Advanced Foundation Engineering

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CHAPTER 10: GEOTEXTILES REINFORCED EARTH AND GROUND ANCHORS

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Chapter 10

Geotextiles Reinforced Earth and Ground Anchors

10.1 Introduction

Long ago, when difficult sites for construction purposes were to be dealt, the conventional practice was limited to either the replacement of unsuitable soils or adopting suitable foundation which sometimes increases the cost of foundations. Innovative soil modification approaches are evolved to solve soil related problems. One among them is the usage of geosynthetics. When used to enhance the soil strength they have many advantages. They are space savings, material quality control, construction quality control, cost savings, technical superiority, construction timing, material deployment, material availability, environmental sensitivity. Used as Separators, Filter planar drain, Reinforcement, Cushion protection. Geosynthetics are of many types. They are Geotextiles, Geomembranes, Geonets, Geogrids, Geosynthetic clay liners, Geofoam, and Geocomposites.

10.1.1 Geotextiles:

Geotextiles are indeed textiles in a traditional sense, but consist of synthetic fibres rather than natural ones like cotton, wool and silk. Thus biodegradation is not a problem. The major point is that they are porous to water flow across their manufactured plane and also within their plane, but to a widely varying degree. Geotextile Polymer is manufactured from polyester or polypropylene. Polypropylene is a material lighter than water (it has a specific gravity of 0.9). It is considered to be strong and very durable. Polyesters used are heavier than water and it gives excellent strength and creep properties. There are two types of geotextiles. They are woven and non-woven geotextiles. The woven yarns and non-woven geotextiles are manufactured using polypropylene filaments and staple fibers. Non-woven types are manufactured from Staple fibers. They usually are 1 to 4 inches in length or a continuous filament randomly distributed in layers onto a moving belt to form a felt like “Web”. It is mainly used as a surface drainage. Woven geotextiles are made from weaving monofilament, multifilament or slit film yarns. Slit film yarn is further classified into Flat tapes and Fibrillated yarns. There are two steps in the
process of making woven textiles. They are manufacturing of the filaments and weaving. Slit films are used in sediment control and road stabilization works but are poor choice for sub surface drainage and erosion control works as they have low permeability. Alternatively fabrics made with fibrillated tape yarns have better more uniform openings and permeability than the flat tape.

10.1.2 Geogrids:

Geogrids are plastics formed into a very open netlike configuration. Single or Multi-layer materials are usually made from extruding and stretching high density polyethylene or by weaving or knitting the polypropylene. The resulting grid structure possesses large openings called apertures. These apertures enhance the interaction with the soil and aggregate. It is a good soil and aggregate reinforcement due to its good tensile strength and stiffness.

10.1.3 Geonets:

Geonets are stacked criss-crossing polymer strands that provide in-plane drainage. The geonets are all made of polyethylene. The melted polymer is extruded through slits in counter rotating-dies which forms a matrix or a net of closely spaced “stacked” strands. When the layers of strand are two then it is called as “biplanar” and three layers of strand are called “triplanar”.

10.1.4 Geocomposites:

Geocomposites are geotextile filters surrounding a geonet. Some of the functions of the Geocomposites are as blanket drains, panel drains, edge drains and wick drains. Blanket drains are generally used as Leachate, Infiltration collection, removal layers within landfill. Panel drains are placed adjacent to the structure to reduce the hydrostatic pressure. Edge drains are used adjacent to pavement structures which helps collect and remove lateral seepage from the road base.

10.1.5 Geomembranes:

Geomembranes are impervious thin sheets of rubber or plastic material primarily used for linings and covers of liquid- or solid-storage impoundments. Thus the primary function is always as a liquid or vapour barrier. They are relatively impermeable when compared to soils or geotextiles. They are divided into two general categories, they are, Calendered and Extruded. For
Calendered type, materials used are polyvinylchloride, chlorosulphonated polyethylene, chlorinated polyethylene and polypropylene. For Extruded type, material used is high dense polyethylene.

**10.1.6 Geosynthetic Clay Liners:**

Geosynthetic clay liners (GCLs) include a thin layer of finely-ground bentonite clay. The clay swells and becomes a very effective hydraulic barrier when wetted. GCLs are manufactured by sandwiching the bentonite within or layering it on geotextiles and/or geomembranes. The bonding of the layers are done with stitching, needling and/or chemical adhesives.

**10.1.7 Geofoam**

Geofoam is a newer category of the geosynthetic product. It is a generic name for any foam material utilized for geotechnical applications. Geofoam is manufactured in large blocks which are stacked to form a lightweight and thermally insulating mass buried within the soil or pavement structure. The most common type of polymer used in the manufacturing of geofoam material is polystyrene. The applications of geofoams are

1. It is used within soil embankments built over soft, weak soils
2. Used under roads, airfield pavements and railway track systems which are subjected to excessive freeze-thaw conditions
3. Used beneath on-grade storage tanks containing cold liquids.

