Design of Reinforced Soil Slopes and Walls

1. Introduction

The first modern geosynthetic reinforced soil structures were built in France and in the USA in the 1970s when polymeric materials were used to reinforce free draining granular backfill. Although there are several reasons for specifying good quality granular backfill, this requirement has limited the use of reinforced soil structures in cases where such material is not readily available.

The development of suitable polymer based synthetic materials - commonly known as geosynthetics - has led to an increasing application of reinforced soil technology. High tensile strengths at low elongations are the basic requirements fulfilled by certain geosynthetics. For more than 35 years soil reinforcement using geosynthetics has been used in geotechnical engineering to improve the mechanical properties of soil. Dams, bridge abutments, landslide repairs, steep slopes and retaining walls are the most common applications for which reinforced soil is used.

Geosynthetic reinforced walls and slopes are needed in the construction of highways, railways, industrial and commercial areas as well as for landslide repairs and noise protection walls. Further cost benefit can be obtained by using cohesive fill material. However, the drainage aspect within the reinforced soil mass needs to be addressed. Calculations and results from laboratory studies as well as field case histories have shown the efficiency of permeable needle-punched nonwoven reinforcements when used in low plasticity cohesive backfills [1]. High permeability and transmissivity of the geotextile allows drainage of water within the geotextile plane. As a result it allows effective transfer of stresses from the soil to the geotextile at the soil-geotextile interface. This leads to the need for a geosynthetic material which combines both good in-plane drainage properties with high young's modulus and high strength.

This manual provides the knowledge and theory for the design and construction of reinforced soil walls and steep slopes using geosynthetic materials known as TC Polyfelt Rock PEC and TC Miragrid GX. The manual may be used for the design of reinforced soil structures using either cohesive or non-cohesive soils, depending on the type of product.

Although design principles remain basically the same, irrespective of the height of the structure, and geosynthetic structures up to 35 m have been built, the designer is advised to consult experienced geotechnical engineers for all projects. TenCate Geosynthetics Europe maintains a staff of qualified design engineers and can also be retained as design consultant. The designer is advised to obtain professional advice for construction heights exceeding 6 m or where design requirements are complex (high surcharge, step-back structures, poor foundation or backfill conditions, special facings, etc.).

2. Design Parameters

Decisive parameters for the design of reinforced earth structures are:

- The shear parameters of the soil
- Rock PEC or Miragrid GX as reinforcing element (stress-strain behaviour, friction, transmissivity)
- Construction geometry and surcharge load

2.1. Soil

The mechanical and physical properties of soil which are relevant for earth retaining structures are:

- Unit weight of compacted fill material γ [kN/m³]
- Effective internal friction angle φ' [°]
- Effective cohesion c' [kN/m²]

The soil parameters have to be taken into account with an adequate factor of safety to obtain the required design values, which are entered into calculation. In the TC Polyfelt Rock PEC design the cohesion will not be taken into account. However it has to be stated that due to neglecting cohesion and due to the drainage capacity of TC Polyfelt Rock PEC the assumption of considerably improved soil friction properties is correct. For TC Polyfelt Rock PEC reinforced structures the same reduction factor as requested by EC7 may be used for the soil friction properties.

If national codes or standards require different concepts of safety factors, they may be applied accordingly.

2.2. Geosynthetic Reinforcement

The design parameters influencing the performance of reinforced soil are:

- The effective friction angle between the soil and the reinforcement
- The stress-strain behaviour of the reinforcement
- Installation survivability criteria
- Transmissivity if cohesive soil is used as fill material.

The allowable tensile force per unit width of the reinforcement usually depends upon the specific project due to the different kinds of stresses the geosynthetic is exposed to. For this reason the ultimate tensile strength of the geosynthetic usually is divided by several reduction factors which are used to account for potential creep, installation damage and environmental influences.

In the absence of sufficient test data the long term design strength T_{LTDS} can be calculated by the following formula [1]:

$T_{LTDS} = T_{min} / (RF_{creep} * RF_{inst} * RF_{mat} * RF_{env} * \gamma_m)$

RF_{inst}	installation damage
RF_{env}	environmental effects
RF_{mat}	material
RF_{creep}	creep (120 years)
γ_m	material factor of safety

Due to different national standards and guidelines there are different recommendations for the partial factors of safety. Though some of the mentioned values derive from draft versions, they are reasonable and given here as approximate values. It is not allowed to mix up these values between different guidelines. That means that all reduction factors have to be from the same guideline and/or are strongly linked to the product used.

