Length of specimen

$\sigma n$ = Normal stress

$\delta$= Interface friction angle

$S$= Distance between transverse members

$\alpha\beta$= Fraction of total frontal area of reinforcement available for bearing

$h$= Depth of anchorage element

n = Count of anchorage element

$\sigma b$ = Passive bearing of transverse member in soil

$fb$= Pull out interaction of soil-reinforcement

$\emptyset$= Friction angle of soil

$Nt = \left(\frac{LR}{S}\right)$ = Length divided to distance of transverse member

$Ntb$= node number in transverse elements

$Ab$ = area of each rib element (single node and bar between two nodes)

$Nq$ = Bearing resistance factor for transverse members

$F_1$="Ultimate frictional of all longitudinal ribs"

$F_2$="Ultimate frictional resistance of all transverse ribs"

$F_3$="ultimate bearing resistance of all transverse ribs"

$A_l$=surface of longitudinal members

$A_t$=surface of transverse ribs

$A_b$=bearing surface of ribs

$f$=Pull out resistance factor

$\alpha$=correction coefficient of nonlinear shear stress distribution on reinforcement

$(\alpha = 1\ for\ metal\ srip)$

$\boldsymbol{\sigma n}$ = Vertical normal stress

$\boldsymbol{Le}$=Effective length of strip

$\boldsymbol{B}$= Wight of strip

$\boldsymbol{C}$=Effective unite of perimeter on strip

$\boldsymbol{f = \text{adherence coefficient of soil} - \text{geogrid}}$

$\boldsymbol{\alpha = \text{scale correction factor}}$

e = thickness of transverse rib

s =transverse ribs spacing

$\alpha s$=ratio between the plane area of geogrids (transverse and longitudinal)

$\alpha p$ =" Ratio between transverse element where in passive resistance is fully moved and corresponding total era"

$\frac{\emptyset s}{GGR}$ = soil-geogrids friction angle

M = Mass

L = length

T = time

$\tau max = maximum\ shearing\ force$

$\sigma n = normal\ stress$

$D_{10}$ = Particle diameter soil size that 10 % passing

$D_{30}$ = Particle diameter soil size that 30 % passing

$D_{50}$ = Particle diameter soil size that 50 % passing

$D_{60}$ = Particle diameter soil size that 60 % passing

$G_S$ = Specific gravity

$e_{min}$ = Minimum void ratio

$e_{max}$ = Maximum void ratio

USCS Classification = unified soil classification system

$\gamma_d$ = Maximum Dry Unit Weight

w = Optimum moisture content

$C_u$ = Coefficient of Uniformity

$C_c$ = Coefficient of Curvature

$\phi$ = Angle of Friction

$D_r$ = Relative density of soil

$\Psi$ = Dilatancy angle of soil

**KAJIAN KESAN UNSUR SAUH KEATAS KEKUATAN TARIK KELUAR JALUR TETULANG DALAM PASIR**

## ABSTRAK

Sudut ricih permukaan di antara dua jenis bahan suatu parameter yang sangat penting dalam rekabentuk tanah terstabil mekanikal (MSE) kerana ianya berkait terus dengan keupayaan rintangan tarik keluar jalur pengukuh. Dalam penyelidikan ini, anggota sauh telah ditambah keatas jalur pengukuh bagi meningkatkan sudut ricih permukaan dan keupayaan rintangan tarik keluar. Pasir digunakan sebagai bahan isi. Dalam ujian yang dijalankan, satu jalur licin, dua jalur dengan rasuk mudah, dan lapan belas jalur beranggota melintang dengan berbagai kedalaman dan bilangan telah dikenakan beban tarik keluar dengan tegasan pugak berjulat 50 kPa hingga 100 kPa. Teorem π-Buchingham dan analisis regresi menggunakan perisian statistik – SPSS v.14 – telah juga digunakan bagi menentukan persamaan am yang mengaitkan antara keupayaan rintangan tarik keluar dengan parameter jalur, dan membandingkan diantara kekuatan anggaran dengan keputusan sebenar ujian. Hasil kajian mendapati bahawa kaedah baru melibatkan anggota sauh boleh memberi penjimatan penggunaan jalur atau rekabentuk MSE tertentu yang sesuai digunakan bagi ruangan sempit, lantaran peningkatan rintangan tarik keluar bagi setiap jalur boleh mengurangkan panjang keseluruhan atau jumlah bahan yang diperlukan dalam setiap projek. Dalam kajian ini juga, radas ujian rich terus telah digunakan bagi menentukan rintangan ricih permukaan diantara sampel pamsir tergred baik dengan

plat keluli tergalvani. Akhir sekali, pemodelan unsur terhingga telah dijalankan bagi melengkapkan analisis. Keputusan ujian tarik keluar yang digabungkan dengan keputusan pemodelan didapati sangat berguna bagi jurutera menentukan rekabentuk terbaik struktur tanah terkukuh.

**INFLUENCE OF TRANSVERSE ELEMENTS ON THE PULLOUT CAPACITY OF METAL STRIP REINFORCEMENT IN SANDY SOIL**

## ABSTRACT

Interface friction angle between different materials is a very important parameter in the designs of mechanically stabilized earth (MSE) as it corresponds directly to pull out capacity of a reinforcement strip. In this research, anchorage elements have been added to normal reinforcement strip in order to increase interface friction angle and thus the pull out capacity. Sand was used as fill material. In the tests, one plain strip with smooth surface, two strips with simple ribs, and eighteen strips with transverse members of various depths and counts were subjected to pull out forces with normal stresses ranging from 50 kPa to 100 kPa applied. Also, π-Buchingham theorem and regression analysis using statistical software - SPSS v.14 - were used to obtain general equations relating pull out capacity to strip parameters and compare predicted strength values to actual outcomes of the tests. The results of the study indicate that the new method involving transverse members could generally offer saving of strip material or provide particular design criteria for MSE of limited construction space, since the increased capacity of each reinforcement strip would reduce the total length or amount of strips required in a project. Also in this research, direct shear apparatus used for soil testing was employed to measure the interface

shear resistance between well graded sand samples and galvanized steel plates. Finally, finite element computer modelling with Plaxis V 8.2 software was carried out to complete the analyses. The results from pull out tests combined with results from the modelling were found to be very useful for engineers to design better reinforced earth structures.