**10.1.8 Geopipe**

Another significant product which has been adopted as a geosynthetic is the plastic pipe. The specific polymer resins that are used in the manufacturing of plastic pipes are high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), polybutylene (PB), acrylonitrile butadiene styrene (ABS), and cellulose acetate butyrate (CAB). There is a wide variety of civil engineering applications for these products. These include leachate removal systems, interceptor drains, and highway and railway edge drains.

**10.1.9 Turf Reinforcement Mats:**

Turf reinforcement mats (TRMs) are 3-dimensional structures composed of fused polymer nettings, randomly laid monofilaments, or yarns woven or tufted into an open and
dimensionally stable mat. Erosion protection can be increased by applying these Mats, which can provide more protection compared to that of plants grown normally. Proven performance has resulted in the broad use and ensured the acceptance of TRMs as a permanent, cost effective and environmentally friendly alternative to hard armor erosion protection solutions such as concrete and riprap.

10.1.10 Geocell:

3-D honey comb like structures filled with soil, rock and concrete. They are made of strips of polymer sheets/ geotextiles, connected at staggered points inorder to form a large honey comb mat when its strips are pulled apart. Geocells were manufactured from a novel polymeric alloy called Neoloy. The geocell with a higher elastic modulus has stiffness of the reinforced base and a higher bearing capacity. Geocells made from NPA are found to be significantly better in stiffness, ultimate bearing capacity and reinforcement relative to geocells made from HDPE. NPA geocells show better creep resistance and better retention of creep resistance and stiffness particularly at elevated temperatures, as verified by plate load testing and numerical modeling. A full scale research demonstrated that NPA geocells have a lower thermal expansion coefficient and creep reduction factor. It showed a higher tensile stiffness and strength than HDPE geocells and NPA geocells increased the bearing capacity and reduced settlement of compacted sand base courses significantly more than geocells fabricated from HDPE.
10.2 Geotextiles

Geotextiles are porous fabric manufactured from synthetic material such as polypropylene, polyester, polyethylene, nylon, polyvinyl chloride and various mixtures of these. They are available in thicknesses ranging from 10 to 300 mils (1 mil = 1/1000 inch) in widths upto 30 ft, in roll lengths upto 2000 ft. The permeabilities of geotextile sheets are comparable in
range from coarse gravel to fine sand. They are either woven from continuous monofilament fibres or non-woven made by the use of thermal or chemical bonding of continuous fibres and pressed through rollers into a relatively thin fabric. These fabrics are sufficiently strong and durable even in hostile soil environment. They possess a pH resistance of 3 to 11.

The use of geotextiles in geotechnical engineering has been growing in popularity for the last many years. Geotextiles can be used in so many ways. They are used as soil separators, used in filtration and drainage, used as a reinforcement material to increase the stability of earth mass, used for the control of erosion, etc. Some of the uses of geotextiles are described in the following sections.

10.2.1 Geotextiles as Separators

A properly graded filter prevents the erosion of soil in contact with it due to seepage forces. To prevent the movement of erodible soils into or through filters, the pore spaces between the filter particles should be small enough to hold some of the protected materials in place. If the filter material is not properly designed, smaller particles from the protected area move into the pores of the filter material and may prevent proper functioning of drainage.

As an alternative, geotextile can be used as a filter material in place of filter soil as shown for an earth dam in Fig 10.2. The other uses of geotextiles as separator are:

1) Separation of natural soil subgrade from the stone aggregates used as pavement of roads, etc.

2) As a water proofing agent to prevent cracks in existing asphalt pavements.
Geotextiles with good tensile strength can contribute to the load carrying capacity of soil which is poor in tension and good in compression.

Geotextiles placed between a natural subgrade below and stone aggregates above in unpaved roads, serve not only as separators but also increase the bearing capacity of the subgrade to take heavier traffic loads. Here, geotextiles functions as reinforcers as shown in Fig 10.3.
Another major way in which geotextiles can be used as reinforcement is in the construction of fabric-reinforced retaining walls and embankments. This technology is borrowed from the technology for reinforced earth walls. Geotextiles have been used to form such walls which can provide both the facing element and stability simultaneously. The process of construction of the wall with granular backfill is shown in Fig 10.4. The procedure is as follows.

1) Level the working surface.
2) Lay geotextile sheet 1 of proper width on the surface with 1.5 to 2 m at the wall face draped over temporary wooden form as shown in Fig 10.4(a).
3) Backfill over this sheet with granular soil and compact it by using a roller of suitable weight.
4) After compaction, fold the geotextile sheet as shown in Fig 10.4(b).
5) Lay down second sheet and continue the process as before. The completed wall is shown in Fig 10.4(d)

The front face of the wall can be protected by the use of shortcrete or gunite. Shortcrete is a low water content sand and cement mixture, often with additives, which is sprayed on to the surface at high pressures in a manner similar to gunite. The design of geotextile reinforced walls is similar in principle to that of reinforced earth walls.
10.2.3 Geotextiles in Filtration and Drainage