For the design of TenCate reinforced structures, the reduction factors listed in the current product sheets are recommended.

2.3. Soil – Geosynthetic – Interaction

2.3.1. Friction

Ideally it would be useful to perform tests with on-site soil types to obtain adequate and reliable input parameters for the calculation. The friction between the geosynthetic and the adjacent soil is calculated as a function of the internal friction angle of the compacted fill material.
These tests had the result presented in the following table 3a and b.

	Silt/clay	Norm sand
Internal peak friction angle of soil [°]	27	40
Soil to fabric friction angle (Rock PEC) [°]	25	29
Efficiency	0,91	0,72

	Norm sand	Sandy gravel (0/8)	Gravel (0/32)	Gravel (0/45)
Internal peak friction angle of soil [°]	41	43	48	48
Soil to fabric friction angle (Miragrid GX) [°]	38	37	39	39
Efficiency	0,92	0,86	0,82	0,81

Table 3a and b: Frictional efficiencies for frictional soils for TC Polyfelt Geosynthetics acc. EBGEO

Therefore an assumed reduction factor of 0,8 for the coefficient of internal friction may be used to calculate the coefficient of friction between the soil and TC Polyfelt Rock PEC:

$$\tan \varphi'_{soil\text{-}gs} = 0{,}8 * \tan \varphi'_{soil\text{-}soil}$$

Comparative pullout tests on TC Polyfelt Rock PEC and geogrids in cohesive water-saturated soils have yielded shear strength values which are approx. 50% higher for Rock PEC than for the grids (see fig. 3) [3].

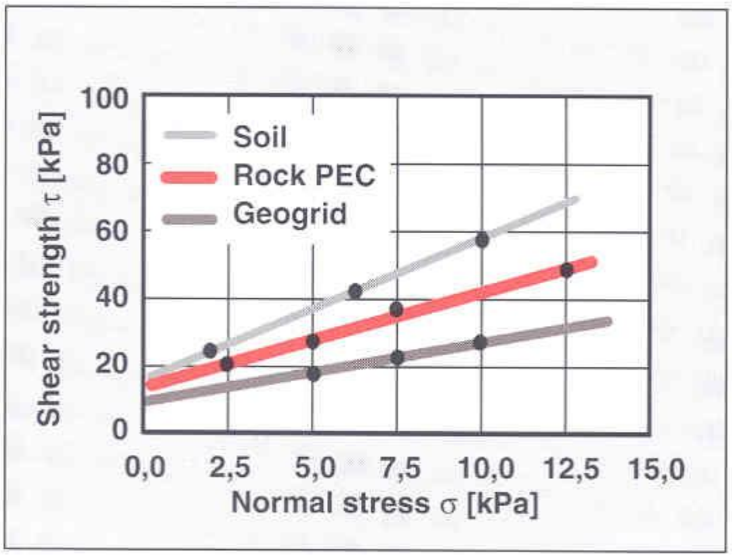


Figure 3:
Pullout test results in saturated clay [3]

2.3.2. In Plane Drainage Capacity

Commonly, free draining granular backfill will be preferred as fill material due to its ability to transfer shear stresses effectively. In that case TC Miragrid GX is the sufficient product. However, in places where such materials are not readily available, the use of poor quality backfills may be considered. In those cases the reinforcing elements must have adequate reinforcing properties and drainage capability.

In fine grained and poor draining soils excess pore water pressures u might build up immediately with installation, compaction or surcharging of the soil. For a normal shear test the relation between u and the shear stress τ is given by

$$\tau = c'_{soil\text{-}gs} + (\sigma - u) \tan \varphi'_{soil\text{-}gs}$$

If the pore water pressure is reduced (by a sufficient in-plane drainage capacity of the geotextile), the transferable shear stress and thus the shear resistance of the soil and the pullout resistance of the geosynthetic is increased.

Large scale pullout tests in saturated clay have shown that the shear strength of TC Polyfelt Rock PEC is approx. 50% higher than that of geogrids [3] (see figure 3).