# CHAPTER 1
# INTRODUCTION

## 1.1 Introduction

Since the first installation of MSE by Vidal in 1961, the structure which is also known as either reinforced retaining wall, reinforced embankment, or reinforced soil, depending on the application, has been widely used in geotechnical projects where it provides a low-strain, strong, and durable solution for stabilization of fill or original material of the site (Bergado et al., 1987). Reinforced earth (Gurung, 2001) is made by reinforcing the soil with tension member like bar, steel plate, galvanized stripes, and geo-membranes. Reinforcement materials are categorized as either extensible such as the geotextiles and the geogrids or inextensible such as the metal strips and the metal grids; tests and analyses have been carried out involving both ( Ochiai et al.,1996; Khedkar and Mandal, 2009 and Balunaini and Prezzi, 2010). Interface friction angles between reinforcement materials and soils have been determined, the effects of various geometrical arrangements have been evaluated, and efforts have been made at having the reinforcement strips shortened while maintaining the required pull capacity such as by having the strips corrugated instead of plain (Potyondy, 1961; Zhang et al., 2008; and Racana et al., 2003).

Design of the MSE wall component of an MSE wall system should consider:

• Internal stability of the reinforced soil mass with regard to rupture and pullout of reinforcing elements such as pullout rupture of reinforcement and interface friction angle.

• External stability along the MSE wall/shoring wall interface such as friction between soil and MSE wall.

• Bearing capacity and settlement of the MSE wall foundation materials.

• Global stability of the composite SMSE wall system.

Generally speaking, the generic term ‘reinforced earth’ or ‘reinforced soil’ is used to describe all types of earth structures strengthened by reinforcements. However, in the industry, a large majority of reinforced earths has come under the more formal name category known as the mechanically stabilized earth or in short, MSE. Henry Vidal has been said as the inventor of the MSE (Haeri et al., 2000). Since the first installation of MSE by Vidal in 1961, the structure which also refers to reinforced retaining wall, reinforced embankment, and reinforced soil, depending on the application, has been widely used in geotechnical projects where it provides a low-strain, strong, and durable solution for stabilization of fill or original material of the site. In a MSE structure, reinforcement strips which are either metallic or synthetic, and plain or ribbed, are placed horizontally in the midst of layers of granular soil that is normally used as backfill or embankment material. Recent experiments and experiences involving MSE have been reported by many researchers (Varuso et al., 2005; Bathurst et al., 2005; Skinner and Rowe 2005; Hufenus et al., 2006; Nouri et al., 2006; Chen et al., 2007; Bergado and

Teerawattanasuk, 2008; Li and Rowe, 2008; Sieira et al., 2009; Palmeira, 2009; Abdelouhab et al., 2010).

Figure 1.1 is profile of a MSE as commonly installed today for road embankments where they apply. Inside the failure wedge, the reinforcement improves tension weaknesses in the soils, while across the potential slip surface, in the adjacent anchoring ground, the reinforcement holds the wedge against sliding or translational failure by having strips extended into the ground. For getting design parameters, pull-out tests are normally carried out. The pullout mechanisms of various reinforcement strips have been investigated not only by full-scale and laboratory model tests, but also by numerical methods (Palmeira and Milligan, 1989; Alagiyawanna et al., 2001; Gurung, 2001; Moraci and Cardile, 2009; Abdi and Arjomand, 2011; Goodhue et al., 2001; Sugimoto, 2003; Desai and Hoseiny, 2005; Moraci and Gioffre', 2006; Subaida et al., 2008; Su et al., 2008; Yin et al., 2008; Abdi et al., 2009; Zhou et al., 2011; Moraci and Cardile, 2012).

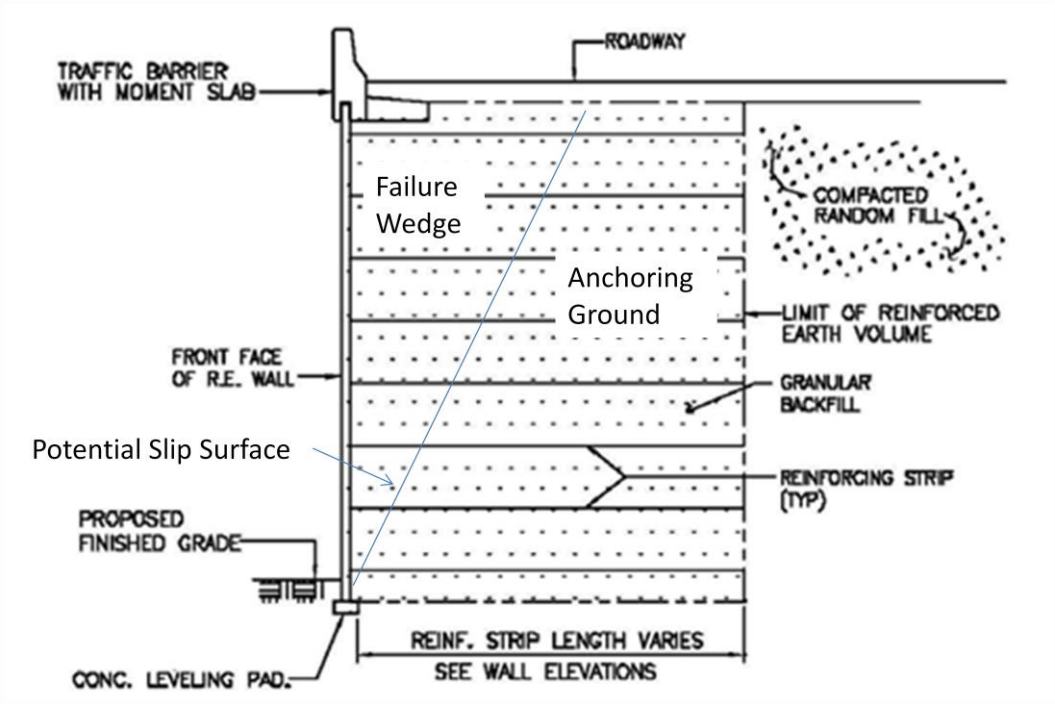


Figure 1.1: A profile of a commonly installed mechanically reinforced earth.(Sawicki, 2000)

## 1.2 Applications in Malaysia and abroad

The application of reinforced soil went back to ancient time, but since 1966 the method has been reinvented for design of reinforced retaining wall (Shukla et al., 2009). In the international arena of modern times, the use of reinforced retaining wall intensified in the 1980s and 1990s (Walls, 2009). In Malaysia, where soil reinforcement methods have been widely used in geotechnical projects, the use of reinforced earth for various geotechnical structures has become very popular in recent years. They can provide a low-strain, strong, and durable solutions for the stabilization of soils. From the front, outside of the reinforcement volume, view like shown in Figure 1.2 has become common sights in the country.