Geotextile sheets have been successfully used to control erosion of land surfaces. Erosions of exposed surfaces may occur due to the falling rain water or due to flowing water in rivers, etc. Fig 10.5(b) shows a schematic sketch for the protection of the banks of flowing water.
10.3 Reinforced Earth and General Considerations

Reinforced earth is a construction material composed of soil fill strengthened by the inclusion of rods, bars, fibres or nets which interact with the soil by means of frictional resistance. The concept of strengthening soil with rods or fibres is not new. Throughout the ages attempts have been made to improve the quality of adobe brick by adding straw. The present practice is to use thin metal strips, geotextiles and geogrids as reinforcing materials for the construction of reinforced earth retaining walls. A new era of retaining walls with reinforced
earth was introduced by Vidal (1969). Metal strips were used as reinforcing material. Here the metal strips extend from the panel back into the soil to serve the dual role of anchoring the facing units and being restrained through the frictional stresses mobilized between the strips and the backfill soil. The backfill soil creates the lateral pressure and interacts with the strips to resist it. The walls are relatively flexible compared to massive gravity structures. These flexible walls offer many advantages including significant lower cost per square metre of exposed surface. The variations in the types of facing units, subsequent to Vidal’s introduction of the reinforced earth walls, are many. A few of the types that are currently in use are (Koerner, 1999).

1) Facing panels with metal strip reinforcement.
2) Facing panels with wire mesh reinforcement.
3) Solid panels with tie back anchors.
4) Anchored gabion walls.
5) Anchored crib walls.
6) Geotextile reinforced walls.
7) Geogrids reinforced walls.

In all cases, the soil behind the wall facing is said to be mechanically stabilized earth (MSE) and the wall system is generally called an MSE wall.
The three components of the MSE wall are the facing unit, the backfill and the reinforcing material. Fig 10.6 shows a side view of a wall with metal strip reinforcement and Fig 10.7 shows the front face of a wall under construction (Bowles, 1996).

**Fig: 10.6: Reinforced earth walls (Bowles, 1996)**

Two MSE panel walls, that were over 125cm in height were constructed to build a bridge over an existing rail line.
Modular concrete blocks, presently called as segmental retaining walls [SRWS, Fig 10.8 (a)] are most common as facing units. Some of the facing units are shown in Fig 10.8. Most interesting in regard to SRWS are the emerging block systems with openings, pouches, or planting areas within them. These openings are soil-filled and planted with vegetation that is indigenous to the area [Fig 10.8 (b)]. Further possibilities in the area of reinforced wall systems could be in the use of polymer rope, straps, or anchor ties to the facing in units or to geosynthetic layers, and extending them into the retained earth zone as shown in Fig 10.8 (c)

Fig 10.8: Geosynthetic use for reinforced walls and bulkheads (Koerner, 2000):

(a) Geosynthetic reinforced wall, (b) Geosynthetic reinforced live wall and (c) Future types of geosynthetic anchorage.
A recent study (Koerner, 2000) has indicated that geosynthetic reinforced walls are the least expensive of any wall type and for all wall height categories (Fig 10.9).

**Fig 10.9: Mean values of various categories of retaining wall costs (Koerner, 2000):**

### 10.4 Backfill and Reinforcing Materials

#### 10.4.1 Backfill

The backfill is limited to cohesionless, free drainage material (such as sand), and thus the key properties are the density and the angle of internal friction.

#### 10.4.2 Reinforcing Material

The reinforcements may be strips or rods of metal or sheets of geotextile, wire grids or geogrids (grids made from plastic).

Geotextile is a permeable geosynthetic comprising solely of textiles. Geotextiles are used with foundation soil, rock, earth or any other geotechnical engineering-related material as an integral part of a human made project, structure or system (Koerner, 1999). AASHTO (M288-96) provides Table 10.1 geotextile strength requirements (Koerner, 1999). The tensile strength of geotextile varies with the geotextile designation as per the design requirements. For example, a woven slit-film polypropylene (weighing 240 g/m²) has a range of 30 to 50 kN/m. The friction
angle between soil and geotextiles varies with the type of geotextile and the soil. Table 10.2 gives values of geotextile friction angles (Koerner, 1999).

The test properties represent an idealized condition and therefore result in the maximum possible numerical values when used directly in design. Most laboratory test values cannot generally be used directly and must be suitably modified for in-situ conditions. For problems dealing with geotextiles the ultimate strength $T_u$ should be reduced by applying certain reduction factors to obtain the allowable strength $T_a$ as follows (Koerner, 1999).

$$T_a = T_u \left( \frac{1}{RF_{ID} \times RF_{CR} \times RF_{CD} \times RF_{BD}} \right)$$

[Eq 10.1(a)]

where, $T_a$ = allowable tensile strength.

$T_u$ = ultimate tensile strength.

$RF_{ID}$ = reduction factor for installation damage.

$RF_{CR}$ = reduction factor for creep.

$RF_{CD}$ = reduction factor for chemical degradation.