Figure 4 shows the results of an experimental retaining structure, which was constructed to investigate the possibility of using poor and wet soils [4]. High-strength nonwoven geotextiles like TC Polyfelt Rock PEC with additional drainage capability showed an immediate dissipation of excess pore water pressure during construction.

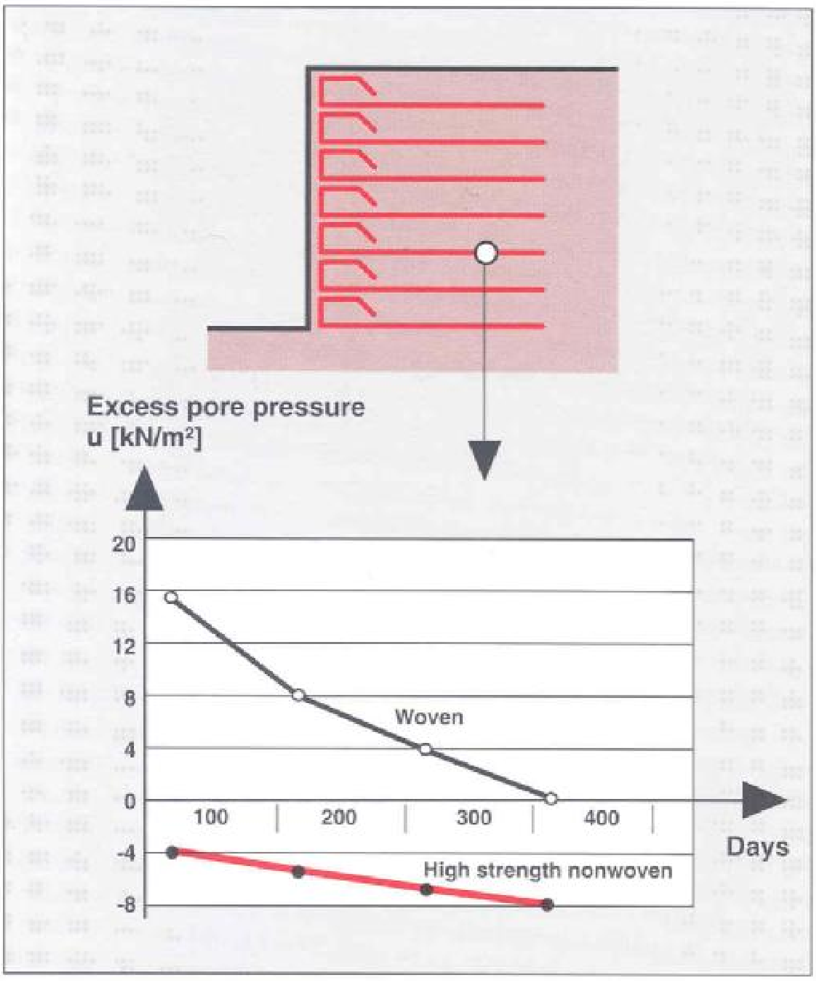


*Figure 4:
Pore water pressure recorded in an experimental retaining structure [4]*

2.4. Wall / Slope Geometry

2.4.1. Height and Surcharge Loads

In most cases height H and inclination b of the reinforced soil mass will be given. Therefore they are decisive input parameters for any design calculation. A surcharge load may be taken into account as additional (virtual) height of the structure. The geotextile reinforcement of a reinforced structure with a height H and a surcharge q is then designed for the same (but unloaded) structure with the virtual height H':

$H' = H + q/\gamma$

where g is the unit weight of the installed soil. This assumption is limited to

$q/\gamma < 0{,}1 * H$

2.4.2. Reinforcement Length

The required reinforcement length of a geosynthetic reinforced structure can be defined by two limiting conditions:

- pull out failure (usually a problem of internal stability)
- sliding failure for steep and narrow constructions.

Traditionally the minimum length of the reinforcement has been empirically limited to 0,8 * H. Current research indicates that walls on firm foundations which meet all external stability requirements can be safely constructed using lengths as short as 0,5 * H [5]. In any case it has to be proved that both in the active and in the passive zone a sufficient anchorage length L_e is available.