Figure 1.2: A view of MSE from the front showing decorative facing.

Inside the reinforcement volume, the interface friction angle between different materials is a very important factor in the design. The interface frictions between sand and galvanized steel is less than those between sand and sand because of the smooth surface of galvanized steel. Potyondy and Eng (1961) used smooth and rough materials, such as steel, wood, and concrete, to determine the interface friction between soil and these materials, restricting the moisture content and different normal loads between material and soil to find the interface friction of surfaces. The roughness of the steel, grain size of SW, and type of SW has been found to have an important effect on friction between two materials (Vesugi and kishida, 1981). Kishida et al. (1987) conducted some tests on the sand–steel interface using a simple apparatus and compared the results with those using others conventional apparatuses, such as direct shear test, annular shear test, and ring torsion experimental on the sand–plates interface; they compared the final results with those of other

experiments. The hardness of a material is the amount of surface resistance to the permanent indentation and may be considered a measure of the material strength. Hardness depends on both the geometry of the indenter and the material properties, including yield stress and bulk modulus. Moreover, it is not a true material property but rather a measurement. All materials with a low hardness amount have a high interface friction angle (Frost et al., 2002). Zhang et al. conducted a triaxial test to evaluate the interaction of horizontal-vertical orthogonal elements with sand and compared it with the ordinary horizontal type (Zhang et.al, 2008).

### 1.3 Recent trends in the use of geosynthetics

The recent development in the industry has found increased use of geosynthetics – geomembrane, geotextile, geogrids – in replacing more traditional reinforcements made of metal strips, timbers, and geofabrics.

When geomembrane is used, soil interface parameter ($\delta$) and shear strength of a smooth geomembrane–soil interface are discussed as in many studies by different researchers. Interface testing procedures and their effects on measured interface strength parameters have been investigated by Takasumi et al. (1991) and Fishman and Pal (1994). They gave a comprehensive review of the geomembrane–soil interface characteristics (Fleming et al., 2006).

When geotextile and geogrids are used, friction between soil and the geosynthetics materials facilitates the simple interface shear resistance of the soil against them - soil particles are not really engaged in the small space of the thin

geosynthetics sheet. However, the direct shear resistance is more complex for the thicker and more gripping geogrid. The wider ribs and soil contact enable greater interface shear resistance. At the same time, the friction resistance of soil particles on the top and bottom of the geogrid occurs within geogrid apertures. Therefore, the shear resistance of the soil–geogrid interface contains at least the shear resistance between soil and the surface of geogrids ribs and the internal shear resistance of the soil in the spaces of the geogrid. Interface between the granular fills and geogrid strip reinforcements in order to measure bearing resistance between the geogrid and soils have been studied by other researchers (lin et al., 2005).

Yildize wasti et al., (2001) studied the subject by conducting the shearing test on PVC geomembranes, smooth and rough HDPE, nonwoven needle-punched geotextiles with 5–50 KPa range of normal stress, inclined board tests, and different sizes of interface surfaces. The length of reinforcement plate could be decreased by increasing the friction between the soil and reinforcement material, reducing the cost of soil reinforcing projects.

In future, with increased use in geogrid type of geosyhthetics, but with thicker diameter threads, the knowledge on how resistance could be increased by having protrusions and shear elements is needed. In the study to be described next, the interface friction between sand and galvanized steel plate is increased by adding extra elements to the galvanized plate. The effect of different sizes and geometries of

shearing elements is evaluated using pull out tests, direct-shear tests, and Finite element modelling using Plaxis software.

### 1.4 Problem Statement

MSE has been widely used and the future is expected to see more usage including for narrow and complicated spaces where limitation of strips length is necessarily. Limitation on the use of strips is also caused by economy – the lesser the strips, the cheaper would the constructions be in terms of cost. However, with smaller number of strips used in an MSE, the force associated with a single strip becomes more, which in turn is affecting the mechanisms of tying the strip against the segmental concrete crust. In order to increase reinforcement capacity per strip, changing the geometry of the strip could be the solution.

In fact, the results of this study indicate that the new method involving transverse members could generally offer saving of strip material or provide particular design criteria for MSE of limited construction space, since the increased capacity of each reinforcement strip would reduce the total length or amount of strips required in a project. The test program described in this research was another attempt at having shorter or lesser number of strips involving inextensible material. The transverse members, also called anchorage elements, with element stiffeners, are part of a direct and simple means of improving anchorage through having rigid protrusions positioned 90 degrees to the direction of potential movement. The

expected outcomes were saving in strip material and new design criteria of MSE for narrow or limited construction spaces.

### 1.5 Objectives of the research

1. To develop new strip for narrow place, with more pullout capacity and therefore economic benefits for projects.

2. To determine optimum depth of anchorage with given anchorage spaces or alternatively speaking, optimum anchorage distance for given anchorage depth.

3. To formulate pullout capacity for various given parameters based on pullout experimental results.

4. To study failure surfaces in soil reinforced with strips of various design and test conditions using finite element method (Plaxis software).

### 1.6 Scope of Research

This research proposed to investigate the results to pull out capacity of strips with new geometries for mechanically stabilized earth, as would be applicable in walls in narrow or complicated spaces. Furthermore this research will utilise strips with different geometrise in pullout tests and carry out interface direct shear and direct pull out tests with different normal stresses. Statistical analysis and finite element modelling are needed to estimate final pull out strengths and investigate failure surface and behaviour of anchorage elements in the pullout tests.

## 1.7 Structure of Thesis

This thesis is presented in five (5) chapters. First chapter introduces the research, objectives, problem statement, and scope. A review of previous study on pullout capacity and interface interactions, interface direct shear tests, past theories and experiments, and finite element methods are presented in Chapter 2. Chapter 3 presents research methodology implemented in this research. In chapter 4, results and discussion of tensile tests, pullout tests, interface direct shear tests, triaxial tests, and compaction tests are discussed. Finally the conclusion and recommendation for future work are presented in chapter five.

# CHAPPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The research and industry of reinforced earth are generally more concerned with reinforcement material than with the earth fill material. The reinforcement materials, in turn, are comprised of steel and geosynthetics. The related tests carried out on these reinforcements are mainly the pull out tests and the direct shear tests. Computer modelling is carried out to corroborate the results. Pull out test and direct shear test are tow important experimental to investigate on soil and other material interface. For active zone of colomb failure surface and passive zone of MSE based on Mohr- colomb criteria direct shear test and pullout test are employed.

## 2.2 Pull out and direct shear tests involving reinforcement material

In study by Bakeer et al. (1998b), pull out test and interface shear test on geogrids were carried out against light aggregate with different confining pressures. In this study, the friction angles from pull out test was 52 degrees while from

interface friction test was 48 degrees, as given in Figure 2.1 and 2.2. Also, they found that some crushing actually had happened to the reinforced material with higher normal loads (Bakeer et al., 1998b).

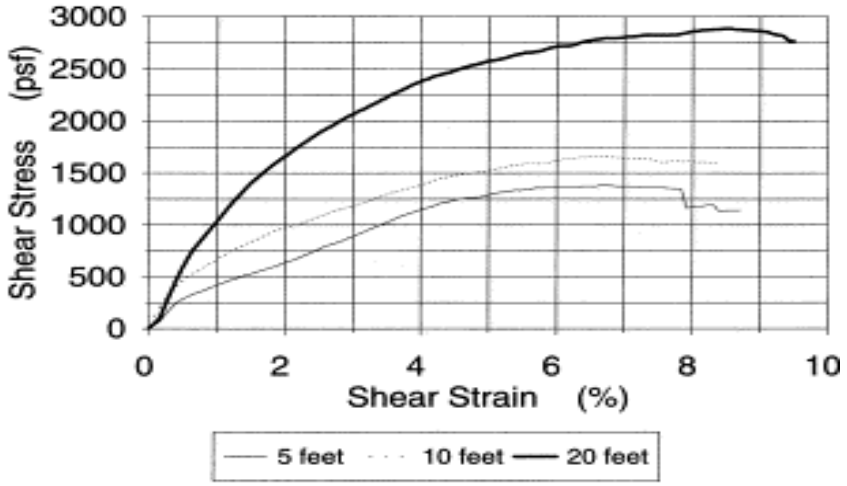


Figure 2.1: Results from pull out tests using geogrid and lightweight aggregate (Bakeer et al., 1998b)

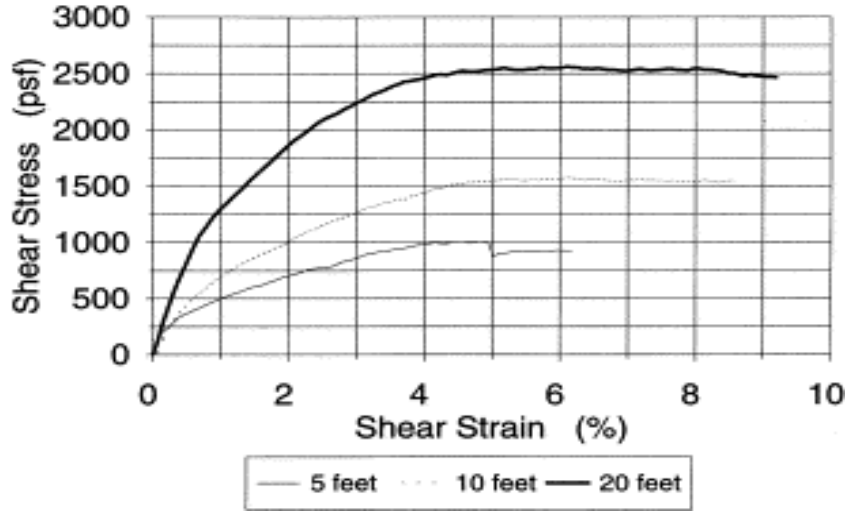


Figure 2.2: Results from interface shear tests using geogrid and lightweight aggregate (Bakeer et al., 1998b)

Boundary condition on pull out results was studied by Palmeira and Milligan (1989b). In this study, the results showed that certain friction on the inside of front wall of test box made it hard to predict the internal friction angle between soil and reinforcement material. They found that a larger scale pull out box and lubricating would be better in getting more accurate friction coefficient between materials.

In a study by Bergado et al. (1987), the interaction between soil and geogrids by using both direct shear and pull-out tests was investigated and the results were applied in a case study. Two types of Thailand soil - clayey sand and weathered clay – were used as backfill together with two types of reinforcement - polymer geogrid and bamboo grids. They found that the strength between soil and reinforcement has come from two factors: (a) the adhesion between soil and reinforcement on the solid surface area of the geogrid; and (b) the bearing withstand of soil in the fronts of the transverse members of geogrid that acted as a strip footing embedded in the soil. The design procedure for pull-out resistance coincided really well with the laboratory pull-out test results. Also their results showed that bamboo grids had higher pull-out resistance per unit area than the polymer geogrids. Furthermore, cohesive fills were found to be totally effective when used with geogrid reinforcement. Towards the end of their study, the results were applied in a design procedure to a case study involving an irrigation canal bank being repaired by the Public Works in Thailand. With Tensar SS2 geogrids as reinforcement and cohesive soils as backfill, a much improved embankment with very satisfactory slope stability was achived.

Wilson Fahmy et al. (1994) carried out an investigations involving extensible reinforcement and dense sand in a series of pull out tests. They found that failures could take place by either sheet pull out or tension failure in the fill material. They have suggested that a great portion of pull out capacity was provided by the transverse elements thus the role of junctions in the reinforcement grids was very important. Also, the flexural capacity of traverse elements and the longitudinal extensibility of reinforcement should be considered as the main factor affecting the design involving this type of reinforcement.

A series of pull out tests have been carried out on extensible reinforcement and cohesion less soil by Oostveen et al. (1994). The results emphasized that front wall proximity was an important factor for the type of stress distribution on reinforcement - as suggested earlier by Palemira amd Miligan (1989).

