Chapter 4

APPLICATION OF FIBRE REINFORCEMENT IN EARTH STRUCTURES – FAILURE MECHANISMS AND REQUIREMENTS

In the previous chapters, it was pointed out that reinforced earth is a practical solution to improvement of stability of canal slopes and erosion control with adequate ground improvement for base stability as an alternative to gravity type structures or easy slopes. However for reinforcing earth, the reinforcement material should be able to restrain movement by the greater stiffness and transfer of stresses by friction or adhesion. But there are many situations in which very stiff reinforcements are not needed and a limited and compatible allowable deformation for soils can be allowed. It is in this category that non metallic reinforcements fall and they have the advantage of less corrosion and sustainability with lower cost.

Reinforcements used in geotechnical applications can be classified as ideally inextensible inclusions and extensible inclusions (Mc Gown et al. 1978). The comparative behaviour of reinforcement in the case of inextensible and extensible inclusions is shown in Table 4.1. The stress-strain behaviour of the reinforcement is quite different in these two cases. The inextensible inclusions may rupture at strains less than the maximum tensile strain in unreinforced soil and may result in catastrophic failure; whereas the extensible inclusions can take larger strains and never rupture. The extensible inclusions provide greater extensibility (ductility) and smaller loss of post-peak strength as compared to soil alone or soil reinforced with inextensible inclusions.

Fibre reinforcement comes in the category of extensible inclusions (i.e., plysoil). The concept of fibre reinforcement is analogous to the reinforcement of soils with plant roots. The influence of root reinforcement on the shear strength and the stability of natural slopes have been reported by several investigators (Gray 1986). It was reported that plant roots particularly live roots significantly improve the shear strength of soils and the stability of natural slopes. The extent of increase in shear strength of root-reinforced soils was found to depend upon the concentration and properties of roots. The relative increase in strength, i.e., percentage gain in strength over
unreinforced soil was observed to be 98% to 290% with varying concentration of roots from 0.2% to 1.0% for different types of plant roots.

Table 4.1 Comparative behaviour of soil reinforcement

<table>
<thead>
<tr>
<th>Type of Reinforced Soil</th>
<th>Type of Reinforcement</th>
<th>Stress-strain Behaviour of Reinforcement</th>
<th>Role and Function of Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced earth</td>
<td>Ideally inextensible inclusions (metal strips, bars, etc) $E_r/E_s &gt; 3000$</td>
<td>Inclusions may have rupture strains which are less than the maximum tensile strains in the soil without inclusions, under the same operating stress conditions; i.e. $\epsilon \leq \varepsilon_{rup} &lt; \varepsilon_{max}$</td>
<td>Strengthens soil (increases apparent shear resistance) and inhibits both internal and boundary deformations. Catastrophic failure and collapse of soil can occur if reinforcement breaks.</td>
</tr>
<tr>
<td>Plysoil</td>
<td>Ideally extensible inclusions (natural and synthetic fibres, roots, fabrics ‘geotextiles’) $E_r/E_s &gt; 3000$</td>
<td>Inclusions may have rupture strains greater than the maximum tensile strains in the soil without inclusions, i.e. $\epsilon \leq \varepsilon_{rup} &lt; \varepsilon_{max}$ These inclusions cannot rupture, no matter their ultimate strength or the imposed load</td>
<td>Some strengthening, but more importantly provides greater extensibility (ductility) and smaller loss of post peak strength compared to soil alone or to reinforced earth</td>
</tr>
</tbody>
</table>

$E_r/E_s = \text{the ratio of reinforcement modulus (longitudinal stiffness) to average sand modulus. The limits shown are tentative (After Ranjan & Charan, 1998).}$
4.1 Comparative performances of fibres

Both natural and synthetic fibres are used for civil engineering purposes. Table 4.2 presents the properties of commonly used fibres.