$RF_{BD}$ = reduction factor for biological degradation
Table 10.1: AASHTO M288-96 geotextile strength property requirements

<table>
<thead>
<tr>
<th>Test methods</th>
<th>Units</th>
<th>Geotextile Classification</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Elongation</td>
<td>&lt; 50%</td>
<td>≥ 50%</td>
<td>&lt; 50%</td>
</tr>
<tr>
<td>Grab strength</td>
<td>ASTM</td>
<td>N</td>
<td>1400</td>
<td>900</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>D4632</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sewn seam Strength</td>
<td>ASTM</td>
<td>N</td>
<td>1200</td>
<td>810</td>
<td>990</td>
</tr>
<tr>
<td></td>
<td>D4632</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tear strength</td>
<td>ASTM</td>
<td>N</td>
<td>500</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>D4533</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Puncture strength</td>
<td>ASTM</td>
<td>N</td>
<td>500</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>D4833</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burst strength</td>
<td>ASTM</td>
<td>kPa</td>
<td>3500</td>
<td>1700</td>
<td>2700</td>
</tr>
<tr>
<td></td>
<td>D3786</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. As measured in accordance with ASTM D4632. Woven geotextiles fail at elongations (strains) < 50%, while non-woven’s fail at elongation (strains) ≥ 50%

2. When sewn seams are required. Overlap seam requirements are application specific.

3. The required MARY tear strength for woven monofilament geotextiles is 250 N.
Table 10.2: Peak soil-to-geotextile friction angles and efficiencies in selected cohesionless soils*

<table>
<thead>
<tr>
<th>Geotextile type</th>
<th>Concrete sand (f = 30°)</th>
<th>Rounded sand (f = 28°)</th>
<th>Silty sand (f = 26°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven, monofilament</td>
<td>26°(84%)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Woven, slit film</td>
<td>24°(77%)</td>
<td>24°(84%)</td>
<td>23°(87%)</td>
</tr>
<tr>
<td>Non-Woven, heat bonded</td>
<td>26°(84%)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Non-Woven, needle punched</td>
<td>30°(100%)</td>
<td>26°(92%)</td>
<td>25°(96%)</td>
</tr>
</tbody>
</table>

* Numbers in parentheses are the efficiencies. Values such as these should not be used in final design. Site specific geotextiles and soils must be individually tested and evaluated in accordance with the particular project conditions: saturation, type of liquid, normal stress, consolidation time, shear rate, displacement amount, and so on (Koerner, 1999).

10.5 Geogrid

A geogrid is a geosynthetic material consisting of connected parallel sets of tensile ribs with apertures of sufficient size to allow strike-through of surrounding soil, stone, or other geotechnical material (Koerner, 1999).

Geogrids are matrix like materials with large open spaces called apertures, which are typically 10 to 100 mm between the ribs, termed longitudinal and transverse respectively. The primary function of geogrids is clearly reinforcement. The mass of geogrids ranges from 200 to 1000g/m² and the open area varies from 40% to 95%. It is not practicable to give specific values for the tensile strength of geogrids because of its wide variation in density. In such cases, one has to consult manufacturer’s literature for the strength characteristics of their products. The allowable tensile strength, $T_a$, may be determined by applying certain reduction factors to the ultimate strength $T_u$ as in case of geotextiles.
The equation is

\[ T_a = T_u \left( \frac{1}{RF_{ID} \times RF_{CR} \times RF_{CD} \times RF_{BD}} \right) \]

[Eq 10.1(b)]

where,  \( T_a \) = allowable tensile strength.

\( T_u \) = ultimate tensile strength.

\( RF_{ID} \) = reduction factor for installation damage.

\( RF_{CR} \) = reduction factor for creep.

\( RF_{CD} \) = reduction factor for chemical degradation.

\( RF_{BD} \) = reduction factor for biological degradation.

This is same as Eq 10.1(a). However, the values of the reduction factors are different.

### 10.6 Construction Details

The method of construction of MSE walls depends upon the type of facing unit and reinforcing material used in the system. The facing unit which is also called the skin can be either flexible or stiff, but must be strong enough to retain the backfill and allow fastening for the reinforcement to be attached. The facing units require only a small foundation from which they can be built, generally consisting of trench filled with mass concrete giving a footing similar to those used in domestic housing.

The construction procedure with the use of geotextiles is shown in Fig 10.10 Here, the geotextile serve both as reinforcement and also as a facing unit. The following procedure is described (Koerner, 1985) with reference to Fig 10.10.
Fig. 10.10: A general construction procedures for using geo-textiles in fabric wall construction

1. Start with an adequate working surface and staging area (Fig 10.10)
2. Lay a geotextile sheet of proper width on the ground surface with 4 to 7 feet at the wall face draped over a temporary wooden form (b).
3. Backfill over this sheet with soil. Granular soils or soils containing maximum 30 percent silt and/or 5 percent clay are customary (c).