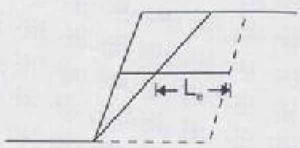
The length of the fabric layers L_e in the anchorage zone is influenced by the following parameters:

- Design strength of the geosynthetic reinforcement

- Normal pressure induced by the overlaying soil and external surcharge loads

- Friction angle of the adjacent soil taken into account with an adequate reduction factor, respectively the soil to fabric friction angle obtained from site-specific pull out – and friction tests.

$$L_e = T_{des} \,.\, FS / [2 \,.\, ([\gamma \,.\, \Sigma h] - u) \,.\, \tan(\varphi'_{soil\text{-}geot})]$$



2.4.3. Spacing of the Reinforcement

The vertical spacing of the reinforcement depends mainly on the compatibility of the fill material.
TenCate recommends a vertical spacing of the reinforcement of 50-60cm. This depends on national specifications. The soil should be installed in two 30cm thick layers which shall be compacted separately. Otherwise a sufficient compaction can not be performed.

Once vertical spacing exceeds 60 cm there is an increased tendency for soft facings to sag. Such a serviceability failure does not enhance aesthetics.

3. External Stability Check

In practice for geosynthetic reinforced slopes and walls, the methods normally employed for designing gravity type systems will be used for the external stability check. Where appropriate national codes or standards exist, these methods may also be used for TC Polyfelt Rock PEC reinforced retaining slopes and walls.

The following design is suggested to check the external stability. As with classical unreinforced structures, four potential mechanisms of external failure are usually considered for reinforced soil structures (see figure 5):

- Sliding on the base
- Overturning (for reinforced steep slopes and walls only)
- Bearing capacity failure
- Overall stability (deep seated rotational slip surface or slip along a plane of weakness).

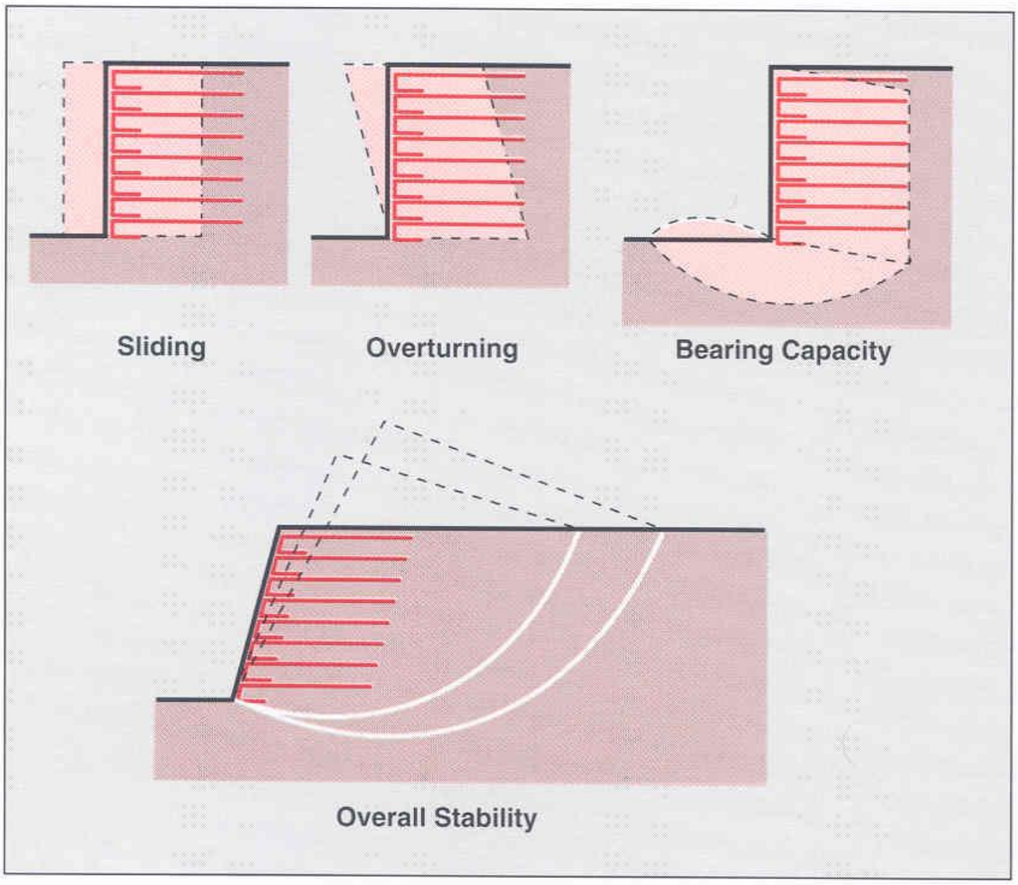


Figure 5:
External failure modes

Any suggested factors of safety for the failure mechanisms may require modification in accordance with existing national standards.