Geogrids with various specifications and lengths were used in pull out tests by Frsman and Slunga (1994) in crushed rock, light clay aggregate, and sand material. Their results showed that, in a pull out test, when length of strips was increased, the average shear resistance was decreased because of progressive failure along the length of geogrid. With longer strip length, the lesser rigid would be the strip parts. Their results emphasized the roles of various factors such as strength of junction, rigidity of transverse bearing members, reinforcement strength, and modulus of deformation, on the pull out-displacement relationship.

According to Gurung and Iwao (1999), pull-out tests are widely employed to measure the soil-reinforcement interface interaction mechanism. They founded a simplified analysis for evaluation of the interaction mechanism in a general pull-out test which is proposed for geo-reinforcement. They also have done numerical studies for pull-out tests of different strains (large and small) for each type of inextensible to extensible reinforcements. They also have made comparison between the steel geostrap and polymer strip to verify the theories on both extensible and inextensible reinforcements. These researches have produced experimental and theoretical pull-out test results for various materials such as geotextiles, polymers, nylon geosynthetics and steel strip reinforcements. The predictions of pull out capacities were based from the models and their satisfactory comparisons with experimental results. The incorporated bi-linear relation allowed prediction of pre and post yield deformations, tensile force, and shear stress variations along the required length of the reinforcement.

In general, reinforcements are categorized in two major types, inextensible and extensible. Galvanized metal strips (straps), rock bolt, steel grids are called inextensible while geosynthetics, fibres, and polymers are called extensible reinforcement according their large strains resulted in pull out tests, as shown in Figure 2.3 (Gurung, 2001).

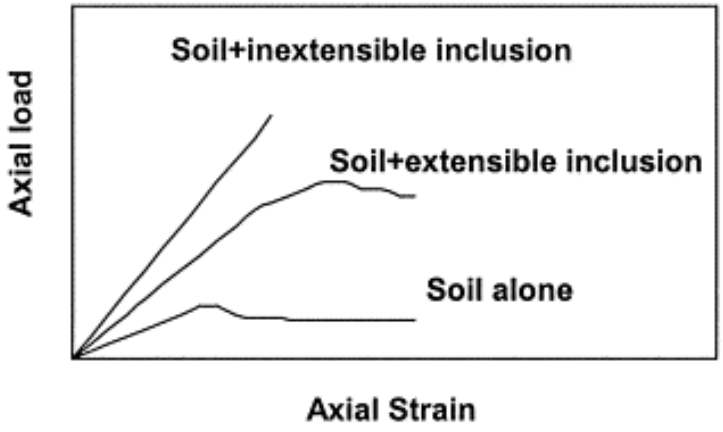


Figure 2.3: Description for inextensible and extensible reinforcements ( Gurung, 2001))

Alagiyawanna et al. (2001) carried out pull out tests using extensible geogrid with high strain of geometries as shown in Figure 2.4. Their results indicate that in case on extensible reinforcement, longitudinal members were more significant member in providing the required pull out capacity in comparison to the lateral bearing member during the failure phase of the geogrid. In this case, the large displacement of reinforcement will limit role of transverse members in providing the pull out capacity. Figure 2.5 depicts some results from pull out tests using feasible and rigid fronts.

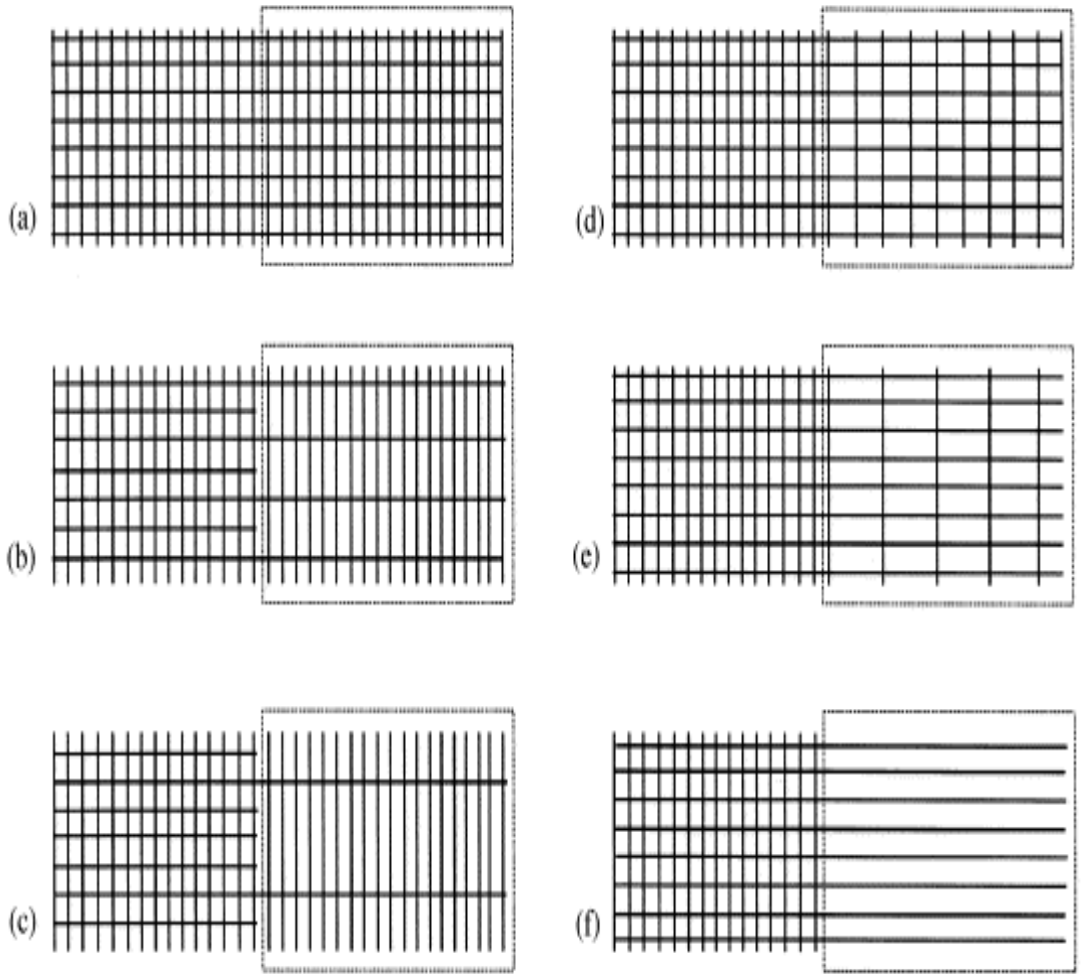


Figure 2.4: Geogrids used in pull out tests by Alagiyawanna et al., (2001)