**Table 4.2 Characteristics of commonly used fibres**

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Specific gravity</th>
<th>Tensile strength, $10^4$kPa</th>
<th>Modulus of elasticity $10^6$kPa</th>
<th>Elongation at break, %</th>
<th>Fibre volume in composites, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inorganic Fibres</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asbestos</td>
<td>1.90-3.37</td>
<td>180-350</td>
<td>38-190</td>
<td>2-3</td>
<td>-</td>
</tr>
<tr>
<td>Glass</td>
<td>2.70</td>
<td>125-250</td>
<td>70-80</td>
<td>2-3.5</td>
<td>2-8</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.90</td>
<td>260</td>
<td>230</td>
<td>0.5-1</td>
<td>2-12</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.91</td>
<td>500-700</td>
<td>5-77</td>
<td>20</td>
<td>0.2-102</td>
</tr>
<tr>
<td>Kevlar</td>
<td>1.45</td>
<td>290</td>
<td>65-133</td>
<td>2.1-4.0</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.14</td>
<td>-</td>
<td>Up to 4</td>
<td>13.50</td>
<td>0.1-6</td>
</tr>
<tr>
<td>Plastic</td>
<td>0.92</td>
<td>15-20</td>
<td>303-305</td>
<td>40-60</td>
<td>0.5-3</td>
</tr>
<tr>
<td><strong>Organic Fibres</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coir</td>
<td>0.7-1.30</td>
<td>9-14</td>
<td>4-6</td>
<td>15-40</td>
<td>-</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.3-1.5</td>
<td>100-200</td>
<td>34-62</td>
<td>3-7</td>
<td>-</td>
</tr>
<tr>
<td>Jute</td>
<td>1.36</td>
<td>400-500</td>
<td>17.4</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>Bhabar</td>
<td>0.8-1.3</td>
<td>5-7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hemp</td>
<td>1.36</td>
<td>40-200</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Munja</td>
<td>1.29</td>
<td>20-75</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bamboo</td>
<td>1.50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Banana</td>
<td>1.30</td>
<td>110-130</td>
<td>200-510</td>
<td>1.8-3.5</td>
<td>-</td>
</tr>
</tbody>
</table>

(After Ranjan and Charan, 1998)

Synthetic fibres, e.g.: polypropylene, nylon and plastic are resistant to sea water, acids, alkalies and chemicals. Polypropylene fibres have high tensile strength and high melting temperature ($165^\circ$C). However, they are susceptible to combustion and sunlight (U.V.rays). Asbestos, glass and carbon fibres are resistant to alkalies and chemicals. But, asbestos fibres suffer a certain amount of corrosion in the long term.
Natural fibres are known to have poor resistance to alkalies. They get damaged in alkaline environment. Except coir fibres, other natural fibres, e.g.: sisal, jute, bhabar, hemp, munja and banana deteriorate and lose strength when subjected to alternate wetting in saturated lime solution and 0.1N solution of sodium hydroxide for 24 hours, washing with water and drying at a temperature of $20^\circ C$ to $30^\circ C$.

4.2 Review of studies on fibre reinforced soils

This section reports the results of comparison tests on the stress-deformation response of a dry sand reinforced with continuous, oriented fabric layers as opposed to discrete, randomly distributed fibres. Oriented fabric layers or geotextiles are widely used in engineering practice in a variety of reinforcement applications. Reinforcement with randomly distributed, discrete fibres has attracted considerable attention in concrete technology especially for impact resistance. Very little information has been reported, on the other hand, on the use of this technique for reinforcing soils.

A secondary objective here is to describe the influence of various inclusion properties, soil properties, and test variables on the stress deformation response of fabric or fibre reinforcement to improve the performance of granular trenches or columns used to stabilize footings in weak clays.

4.2.1 Continuous, oriented fabric layers

Most engineering fabrics or geotextiles in widespread use are made from polymeric materials or fibres. Typical polymers are polypropylene, polyester, polyethylene, and polyamide. The two most common types of geotextiles are woven and nonwoven fabrics. The former are manufactured from two sets of parallel filaments or yarn oriented in two mutually perpendicular directions. Nonwovens consist of a mat of fibres of either continuous or discrete length filaments, arranged in a random pattern and bonded together mechanically, or chemically.

A number of investigators have conducted strength tests on sand specimens reinforced with fabric inclusion. The fabric inclusions were placed horizontally in the direction of the major principal plane. In general, results have shown that ultimate strength increased with increasing layers of fabric and that axial deformation tended to increase with decreasing spacing between fabric layers (increased number of
layers). Results of these tests have also shown that the strain required to reach peak strength increased and that the tendency towards brittle behaviour or loss of post-peak strength in dense sand was markedly reduced by the presence of reinforcement. Furthermore, results showed that larger strains were required to reach peak stress in reinforced loose, as opposed to dense sand.