3.1. Sliding

The reinforced soil structure has to be sufficiently wide to resist sliding along the reinforcement. To check sliding stability a wedge type failure surface behind the ends of the reinforcements is assumed. The reinforced soil mass is taken into account as a rigid structure. The factor of safety FOS sliding is defined as the ratio between Resisting Force P_r and Sliding Force P_{sl}.

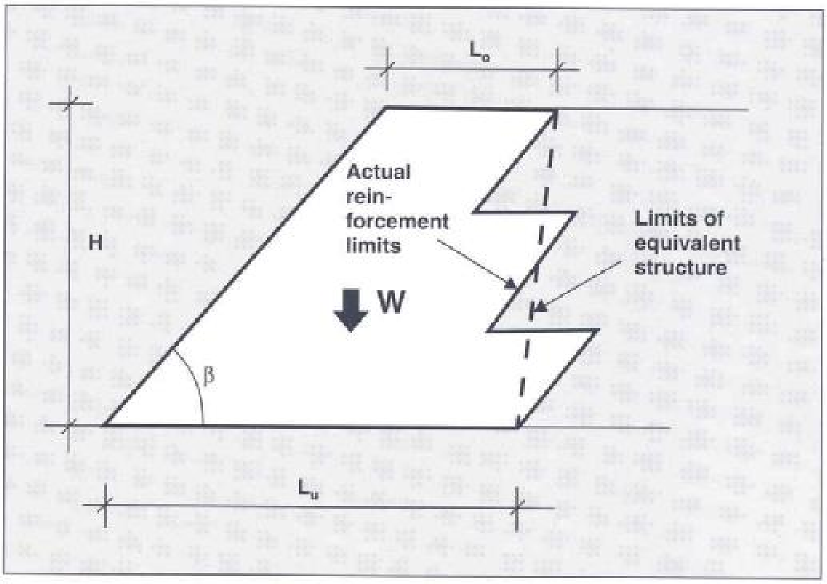


Figure 7:
Parameters for the evaluation of sliding stability of geotextile reinforced slopes

Calculation steps are as follows :

1. Determine the lateral earth pressure coefficient K_a

$$K_a = \frac{\cos^2(\varphi'+\alpha)}{\cos^2\alpha\left[1+\sqrt{\dfrac{\sin(2\varphi')\sin\varphi'}{2\cos(\alpha-\varphi')\cos\alpha}}\right]^2}$$

where

φ' internal friction angle

α inclination angle between the vertical and the slope

2. Calculate the horizontal thrust

$P_{sl} = 0{,}5 \cdot \gamma \cdot H^2 \cdot Ka - 2 \cdot c \cdot H \cdot \sqrt{Ka} + q \cdot Ka \cdot H$

3. Calculate the resisting force

$P_r = W \cdot \tan\varphi' + c' \cdot L_e$

where

φ' the lesser of the friction angles:

φ'_f friction angle of foundation soil

φ'_{soil} friction angle of the reinforced soil

$\varphi'_{soil/geot}$ soil-reinforcement friction angle

W weight of reinforced soil mass

4. Check that the safety factor is greater than 1,5.

$FS_{sliding} = Pr / P_{sl} > 1,5$

5. If not, increase the reinforcement length at the base of the slope or both at the base and the top of the slope.

3.2. Overturning

(for steep slopes and walls only).

Owing to the flexibility of reinforced soil structures, it is unlikely that a block overturning failure could occur. Nonetheless, an adequate factor of safety against this classical failure mode will limit excessive out-ward tilting and distortion of a suitably designed wall.