4. Construction equipment must work from the soil backfill and kept off the unprotected geotextile. The spreading equipment should be a wide-tracked bulldozer that exerts little pressure on the ground on which it rests. Rolling equipment likewise should be relatively lightweight.

5. When the first layer has been folded over the process should be repeated for the second layer with the temporary facing from being extended from the original ground surface or the wall being stepped back about 6 inches so that the form can be supported from the first layer. In latter case, the support stakes must penetrate the fabric.

6. This process is continued until the wall reaches its intended height.

7. For protection against ultraviolet light and safety against vandalism the faces of such walls must be protected. Both shortcrete and gunite have been used for this purpose. Fig.10.11 shows complete geotextile walls.

![Fig 10.11: Geotextile Walls](image)

**10.6.1 Design Consideration for a Reinforced Earth Wall (or MSE)**

The design of a MSE (Mechanically Stabilized Earth) wall involves the following steps:

1. Check for internal stability, addressing reinforcement spacing and length.
2. Check for external stability of the wall against overturning, sliding, and foundation failure.

The general considerations for the design are;

1. Selection of backfill material: granular, freely draining material is normally specified. However, with the advent of geogrids, the use of cohesive soil is gaining around.

2. Backfill should be compacted with care in order to avoid damage to the reinforcing material.

3. Rankine’s theory for the active state is assumed to be valid.

4. The wall should be sufficiently flexible for the development of active conditions.

5. Tension stresses are considered for the reinforcement outside the assumed failure zone.

6. Wall failure will occur in one of the three following ways.
   i. tension in reinforcements.
   ii. bearing capacity failure.
   iii. sliding of the whole wall soil system.

7. Surcharges are allowed on the backfill. The surcharges may be permanent (such as roadway) or temporary.
   i. Temporary surcharges within the reinforcement zone will increase the lateral pressure on the facing unit which in turn increases the tension in the reinforcements, but does not contribute to reinforcement stability.
   ii. Permanent surcharges within the reinforcement zone will increases the lateral pressure and tension in the reinforcement and will contribute additional vertical pressure for the reinforcement friction.
   iii. Temporary or permanent surcharges outside the reinforcement zone contribute lateral pressure which tends to overturn the wall.

8. The total length $L$ of the reinforcement goes beyond the failure plane $AC$ by a length $L_e$. Only length $L_e$ (effective length) is considered for computing frictional resistance. The length $L_R$ lying within the failure zone will not contribute for frictional resistance [Fig 10.12 (a)].
9. For the propose of design the total length \( L \) remains the same for the entire height of wall \( H \). Designers, however, may use their discretion to curtail the length at lower levels. Typical ranges in reinforcement spacing are given in Fig 10.13

**10.6.2 Design Method**

The following forces are considered:

1. Lateral pressure on the wall due to backfill.
2. Lateral pressure due to surcharge if present on the backfill surface.
3. The vertical pressure at any depth \( z \) on the strip due to
   - (a) Overburden pressure \( p_0 \) only.
   - (b) Overburden pressure \( p_0 \) and pressure due to surcharge.
4. Lateral earth pressure due to overburden
   - At depth \( z \) \( p_0 = p_{0z}K_A = \gamma ZK_A \) (Eq. 10.2a)
   - At depth \( H \) \( p_0 = p_{0H}K_A = \gamma HK_A \) (Eq. 10.2b)
5. Total active earth pressure
   \( P_a = 0.5\gamma H^2K_A \) (Eq. 10.3)

**10.6.2.1 Pressure due to Surcharge (a) of Limited Width, and (b) Uniformly Distributed**

(a) \( q_h = \frac{2q_s}{\pi} (\beta - \sin\beta\cos2\alpha) \) (Eq. 10.4a)

(b) \( q_h = q_sK_A \) (Eq.10.4b)

Total lateral pressure due to overburden and surcharge at any depth \( z \)
\[ p_h = p_a + q_h = (\gamma zK_A + q_h) \] (Eq. 10.5)
Fig. 10.12 – Principles of MSE wall design (a) Reinforced earth wall provided with a surcharge load, (b) lateral pressure distribution diagram
10.6.2.2 Vertical Pressure

Vertical pressure at any depth $z$ due to overburden only

$$P_0 = \gamma z \quad \text{(Eq. 10.6a)}$$

Due to surcharge (limited width)

$$\Delta q = \frac{q_s B}{B + z} \quad \text{(Eq. 10.6b)}$$

where the 2 : 1 (2 vertical: 1 horizontal) method is used for determining $\Delta q$ at any depth $z$.

Total vertical pressure due to overburden and surcharge at any depth $z$;

$$\bar{P}_0 = p_0 + \Delta q \quad \text{(Eq. 10.6c)}$$
10.6.2.3 Reinforcement and Distribution

Three types of reinforcements are normally used. They are:

1. Metal strips
2. Geotextiles

Galvanized steel strips of widths varying from 5 to 100 mm and thickness from 3 to 5 mm are generally used. Allowance for corrosion is normally made while deciding the thickness at the rate of 0.001 in. per year and the life span is taken as equal to 50 years. The vertical spacing may range from 20 to 150 cm (8 to 60 in.) and can vary with depth. The horizontal lateral spacing may be on the order of 80 to 150 cm (30 to 60 in.). The ultimate tensile strength may be taken as equal to 240 MPa (35,000 lb/in^2). A factor of safety in the range of 1.5 to 1.67 is normally used to determine the allowable steel strength fa.