4.2.2 Randomly distributed discrete fibres

A considerable amount of research has been conducted on fibre reinforcement of soil using regular arrays of oriented fibres. Very few papers have been published, on the other hand, on randomly distributed, discrete fibre reinforcement in soils. Unlike geotextiles, such fibres are not currently marketed for soil reinforcement purposes. Short fibres consisting of steel and fibreglass are available commercially, however, as admixes for fibre reinforcement of concrete.

Lee, et al. (1973) reported the results of a single triaxial test on sand reinforced with fir wood shavings. Their results showed that small amounts of fibre markedly increased both the strength and rigidity of the sand. Andersland and Khattak (1979) presented the results of triaxial tests on a kaolin clay reinforced with paper pulp (cellulose) fibres. The specimens were consolidated to form a slurry mix. The addition of fibres increased both the stiffness and undrained strength of the kaolinite.

4.2.3 Discrete fibres versus fabrics

In fibre reinforced soil, the fibres are mixed with the soil to produce a relatively homogeneous and isotropic material in order that the physical and mechanical properties are consistent. This ought to be differentiated from oriented sheet/ disc reinforcement, which will produce an anisotropic effect. The confining stress causes the friction between fibre and the soil particles to develop, thereby not allowing the particles to slide, resulting in tensioning the fibres. This could be causing an apparent confining effect at micro level and in view of the randomly oriented and well distributed fibres, is expected to result in a reinforced soil mass to behave like a dense soil or over-consolidated soil.

The mode of placement of fibres in soil is an important aspect. The fibres may be placed at certain preferred direction, or they may be randomly distributed in soil.
mass. Depending upon the placement of the reinforcement, the fibre-reinforced soil may be categorized as:

(a) Oriented fibre-reinforced soil: where the fibres are placed along a certain direction, or at a certain angle with respect to shear failure plane.

(b) Randomly distributed fibre-reinforced soil: where the fibres are mixed with soil homogeneously, resulting in randomly distributed fibre-soil mass.

The sand-fibre composite can sustain large axial strain exhibiting greater ductility in the composite. The shear strength of sand-fibre composites depends upon fibre parameters (i.e., weight fraction, aspect ratio, surface friction), sand granulometry (particle shape, size and gradation) and confining stress. The failure envelopes of fibre reinforced sands are curvilinear/bilinear showing the existence of critical confining stress $\sigma_{\text{crit}}$ below which the fibres pull out or slip during deformation.

4.3 Engineering properties of fibre reinforced soils

Limited studies reported on unconfined compression tests, CBR tests, tensile strength tests and flexural strength tests reveal that unconfined compressive strength, CBR values and tensile strength of silty/clayey soils increase due to addition of discrete fibres. However, the flexural strength of lime-fibre-laterite mixes and clay-fibre mixes is lower, particularly at Proctor's density.

A review of compaction test results indicates that the inclusion of fibres in soil causes an increase in porosity of the composite, which is independent of type of compaction. The addition of fibres to soil offers resistance to compaction in case of synthetic fibres, causing a decrease in maximum dry density. However, natural coir fibre reinforced soils do not exhibit any reduction in maximum dry density.

A very limited laboratory-field model test results reported in the literature indicate that in general, the strength of sands, in terms of either ultimate bearing capacity or $c$ and $\phi$ values, increases due to fibre inclusion.

Hoare (1977) reported the results of laboratory compression and CBR tests on a sandy gravel reinforced with very small amounts (less than 2% by weight) of random fibres. Compaction tests showed that the fibres increased the resistance to densification. When a constant compactive effort was applied to a range of samples
with increasing fibre content, the strength either increased hardly at all or actually decreased. This was caused by the concomitant increase in porosity or void ratio, which would tend to negate any increase in strength from fibre reinforcement.

Triaxial compression tests were run on dry sand reinforced with randomly distributed, discrete fibres and oriented continuous fabric layers by Gray et al (1983). Test results showed that both types of reinforcement systems increased strength and modified the stress-deformation behaviour of sand in a significant manner. The following main conclusions emerged from the study of Gray et al (1986) and are given in figures 4.1 to 4.3.

1. Continuous, oriented fabric inclusions markedly increased the ultimate strength, increased the axial strain at failure, and in most cases limited reductions in post-peak loss of strength.