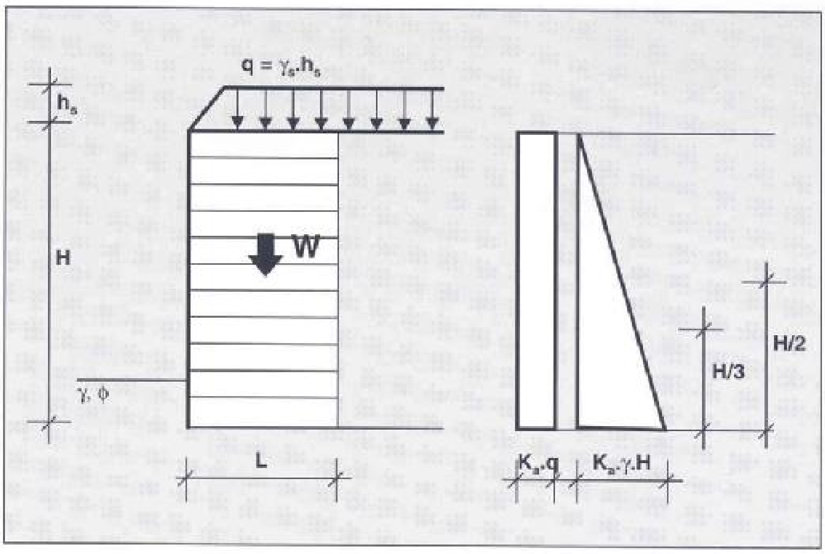


Figure 6: Parameters for the evaluation of sliding and overturning stability of geotextile reinforced retaining walls.

Overturning stability is analyzed by considering rotation of the wall over its toe. It is required that:

FS = resisting / driving moments > 2.

The resisting moments result from the weight of the reinforced fill, the vertical component of the thrust, and the surcharge applied on the reinforced fill (dead load only). The driving moments result from the horizontal component of the thrust exerted by the retained fill on the reinforced fill and the surcharge applied on the retained fill (dead load and live load).

The calculation shall be done in the following steps:

1. Calculate the driving moment

$M_D = P_a . H/3$

2. Calculate the resisting moment due to the weight of all the mass above the base:

$M_R = W . L/2$

3. Calculate the factor of safety

$FSO = (W . L/2) / (P_a . H/3)$

and check that it is greater than the required value.

4. If not, increase the reinforcement length.

5. Calculate the eccentricity e, of the resulting force at the base of the wall and check that eccentricity does not exceed L/6. If e > L/6, increase the reinforcement length.

3.3. Bearing Capacity

For undrained cohesive soils the bearing capacity of any foundation may be roughly calculated using classical soil mechanics methods which use limit equilibrium analyses. Consideration must be given to the thickness of possible underlying deposits with respect to the reinforced section. High lateral stresses in the confined cohesive stratum beneath the reinforced section could lead to a lateral squeeze or plastic flow type failure. The shear forces developed under the reinforced section should be compared to the corresponding shear strength of the soil. The external stability may be checked using the Prandtl Formula [6]

$p_u = c_u (2 + \pi) = \gamma * H * FS$

The bearing capacity failure load depends on the undrained shear strength of the foundation soil. The required factor of safety is 2. This safety factor is lower than normally used. It may be applied due to the flexibility of the structure and if subsurface investigations are performed. Where the bearing stratum consolidates within the design life of the wall or slope it is also necessary to check the drained bearing capacity to ensure that this is adequate.

3.4. Overall Stability

Overall stability is determined using rotational or wedge analyses, as appropriate, which can be performed using a classical slope stability analysis method. Computer programs are available for most of them. The reinforced soil wall is considered as a rigid body and only failure surfaces completely outside a reinforced mass are considered.

For simple structures with rectangular geometry, relatively uniform reinforcement spacing and a near vertical face, compound failures passing both through the unreinforced and reinforced zones will not generally be critical.

However, if complex conditions exist such as changes in reinforced soil types or reinforcement lengths, high surcharge loads, sloping faced structures, stepped back or otherwise stacked structures, compound failures must be considered. If the minimum safety factor is less than the required value, increase the reinforcement length or improve the foundation soil.

4. Internal Stability Check

For the internal stability a sliding mechanism is assumed to occur following certain failure surface. On this failure surface the equilibrium of forces has to be checked. The weight of the sliding soil mass acts as disturbing force, cohesion and friction cause restoring forces. The tensile force of the reinforcing elements is taken as required restoring force to obtain an adequate factor of safety.