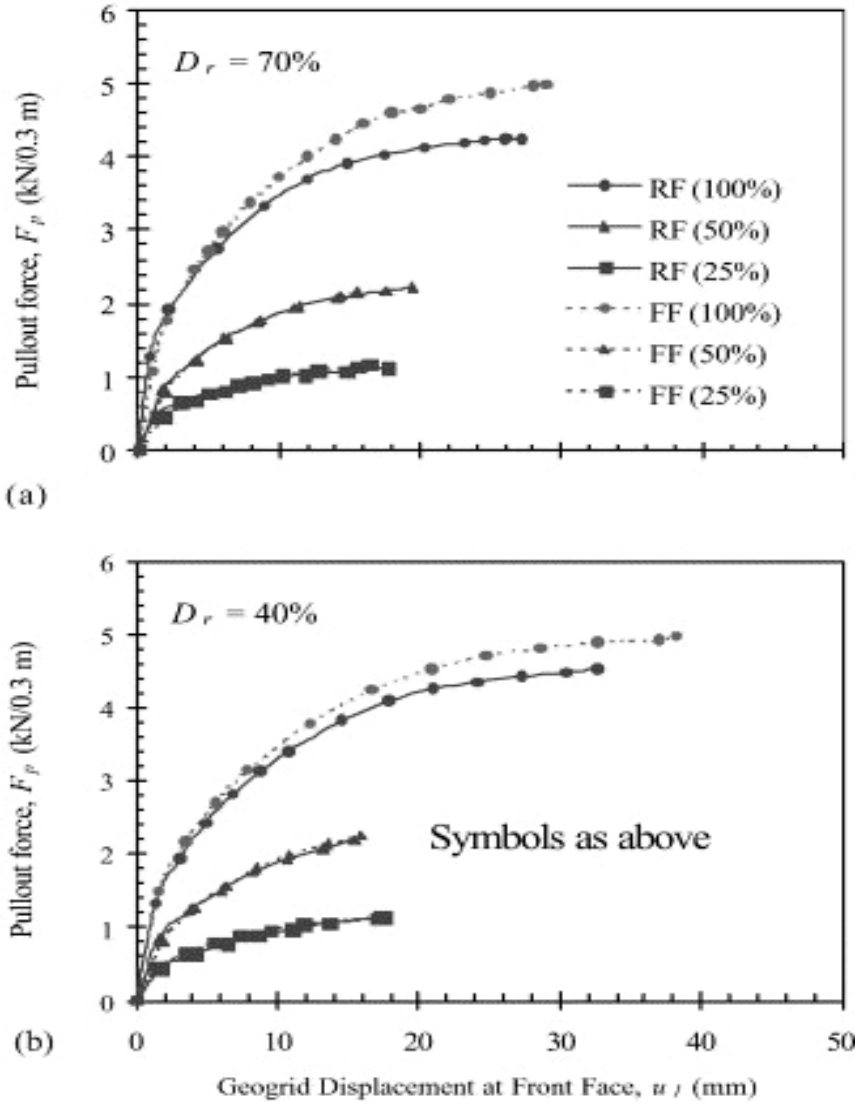


Figure 2.5: Results of pull out tests for flexible and rigid reinforcement members by Alagiyawanna et al. (2001)

Interface shear strength parameters of Geomembrane–geotextile were studied by Wasti and BahadIr Özdüzgün (2001) using 3 types of tests involving, the inclined board (tilting table), the standard sized direct shear box (60 mm×60 mm), and the large-scale direct shear box (300 mm×300 mm). HDPE, PVC geomembranes with Smooth and rough surfaces, and nonwoven needle-punched geotextiles were used in

the study. The inclined board tests were done under 5 to 50 kPa normal stresses on interface with various areas. The direct shear tests were conducted on normal stresses of 25 to 300 kPa for the smaller box and 110 to 400 kPa for the larger box. The results are given in Figure 2.6.

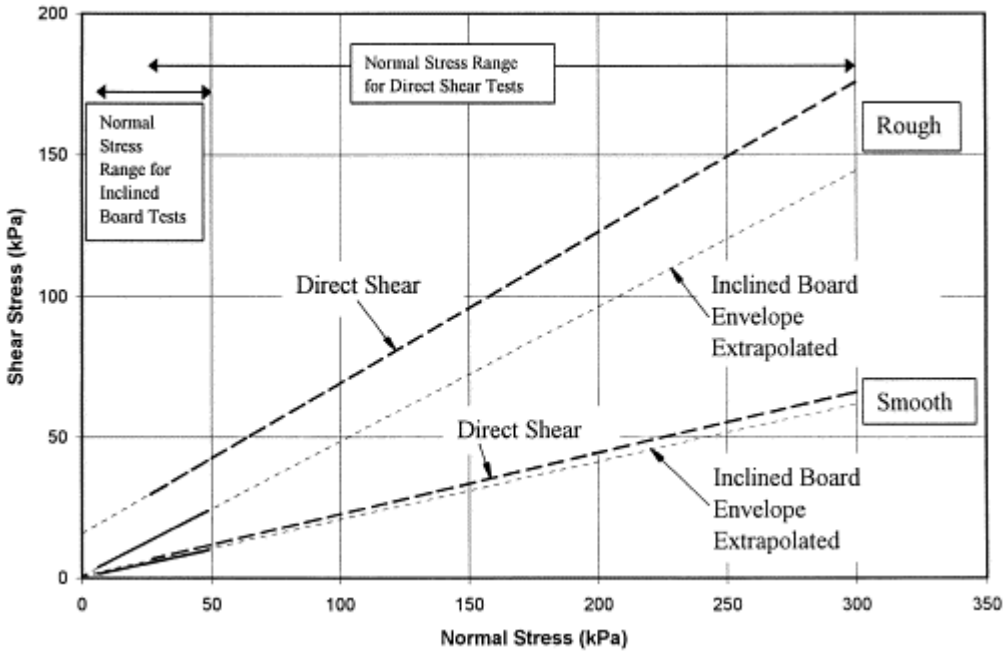


Figure 2.6: Results from inclined board test and large direct shear box tests involving 60 mm×60 mm geomembrane and geotextile interfaces (Wasti and BahadIr Özdüzgün, 2001)

The results with cohesion and interface friction angle values by fitting a straight line through the plots of interface shear strength versus the normal stresses were compared for different tests. They found that the inclined board test both smooth and rough HDPE geomembrane–geotextile interfaces had produced envelopes with small amount of adhesion. The interface size however was not significant factor. For smooth geomembranes, direct shear and inclined board tests both gave different interface friction angle and cohesion values. Their results showed

that the direct shear adhesion and friction values were markedly higher compared to those obtained from the inclined board tests, as given in table 2.1.