2. At very low strains (<1%) fabric inclusions produced a loss in compressive stiffness of triaxial specimens. The loss in stiffness was more pronounced when the number of layers or the tensile modulus of the fabric was greater.

3. Fabric reinforcements placed at spacing/diameter ratios greater than one had little effect on strength.

4. Discrete, randomly distributed fibres increased both the ultimate strength and the stiffness of reinforced sand. The decrease in stiffness at low strains, observed with fabric inclusions, did not occur with the fibres.

5. The increase in strength with fibre content varied linearly up to a fibre content of 2% by weight, and thereafter approached an asymptotic upper limit. The rate of increase was roughly proportional to the fibre aspect ratio.

6. At the same aspect ratio, confining stress, and weight fraction, rougher (not stiffer) fibres tended to be more effective in increasing strength.
Figure 4.1: Stress-strain relationship from triaxial compression tests on reinforced muskegon dune fabric sand: (a) Oriented, fabric layers, and (b) Random, discrete fibres ($N =$ Number of layers, $w_f =$ Weight fraction of fibres) (After Gray and Al-Refaei, 1986)
Figure 4.2: Failure envelopes from triaxial compression tests on reinforced Muskegon dune sand: (a) Oriented, fabric layers; and (b) Random, discrete fibres (N= Fibre aspect ratio) (After Gray and Al-Refae, 1986)
Figure 4.3: Normalised secant modulus versus strain in reinforced Muskegon dune sand:
(a) Oriented, fabric layers; and (b) Random, discrete fibres (After Gray and Al-Refeai, 1986)
7. Internet fabric or fibre reinforcement of a granular trench used to stabilize a weak clay soil should substantially increase the bearing capacity of a strip footing placed on the soil.

4.4 Mechanism of shear resistance

Several investigators have reported the results of triaxial and plane strain compression tests on cylindrical samples of dry sand containing thin, horizontal layers of tensile reinforcing material. The results of these triaxial tests on fabric-reinforced sand have been interpreted in two different, yet refined ways.

Equivalent confining stress concept. Yang (1972) hypothesized on the basis of his tests that tensile restraint in the reinforcement induced an "equivalent confining stress" increase. Accordingly, from the Mohr Coulomb formulation for the strength of a cohesionless material, it follows that

\[(\sigma_{1f})_R = (\sigma_3 + \Delta \sigma_3) k_p \]

in which \((\sigma_{1f})_R\) = major principal stress at failure in reinforced sand; \(\sigma_3\) = applied confining stress on the sample; \(k_p = \tan^2 (45 + \phi/2); \phi = \) friction angle of the unreinforced sand

Pseudo-cohesion concept - Schlosser and Long (1974) proposed that the reinforcements induced an anisotropic or pseudo cohesion that was a function of their spacing and tensile strength. Thus, the strength of the reinforced composite is given by

\[(\sigma_{1f})_R = \sigma_3 k_p + 2c_R \sqrt{k_p} \]

The anisotropic pseudo cohesion was computed from a force equilibrium analysis of a reinforced composite.

The following expressions can be derived:

Horizontal reinforcement: \(c_R = \frac{\alpha_f \sqrt{k_p}}{2\Delta H} \)

Inclined reinforcement: \(c_R = \frac{\alpha_f (k_p \cos^2 \beta - \sin^2 \beta)}{2\Delta H \sqrt{k_p}} \)
in which $\alpha_F = \text{force per unit width of reinforcement at failure}$; $\Delta H = \text{spacing} \text{ between reinforcements}$; and $\beta = \text{angle of inclination of reinforcement counterclockwise from the major principal plane}$.

Comparison of equations 1 and 2 indicates a correspondence between $\Delta \sigma_3$ and $c_R$, i.e.,

$$c_R = \frac{\sigma_3 \sqrt{k_p}}{2} \quad \text{.........................................................(5)}$$

Comparison of equations 3 and 5, in turn, shows the following:

$$\Delta \sigma_3 = \frac{\alpha_F}{\Delta H} \quad \text{.........................................................(6)}$$

Thus, the tensile resistance of the reinforcement $\alpha_F/\Delta H$ is directly equal to the equivalent confining stress increase ($\Delta \sigma_3$). If the reinforcements break, $\alpha_F$ is replaced by the tensile strength $R_T$ of the fabric. On the other hand, if they merely stretch, the usual case with highly extensible, low-modulus fabrics, $\alpha_F$ is equal to the tensile strain in the fabric times its modulus.