Fig 10.13 depicts a typical arrangement of metal reinforcement. The properties of geotextiles and geogrids have been discussed earlier. However, with regard to spacing, only the vertical spacing is to be considered. Manufacturers provide geotextiles (or geogrids) in rolls of various lengths and widths. The tensile force per unit width must be determined.

10.6.2.4 Length of Reinforcement

From Fig. 10.12(a)

\[ L = L_R + L_e = L_R + L_1 + L_2 \]  \hspace{1cm} \text{(Eq. 10.7)}

where, \( L_R = (H-z)\tan(45° - \phi/2) \),

\( L_e \) = effective length of reinforcement outside the failure zone,

\( L_1 \) = length subjected to pressure \((p_0+\Delta q)=\overline{p_0}\)

\( L_2 \) = length subjected to \( p_0 \) only.
10.6.2.5 Strip tensile Force at any Depth z

The equation for computing $T$ is,

$$ T = p_h \times h \times \frac{s}{\text{strip}} = (yzK_A + q_h)h \times s \quad \text{(Eq. 10.8a)} $$

The maximum tie force will be

$$ T(\text{max}) = (yzK_A + q_{hH})h \times s \quad \text{(Eq. 10.8b)} $$

where, $p_h = \gamma zK_A + q_h$

$q_h$ = lateral pressure at depth $z$ due to surcharge,

$q_{hH}$ = lateral pressure at depth $H$,

$h$ = vertical spacing,

$s$ = horizontal spacing.

$$ T = P_a + P_q \quad \text{(Eq. 10.9)} $$

where, $P_a = 0.5\gamma H^2 K_A$—Rankine's lateral force

$P_q$ = lateral force due to surcharge

10.6.2.6 Frictional Resistance

In the case of strips of width $b$ both sides offer frictional resistance. The frictional resistance $F_R$ offered by a strip at any depth $z$ must be greater than the pullout force. Trying a suitable factor of safety $F_s$, we may write,

$$ F_R = 2b[(p_0 + \Delta q)L_1 + p_0L_2]tan\delta \leq TF_s \quad \text{(Eq. 10.10)} $$

Or

$$ F_R = 2b[p_0L_1 + p_0L_2]tan\delta \leq TF_s \quad \text{(Eq. 10.11)} $$

$F_s$ may be taken as equal to 1.5.
The friction angle $\delta$ between the strip and the soil may be taken as equal to $\phi$ for a rough strip surface and for a smooth surface may lie between $10^\circ$ to $25^\circ$.

**10.6.2.7 Sectional Area of Metal Strips**

Normally, the width $b$ of the strip is assumed in the design. The thickness $t$ has to be determined based on $T_{(\text{max})}$ and the allowable stress $f_a$ in the steel. If $f_y$ is the yield stress of steel, then

$$f_a = \frac{f_y}{F_s(\text{steel})} \quad \text{(Eq. 10.12)}$$

Normally, $F_s(\text{steel})$ ranges from 1.5 to 1.67. The thickness $t$ may be obtained from

$$t = \frac{T_{(\text{max})}}{bf_a} \quad \text{(Eq. 10.13)}$$

The thickness $t$ is to be increased to take care of the corrosion effect. The rate of corrosion is normally taken as equal to 0.001 in./yr for a life span of 50 years.

**10.6.2.8 Spacing of Geotextile layers**

The tensile force $T$ per unit width of geotextile layer at any depth $z$ may be obtained from

$$T = p_hh = (\gamma z K_A + q_h)h \quad \text{(Eq. 10.14)}$$

where, $q =$ lateral pressure either due to a strip load or due to uniformly distributed surcharge

The maximum value of the computed $T$ should be limited to the allowable value $T_0$ as per Eq. 10.1(a). As such we may write Eq. (10.14) as

$$T_a = TF_s = (\gamma z K_A + q_h)hF_s \quad \text{(Eq. 10.15)}$$

Or

$$h = \frac{T_a}{(\gamma z K_A + q_h)F_s} = \frac{T_a}{p_hF_s} \quad \text{(Eq. 10.16)}$$

where $F_s =$ factor of safety (1.3 to 1.5) when using $T_a$. 

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Equation (10.16) is used for determining the vertical spacing of geotextile layers.

### 10.6.2.9 Frictional Resistance

The frictional resistance offered by a geotextile layer for the pullout force $T_a$ may be expressed as

$$F_R = 2[(\gamma z + \Delta q)L_1 + \gamma z L_2] \tan \delta \geq T_a F_s$$  \hspace{1cm} (Eq. 10.17)

Equation (10.17) expresses frictional resistance per unit width and both sides of the sheets are considered.