Geotextile-reinforced structures are characterized by the possibility of attaining high levels of deformation before failure of the reinforcements occurs. The stress-strain behaviour of soil, of the reinforcing elements and the interaction mechanism between the two, have to be taken into account to evaluate the deformation of geosynthetic reinforced constructions. Although complex finite-element models or other computer programs are available to evaluate these requirements they normally are to complicated and time consuming for everyday use by the geotechnical engineer.

4.1. Design Methods

Current design methods are based upon limit equilibrium state calculations. Two design methods are commonly used for reinforced soil structures:

- „Lateral earth pressure method“ acc. Rankine
- „Slip circle analysis“ e.g. acc. Bishop

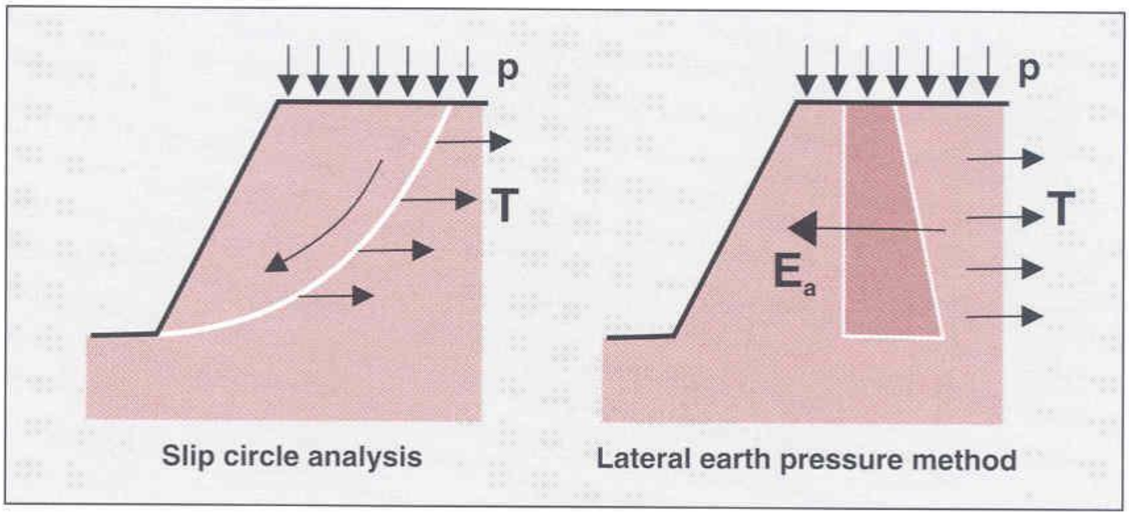


Figure 8:
Design methods for internal stability

4.1.1. Lateral Earth Pressure Method

The design is done by calculating the total active earth pressure, which then has to be taken up by the tensile forces in the reinforcing geosynthetic layers. The total earth pressure E is divided by the number of layers, resulting in a required design tensile force T_{des}. This minimum value has now to be reached by the ultimate tensile strength T_{ult} (see section 3.2).

Design Steps [1]:

1. Establish geometric and loading requirements for design (wall height H, wall inclination angle a, external surcharge loading q, spacing of reinforcing layers).

2. Determine engineering properties of foundation soil and available fill material (shear parameters c', j'; unit weight g, consolidation parameters), soil profile below the base of the wall, location of groundwater table, compaction characteristics of fill material, chemical characteristics of the backfill that may affect the durability of the reinforcement.

3. Check internal stability evaluating the earth pressure, which then has to be taken up by tensile forces in the reinforcing geosynthetic layers.

4. Check external stability as described in chapter 4.

4.1.2. Slip Circle Analysis

Another method is to assume a sufficient number of slip surfaces and to check the stability in each of these failure surfaces (e.g. acc. Bishop). Although experience shows that this failure mechanism is closer to reality, it is a disadvantage that a certain number of design calculations have to be done. Therefore slip circle analysis is often done with computer programs.

A special feature to take into account deformations is used by the "displacement method" [7]. With this method both geometry and stiffness of the geosynthetic reinforcement can be taken into account for design.

4.2. TC Polyfelt Design method

The TC Polyfelt design method has been established using the lateral earth pressure method. Additional control calculations were done using the displacement method [7].

For this method the total active earth pressure was calculated and simplified to a uniform rectangular distribution over the wall height. This resulting force is then divided through the number of geotextile layers to obtain the required geotextile strength.

5. Literature

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