4.5 Fibre Reinforcement

Comparable models have not been developed for predicting strength increases from randomly distributed, discrete fibres in soil. Force-equilibrium models have been developed, however, for oriented, fibre arrays. Models for individual fibres, initially oriented either perpendicularly or inclined to the shear surface in a sand developed by Gray (1986) are shown in Figure 4.4. Shearing stress that develops in the sand mobilizes tensile resistance in the fibres via friction at the fibre-sand interface. Shearing action in the sand causes the fibres to distort as shown; as a result the tensile resistance in the fibres is directed into a normal component, which increases the confining stress on the failure plane and a tangential component that directly opposes shear.

For perpendicular fibres $S_R = t_R (\sin \theta + \cos \theta \tan \phi)$

Inclined fibres $S_R = t_R (\sin (90-\psi) + \cos(90-\psi) \tan \phi)$

in which $\psi = \tan^{-1}(1/k+(\tan i)^{-1})$
Figure 4.4: Model for oriented fibre reinforced in sand

(After Gray and Al-Refeai, 1986)
The experiments on discrete fibre applications are discussed in detail in chapter 7.

4.6 Field applications

Along with the laboratory studies on the use of fibres and fabrics, studies in the ground improvement also were taken up. Most of these are related only to synthetic fibres. They were either discrete staple fibres or continuous fibres or fabrics made out of them. The most important of these is the development of Texsol method in France,(Leflaive, 1988).

The TEXSOL technique is a three-dimensional development of the geotextile technology. It is the mixing of continuous polymer yarn and soil to form a composite in which the yarn brings the tensile resistance, as is applied. In the present practice, the soils used to produce TEXSOL are essentially natural sands. This is for several reasons: mixing of soil and yarn is easier with granular materials than with cohesive materials; mechanical performance of sand is very strongly improved by the tensile strength of yarn; in many areas, local natural sands are cheap materials. However, the principle of the TEXSOL method is also applicable to other types of soils (Leflaive, 1988).

The TEXSOL technology has been developed by the Research Network of the French ministry of public works, which owns the original patent involving mixing of soil and yarn by special machines. For contracting and site application, the TEXSOL Company has been established; the TEXSOL Company is performing jobs in France and developing the method abroad through joint ventures and licensees.

TEXSOL is a new material with unusual performances. The effect of yarn is to create a cohesion in the granular material. However in contrast with materials bound with cement, bitumen or other binders, the TEXSOL material has a fairly high deformability. Simple compression tests lead to failure for 6 to 10% of axial deformation and, secondly, TEXSOL is as permeable as the material without yarn.

According to the method and equipment production the geometrical arrangement of the yarn within the material may vary. In present practices this arrangement is preferably horizontal and it has been shown that the resulting cohesion is anisotropic. Anisotropy of cohesion is taken into account in the design of TEXSOL structures. The TEXSOL material has a wide variety of potential applications:
retaining structures, foundation layers under railroads and roads, shear resistant drains and filters, foundation blankets on soft soils, antiseismic structures, protection against erosion, shock resistant structures, etc. Presently the application, which has been essentially developed, is retaining structures.

As shown in figure 4.5, the TEXSOL solution is a trapezoidal inclined structure. As compared with conventional retaining walls, this solution has two main advantages: cost and appearance. Savings are mainly due to the reduction of earth moving quantities and the use of local natural sand for the production of TEXSOL. Environmental performance is excellent due to grass growing on the TEXSOL surface as shown in figure 4.6. Experience has also shown that maintenance of vegetative cover is performed without any problem, which is not the case when the retaining structure is made of concrete elements intermixed with soil and vegetation.

In a few instance TEXSOL has been used to improve the stability and the erosion behaviour of earth or sand levees built for protection of industrial or military areas. In one case sand levees were displaced by wind action; a fairly thin cover of TEXSOL avoided sand to be blown away and solved the problems. In another instance earth levees were progressively washed down by rain action and TEXSOL allowed to restore their initial slope in some places with a steeper slope, while keeping the shock absorbing ability of the levees, which was required on this site where explosion could occur.