### 10.7 Design with Geogrid Layers

A tremendous number of geogrid reinforced walls have been constructed in the past 10 years (Koerner, 1999). The types of permanent geogrid reinforced wall facings are as follows (Koerner, 1999):

1. **Articulated precast panels** are discrete precast concrete panels with inserts for attaching the geogrid.
2. **Full height precast panels** are concrete panels temporarily supported until backfill is complete.
3. **Cast-in-place concrete panels** are often wrap-around walls that are allowed to settle and, after 1/2 to 2 years, are covered with a cast-in-place facing panel.
4. **Masonry block facing walls** are an exploding segment of the industry with many different types currently available, all of which have the geogrid embedded between the blocks and held by pins, nubs, and/or friction.
5. **Gabion facings** are polymer or steel-wire baskets filled with stone, having a geogrid held between the baskets and fixed with rings and/or friction.

The frictional resistance offered by a geogrid against pullout may be expressed as (Koerner, 1999)

$$F_R = 2C_i C_r L_p p_0 \tan \varphi \geq T F_s$$  \hspace{1cm} (Eq. 10.18)

where $C_i =$ interaction coefficient $= 0.75$ (may vary),

$C_r =$ coverage ratio $0.8$ (may vary).
All the other notations are already defined. The spacing of geogrid layers may be obtained from

\[ h = \frac{T_a C_r}{p_h} \]  

(Eq. 10.19)

where, \( p_h \) = lateral pressure per unit length of wall

**10.8 External Stability**

The MSE wall system consists of three zones. They are:

1. The reinforced earth zone.
2. The backfill zone.
3. The foundation soil zone.

The reinforced earth zone is considered as the wall for checking the internal stability whereas all three zones are considered for checking the external stability. The soils of the first two zones are placed in layers and compacted whereas the foundation soil is a normal one. The properties of the soil in each of the zones may be the same or different. However, the soil in the first two zones is normally a free draining material such as sand.

It is necessary to check the reinforced earth wall (width = \( B \)) for external stability which include overturning, sliding and bearing capacity failure. These are illustrated in Fig 10.14. Active earth pressure of the backfill acting on the internal face \( AB \) of the wall is taken in the stability analysis. The resultant earth thrust \( P_a \) is assumed to act horizontally at a height \( H/3 \) above the base of the wall. The methods of analysis are the same as for concrete retaining walls.
10.9 Reinforced Soil Beds

Binquet and Lee (1975) conducted series of model tests on reinforced soil beds supporting the strip footing. Researchers identified the 3 types of failure mechanism in reinforced soil: (1) shear failure above the uppermost reinforcement layer, which occurs when depth of placement of reinforcement \((u)\) is greater than \(2B/3\) (Figure 10.15a) (2) pull-out failure of reinforcement, which is likely to occur when the depth of placement of reinforcement is less than \(2B/3\), number of layers of reinforcement is three or less and the reinforcement length is short (Figure 10.15b). (3) Tension failure (tie breaks), which is likely to occur when depth of placement of reinforcement is less than \(2B/3\), four or more layers of reinforcement and length of reinforcement is long (Figure 10.15c).
(a) Shearing above reinforcement: $u/B > 2/3$

(b) Pull-out failure; $u/B < 2/3$, $N < 2$ or $3$ and short ties

(c) Tension failure (Breakage of ties); $u/B < 2/3$, $N$ and long ties

**Fig 10.15: Possible failure modes of reinforced soil foundation (after Binquet and Lee, 1975)**

By considering pull-out failure and tension failure, the proposed design criteria for failure modes of 2 and 3 as expressed below,

$$T_D \leq \left( \frac{R_y}{FS_y}, \frac{T_f}{FS_f} \right)$$

where, $T_D$ = the developed tie force in any layer of reinforcement

$R_y$ = breaking strength or yield resistance of reinforcement

$T_f$ = the frictional pull-out resistance of the tie layer and

$FS$ = the specified factor of safety for the condition indicated by the respective
10.9 Design of Geocell Foundations

Koerner (1998) suggested that the increase in the bearing capacity of the foundation bed can be calculated in terms of the relative shear strength ($\tau$) between the geocell wall and the soil contained within it.

The increase in shear strength $\Delta P$,

$$\Delta P = 2\tau$$

where, $\tau = P \tan^2 (45 - \phi/2) \times \tan \phi$

where, $P$ is the applied vertical pressure acting on the geocell reinforcement.

$\phi$ is the angle of shearing resistance between soil and the cell wall material. $\phi$ value varies between 15° to 20° between sand and HDPE and it varies between 25° to 30° between the sand and the non-woven geotextile.