Table 2. 1: Different friction angle with different confining pressure (Wasti ,2001)

| Interface | .Giroud et al (1990) σ=1.1 kPa | Koubouras et al.(1991) σ =2.7 kPa | Girard et al.(1990) σ =3.7 kPa | Prescart study for σ =5or5.5 kPa | Giroud et al (1990) σ =25-160 kPa | Koubouras et al.(1991) σ =30-62 kPa | Girard et al.(1990) σ =100-400 kPa | Prescart study for σ =110-400 kPa |
|---|---|---|---|---|---|---|---|---|
| Smooth HDPE-GT | — | δ =19 | — | δ =14-21 | | σ =2.8 kPa δ =10 | — | σ =0.7-3.3 Kpa δ =12-14 |
| Rough HDPE-GT | δ =45 | δ =34 | — | σ =33-42 | σ =1.1 Kpa δ =15 | σ =17.2 Kpa δ =15 | — | σ =13-30 Kpa δ =13-30 |
| PVC-GT | — | δ =22 | δ =25 | δ =23 | — | σ =0 Kpa δ =26 | σ =0 Kpa δ =34 | σ =1-2 Kpa δ =24-25.5 |

Goodhue et al. (2001) conducted pull out test and direct shear test to find interaction coefficient (*f*) between foundry sand, grids and geotextile, and textiles. Their results showed that interface friction angles had ranged from 25 to 35 degree, with efficiencies amounting to between 0.5 and 0.9. Also, the pull out tests results indicated that the interaction coefficient was varied from 0.2 to 1.7.

Racana et al. (2003), have done pull out tests on vertical, horizontal and corrugated strips of different geometries in order to validate their finite element

equations. They found that if the strain was low, more overall pull out capacity would be realized from the system. Their finite element formula also had 23% higher pull out capacity in comparison with the results from experimental study, as given in Figure 2.7 .

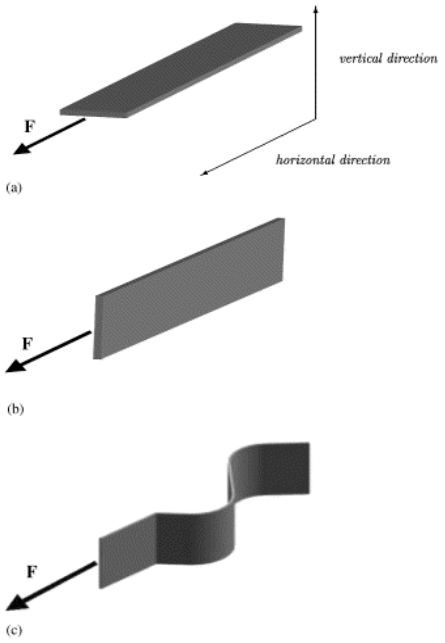


Figure 2.7: Strips of different geometries (Recana et al., 2003)

Numerical and experimental study further indicate that the low strain and overall increased pull out capacity in corrugated stripe was beneficial in the use smaller length of strips in practice as given in Figure 2.8, 2.9, and 2.10.

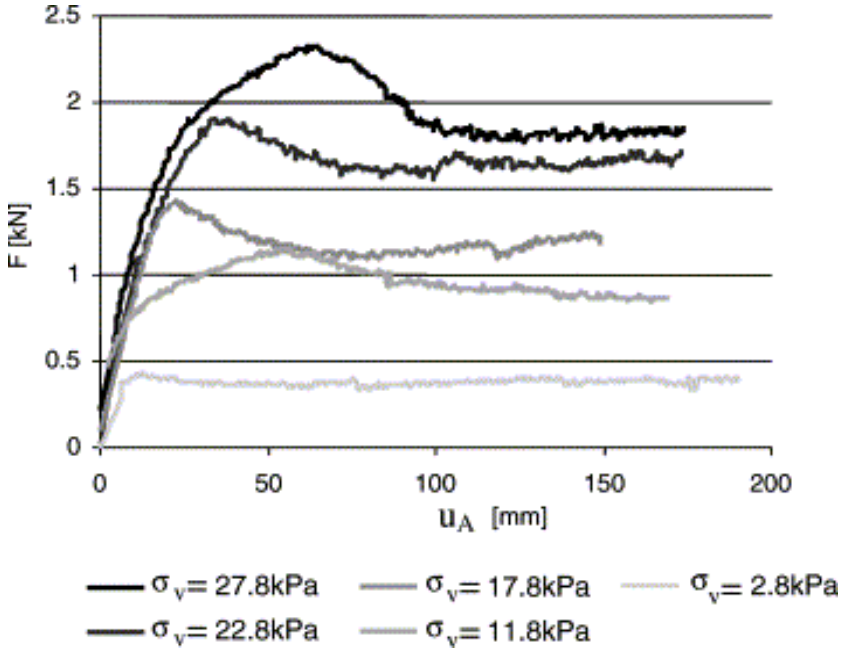


Figure 2.8: Pull out capacity for horizontal strips (Recana et al., 2003)