Other applications are where the shock absorbing ability of TEXSOL will be put to use. One is for protection of roads or constructions against falling rocks in mountainous areas. To stop very large rocks heavy structures are the cheapest means but large embankments often cannot be built because of the slope angle of the natural ground. Thus a TEXSOL wall with a steep slope retaining a mass of ordinary fill is a good solution. In addition to static stability, TEXSOL is a deformable material, which can absorb considerable shock energy through large deformations.

LUONG et al. (1986) performed tests at Ecole Polytechnique near Paris in view of analyzing the mechanical behaviour of TEXSOL as compared with that of simple sand. These tests have explored cyclic loading behaviour, liquefaction and dynamic response as a function of frequency. The results show that TEXSOL ductility and energy absorption capability are of great interest when vibrations are involved.
Figure 4.5: Comparison of concrete wall and Texsol solutions for retaining structures

Figure 4.6: Diagram of full size tests of retaining structures (After Leflaive, 1988)
TEXSOL, new construction material, has already gained acceptance to solve economically and ecologically, conditions, which are mostly of the problems of retaining walls, slope savings, anti-seismic and vibration courses of foundations, protection against noises and shocks. New applications and other research are already moving and the owners and engineers are looking for its development with high interest all around the world.

Another example of field application of synthetic fibres was the construction of a road in Sweden 33 km west of Stockholm reported by Leflaive (1988). In this discrete polypropylene fibres of 48mm length were mixed in quantities of 0.25 to 0.5 % of sand of 100 mm layer for foundation of road. There was a problem of mixing which was solved by using concrete mixer. The reshaping and levelling of the road surface were achieved by a grader even though hand tools were required for increasing the efficiency. The strength of the foundation was considerably increased by the mix and no rutting was reported even after 2 years.

4.7 Conventional design procedures for nonwoven geotextiles

Various design methods have been developed, which are all generally based on introducing tensile forces induced by the fabrics in the soil. The two basic methods are

a. introducing horizontal forces into a slip circle or block sliding analysis

b. taking up the horizontal earth pressure by tensile forces.

These methods have been modified slightly by various authors, trying to approach the design to the actual failure mechanisms as close as possible. Without any respect to technical accuracy, these methods allow a quick and safe approximate design of geotextile reinforced walls, being a highly economical alternative to other retaining structures, even when highly extensible nonwoven geotextiles with a relatively low tensile strength are used. (Studer and Meir (1986) and Chemie linz/Polyfelt (1986)).

4.7.1 Reflections on a New Design Theory

This theory is based on a combined functional mechanism of horizontal reinforcement and a gravity retaining structure. Without gravity retaining wall, the resulting tensile forces Z, will be so high that the resulting force, R from active
pressure, E and tensile forces, Z is transferred into the basement (Figure 4.7). When a gravity retaining wall with the weight, G is placed in front of a slope, the required tensile forces, Z to transfer the resulting force, R into the soil can be reduced significantly (Figure 4.8). Gravity retaining walls are usually concrete walls or gabion walls. However, flexible structures also can act as a retaining wall, when its internal stability is guaranteed. When looking at the construction procedure proposed by Chemie Linz/polyfelt (1986) where completely closed earth filled bags are installed at the edge of the wall, it can be assumed that these “earth bags” act as a retaining wall (Figure 4.9).

For checking the internal stability of the earth bag wall the following types of failure have to be considered.

a) Overturning around the edge point in every level.

b) Horizontal sliding in every level: For this, the friction angle between soil and nonwoven needle punched geotextile can be assumed as $\delta = 0.9 - 1.0 \phi$, whereas for heat bonded nonwovens and wovens with smoother surface this value lies within $\delta = 0.6 - 0.9 \phi$, as proven by various authors, e.g. Richards and Scott (1985).

c) Internal stability of each bag.

The most critical failure seems to be the internal stability of each bag.

Assuming the relationship between N and T as

$$T = l \cdot c + N \cdot \tan \phi$$

where $l$—length of slip line

c—cohesion

$\phi$—friction angle,

the required tensile forces can be calculated. However there are still some open questions:

a) How are the vertical and horizontal forces from the resulting force R distributed over the width b?

b) What friction angle and cohesion can be assumed?

c) What tensile strength can be introduced in the calculations?