Zhao et al. (2009) reviewed the literature on geocell supported embankments and suggested that the geocell layer contributes to the strength through three main aspects: (a) vertical stress dispersion effect, (b) lateral resistance effect and (c) membrane effect. Further, Zhang et al. (2010) proposed a simple bearing capacity calculation method for geocell supported embankment over the soft soil. This method considers only vertical stress dispersion mechanism and the membrane effect mechanism. Earlier, Koerner (1998) had provided the analytical solution to estimate the bearing capacity of the geocell reinforced foundation beds. The method proposed by Koerner considers only lateral resistance effect developed due to the interfacial friction between soil and cell wall. However, the present method considers all the three mechanisms proposed by Zhao et al. (2009) into the formulation.

This model is based on the hypothesis that the lateral resistance effect and the vertical stress dispersion effect mechanisms originated by virtue of geocell while the membrane effect is contributed by basal geogrid. Experimental studies conducted by the authors suggested that geogrid also contribute to the increase in the bearing capacity. It was also observed that geogrid
undergoes considerable bending due to the application of footing load. Bending of the planar geogrid causes the mobilization of the tensile strength within the geogrid. The mobilized tensile strength in the geogrid will contribute to the membrane effect. However, geocell acts as a rigid slab; which undergoes uniform settlement without any significant bending (Dash et al., 2001a; Yang, 2010). Hence, membrane effect was not considered for only geocell case.

Increase in the load carrying capacity of the foundation bed can be expressed in terms of the tensile strength of the geogrids, the applied pressure on the geocell mattress and the allowable limiting settlement. It is very relevant to express the increase in load carrying capacity in terms of pressure applied on the geocell mattress. This is because of the mobilization of shear strength at the cell wall is directly related to applied pressure. The lateral resistance effect component ($\Delta P_1$) is calculated using Koerner (1998) method:

$$\Delta P_1 = 2\tau$$  \hspace{1cm} (Eq. 10.20)

where $\tau$ is the shear strength between the geocell wall and the infill soil and is given by,

$$\tau = P_r \tan^2(45 - \Phi/2)\tan\delta$$  \hspace{1cm} (Eq. 10.21)

where $P_r$ = the applied vertical pressure on the geocell,

$\Phi$ = the friction angle of the soil used to fill the geocell pockets and,

$\delta$ = the angle of shearing resistance between the geocell wall and the soil contained within.

Generally, value of $\delta$ is in the range of 15 to 20° between sand and HDPE (Koerner, 1998). In this particular case, $\delta = 18^\circ$ was considered.

The vertical stress dispersion mechanism is also called as wide slab mechanism. This mechanism was first observed by Binquet and Lee (1975). Schlosser et al. (1983) extended this mechanism to the strip footing resting on the reinforced soil beds. Subsequently, many researchers have reported the wide slab mechanism in their studies (Huang and Tatsuoka, 1988; Huang and Tatsuoka, 1990; Takemura et al. 1992). In addition, the presence of a wide slab mechanism in the geocell reinforced foundation bed was justified by the findings of Dash et al. (2001a, b); Sitharam and Sireesh (2004, 2005) through ‘1-g’ model tests. They observed that the
interconnected cells form a panel that acts like a large slab that spreads the applied load over an extended area leading to the overall improvement in the performance of the foundation soil.

Fig 10.16 is the schematic representation of the vertical stress dispersion mechanism in the geocell reinforced foundation beds.

\[ \Delta P_2 = P_r \left(1 - \frac{B}{B + 2D_r \tan \beta}\right) \]  \hspace{1cm} (Eq. 10.22)

The membrane effect mechanism is contributed by the vertical component of the mobilized tensile strength of the planar reinforcement (Zhang et al., 2010). Hegde and Sitharam (2012) observed that provision of the basal geogrid will resist the downward movement of soil due to the footing penetration through experimental studies. Hence, membrane effect component was considered additionally in the formulation of the load carrying capacity of the foundation bed reinforced with combination of geocell and geogrid. The increase in the load carrying capacity due to the membrane effect (\(\Delta P_3\)) is given by,

\[ \Delta P_3 = \frac{2 \tan \alpha}{B} \]  \hspace{1cm} (Eq. 10.23)
where, $T =$ the tensile strength of the basal geogrid material.

$\sin \alpha$ is calculated as a function of settlement under the given load.

The deformed shape of geogrid is generally parabolic in nature. However, if the footing dimension is very small compared to the geogrid dimension then it resembles the triangular shape. In the present case, geogrid dimension is 5.5 times larger than the footing dimension and hence the triangular shape was considered as indicated by dotted line in Fig 10.17.

\[ 2S \sin \alpha = g_B \]  
\[ \text{Eq. 10.24} \]

where,

$B_g =$ the width of the basal geogrid and,

$S =$ the footing settlement measured at the surface.

The increase in the load carrying capacity of the foundation bed reinforced with combination of geocell and geogrid is represented as:

$\Delta P =$ lateral resistance effect + vertical stress dispersion effect + membrane effect

\[ \Delta P = 2\tau + P_r (1 - \frac{B}{B + 2D_r \tan \beta}) + \frac{2T \sin \alpha}{B} \]  
\[ \text{Eq. 10.25} \]