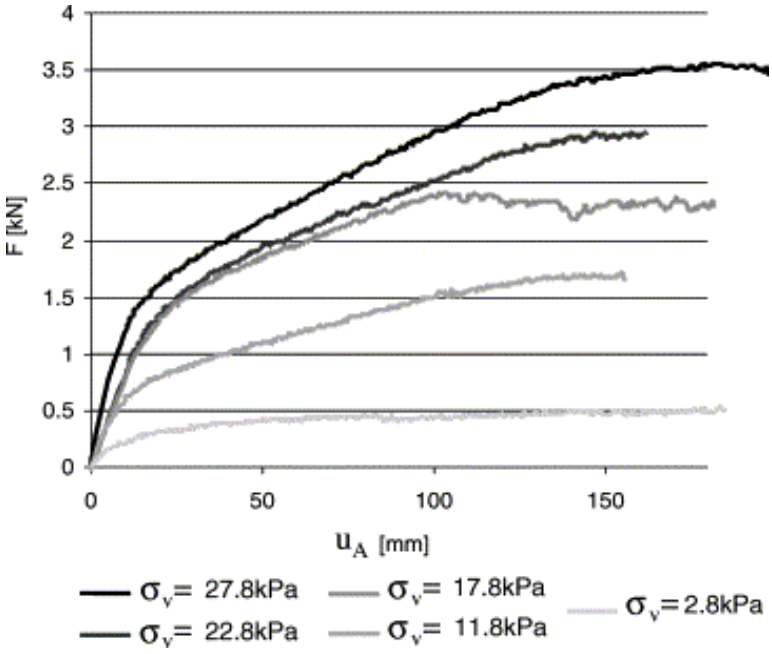


Figure 2.9: Pull out capacity for corrugated strip (Recana et al.,2003)

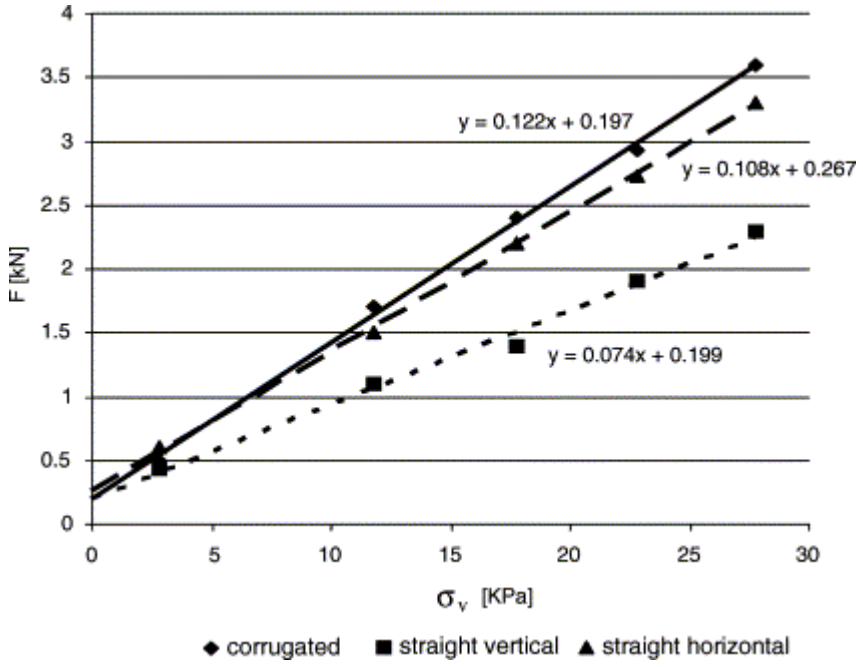


Figure 2.10: Pull out force for straight vertical, straight horizontal, and corrugated strip (Recana et al., 2003)

Palmeira (2004) studied on the mobilization of bearing forces in reinforcement during pull-out test. In this study, a theoretical model was made to describe the effects of having transverse ribs of geogrid in a large scale pull out test. Various mechanical and geometrical properties were tried with the model. Also investigated were the effects of some parameters such as free reinforcement length and test speed. He also found that good fill materials could make for shorter anchorage lengths in reinforced walls and slopes. He concluded that the length of reinforcement would affect overall stability of the reinforced mass, deformations, and final cost. Thus, the interaction between soil and geogrid is very important factor in the design of reinforce earth structure. Some results by Palmiera (2004) are given in Figure 2.11.

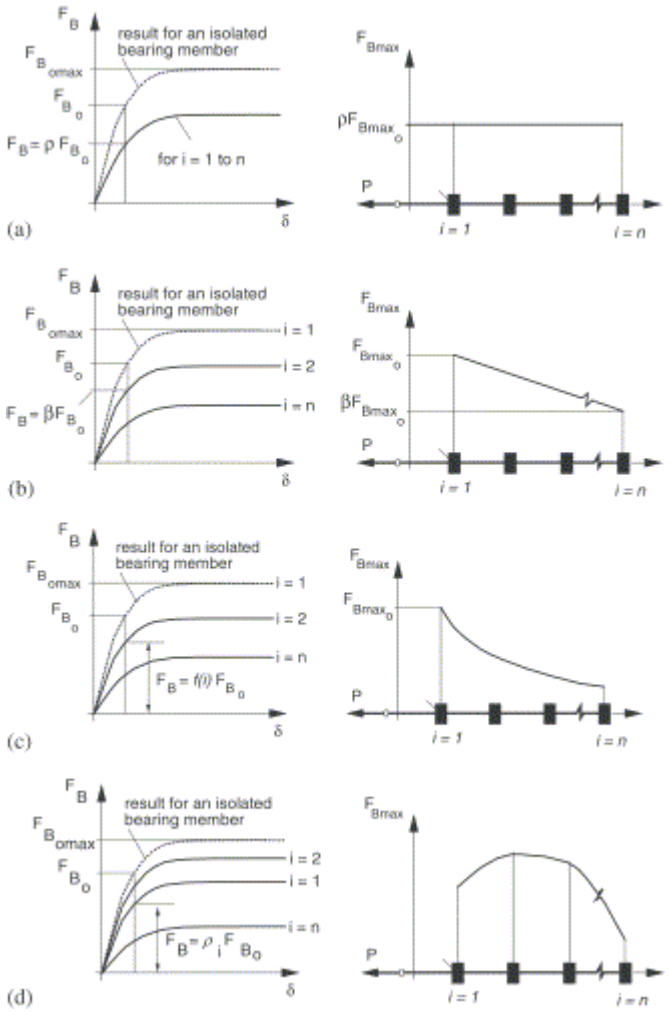


Figure 2.11: Cases of bearing strength degradation: (a) Reduction of uniform bearing force, (b) Reduction of linear bearing force along grid length, (c) reduction of bearing force as a power relation, (d) variable reduction of pull out force along the reinforcement (Palmeira, 2004)

Nejad and Smal (2005) conducted pull out test and direct shear test on geogrids and investigated interface and dilatancy angle and property in two types of soil. They have also compared the results with those coming from equations by Jewell et al. (1984) and Peterson et al. (1980). They results showed that the pull out tests showed higher amount of resistance than the direct shear tests – due to presence