The stress distribution over the width, b is of utmost importance for the stability. In concrete retaining walls, the stresses from the resulting force, R is distributed triangularly, as shown in figure 4.10.a. In the case of earth filled bags, the
Figure 4.7.1: Basic design procedures for reinforced slopes

Figure 4.7.2: Forces without gravity retaining wall
Figure 4.8: Forces with gravity retaining wall

Figure 4.9: "Earth bag" at the edge of geotextile reinforced wall

Figure 4.10: Distribution of the resulting force R
stiffness modulus of the bag is equal to that of the surrounding soil. Therefore a part of the resulting force, R is taken up by the soil (Figure 4.10.b).

4.7.2 Shear strength characteristics of the geotextile wrapped soil.

The actual shear strength situation inside the earth bags can be stated as higher than in the surrounding soil. The reasons for this can be found in various factors:

a) A better compatibility.

As shown by Tatsuoka et al (1986) and Werner and Resl (1986) the friction between soil and nonwoven geotextile reduces the lateral movement of the soil grain, resulting in a better compaction and thus in an increase of shear strength.

b) Introduction of a three dimensional state of stresses, leading to much higher allowable shear stresses (Werner and Resl, 1986)

c) Drainage function of the geotextile:

Especially with cohesive fill material the drainage function is of great importance, in order to drain off pore water during compaction and consolidation as well as seepage water caused by rainfall or by ground water flow (Tatsuoka et al, 1986).

The positive effect of the drainage function has also been demonstrated by Fabian and Fourie (1987) in triaxial tests, where various types of geotextiles have been installed horizontally in the middle of the soil sample. The tests have shown that geotextiles with high permeability (needle punched nonwovens), show a higher increase in shear strength when compared to low permeable geotextiles (heat bonded nonwovens, wovens), which show in some cases even a decrease. Therefore the lower tensile strength of needle punched nonwovens seems to be overcompensated by their ability to dissipate excess pore pressures quickly.

4.7.3 In - soil tensile strength of the geotextiles

The question, which tensile strength should be inserted into the stability calculations is influenced by three factors:

a) factor of safety

b) stress - strain curve in soil confinement

c) long - term behaviour

a) When needle punched nonwovens are used as reinforcing elements, a factor of safety, FS = 3.0 is recommended, by Studer and Meier (1986) and Chemie Linz.
(1986) as long as a more detailed analysis of the functional mechanisms is not possible.

b) The stress strain characteristic of needle punched nonwovens is characterised by slippage and straightening of the fibres and fibre obliquity (Hearle, 1972). Due to the interlocking effect between soil and geotextiles the fibre slippage is reduced and therefore higher strength and lower elongation are yielded compared with the standard tensile test where the geotextile is examined without soil confinement, as proven by Fock and Mc Gown (1987). Additionally the stiffness of the geotextile is increased by preloading during compaction (Studer and Meier, 1986)

c) The load is sustained over a long period of time and hence the long term behaviour is of importance for the stability of the structure. Fock and Mc Gown (1987) however have shown that when embedded in soil creep is not a relevant factor even when polypropylene fabrics are used.

4.8 Practical experience

Numerous projects have been carried out using a nonwoven needle punched pp - endless - fibre geotextile with the brand name “polyfelt TS”. The construction was done according to the recommendations by Chemie Linz/Polyfelt (1986). Nevertheless, the economical benefits have been undeniable:
- low material costs
- low transportation costs
- the in-situ material can be used as fill material
- easy installation with unskilled workers and no heavy equipment was required.

When the retaining wall has to fulfill its function permanently and not only temporary, a UV protection has to be provided in the case of geosynthetics. Possible methods are planting, shotcreting, non-constructive brick walls etc.

In the case of retaining walls constructed using natural nonwovens like coir needled felt durability can be enhanced using suitable impregnations. Moreover shotcreting or guniting techniques can be adopted for eliminating the possible damages likely to happen due to the external agencies such as rodents and human activities. For the construction of retaining walls and maintenance of slopes in the vicinity of canals and for bank protection, rip rap may be provided in addition to ferrocement facing units or shotcreting or as the case may be.
Even geotextiles with low modulus offer an economical method of "reinforcing" steep slopes in spite of their relatively low tensile strength. The stability mechanisms combining horizontal reinforcement and "earth bags" as a gravity retaining wall try to give a more detailed approach to the actual stress situation. Additional mechanisms, especially the increase of shear strength of the geotextile wrapped soil due to compaction and drainage in the plane of the fabric are more important considerations.