Design Funundamentals for Geosynthetic Soil Technique

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ABSTRACT: The contribution introduces the general basis for the design and application of geosynthetic soil technique in view of the current status of the European standardization, which contemporary describes the position of development and scientific knowledge in the European countries. The paper provides a survey of the limit state concept, based on Eurocode 1 (actions on structures) and Eurocode 7 (geotechnical design), which shall be represent the fundamentals for the design of earth structures including geosynthetic soil technique. Furthermore the paper considers the assessments of the European Standard prEN ISO 10318 concerning the geosynthetics terminology and functions as well as the guidelines and recommendations of the newest product of the European standardization prEN 14475: Reinforced fill, which contents the execution of special geosynthetic work. The further particulars of the contribution have a synopsis in view on the design fundamentals of various geosynthetic soil techniques in consideration of geosynthetic testing concepts. In this context the comments deal with the design principles on basal reinforced embankments with and without piled foundation, reinforced fill slopes and walls and reinforced bearing layers as well as on the geosynthetic techniques for waterways, coastal protection measures and finally for landfill structures.

1 INTRODUCTION

Geosynthetic soil techniques are used extensively for a range of design lives and service requirements since about five decades. The field of applications has expanded constantly and is still in an active stage of development and research. The evolution of various geotechnical design methods and their establishment in different national codes has lead to different design approaches being adopted in different countries.

The current state of development and know-how in civil engineering is represented by an uniform and consistent European program of standards and guidelines for the countries of the European Union and the EFTA. In 1975 the Commission of the European Union decided an action program according to art. 95 of the treaty pact, and in the frame of this program the arrangement of technical rules (Eurocodes) for the design planning of civil engineering projects.

These Eurocodes (EC) - published by CEN – content general normative and informal constructive rules on the planning and design of structures and on the application of construction materials. In 1989 it was decided to put the EC on the status of European Standards and this work is now nearly completed. Nevertheless in a transition period it is allowable to supplement the European standards by national documents.

The following discourse should introduce the general basis in design and application of geosynthetic soil techniques in view of the European standardization, which at the same time represents the state of development and research in the European region.

2 BASIS OF GEOTECHNICAL DESIGN (EC1/EC7)

2.1 *Limit state concept*

2.1.1 *General considerations*

The design of earth structures including geosynthetic soil technique, shall be based on EN 1991, Eurocode 1 (actions on structures) and EN 1997, Eurocode 7 (geotechnical design). In the context of these codes two criteria are applied to define failure. The first is the ultimate limit state of collapse, the second is the serviceability limit state, which occurs when deformations of the soil, or strains within structural elements, exceed prescribed limits. Thus limit states can occur either in the ground or in the structure or by combined failure.

For each geotechnical design situation it shall be verified that no relevant limit state is exceeded. In order to establish minimum requirements for geotechnical investigations, calculations and construction control checks, the complexity of each geotechnical design shall be identified together with the associated risks. The detailed specifications as well as the loading conditions, including accidental loads and transient loads during construction, climatic effects and hydraulic conditions, shall be taken into account for both short-term and long-term design situations.

To establish geotechnical design requirements, three **Geotechnical Categories** are introduced, divided to the risk in terms of overall stability, ground movements as well as soil and loading conditions. A preliminary classification of a structure according to the geotechnical category should normally be performed prior to the geotechnical investigations. The category should be checked and changed, if necessary, at each stage of the design and construction process.

The design should take into account reasonable construction tolerances in regard to vertical and horizontal alignments, levels and layout. Consideration should be given to the ability of the structure to tolerate anticipated magnitudes of total and differential settlement, frost heave, deformation and movement. Special considerations shall be made on deformations when earth structures are combined with or located adjacent to rigid structures.

At the geotechnical design stage, the significance of environmental conditions shall be assessed in relation to durability and to enable provisions to be made for the protection or adequate resistance of the materials.

2.1.2 *Ultimate limit states*

The design of earth structures including geosynthetic techniques shall be based on a partial safety concept. This concept and the proper partial safety factors, defined in EN 1997 (annex A) for persistent and transient situations, concern the following components of ultimate limit states which shall be verified, where relevant:

- loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of structural materials and the ground are insignificant in providing resistance (EQU)
- internal failure or excessive deformation of the structure or structural elements, in which the strength of structural materials is significant in providing resistance (STR)
- failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO)
- loss of equilibrium of the structure or the ground due to uplift by water pressure or other vertical actions (UPL)
- hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients (HYD)

2.1.3 *Serviceability limit states*

Serviceability limit states are attained if deformations occurring within the design life exceed prescribed limits.

Verification for serviceability limit states in the ground or in a structural section, element or connection, shall either require that the design value of the effect of an action (E_d) must be less than the limiting design value (C_d):

$E_d \leq C_d$

Values of partial factors for serviceability limit states should normally be taken equal to 1.0, or may be set by the national annex.

2.2 *Design by calculation*

Design by calculation presumes a reliable model and shall be in accordance with the fundamental requirements of EN 1990 / EN 1997, considering the concept of partial safety factors. The design requirements shall be based on two categories of fundamental values:

2.2.1 *Characteristic and representative values*

- of actions (in accordance with EN 1990:2002 and EN 1991),
- of geotechnical parameters derived from tests, complemented by experience
- of geometric data based on measured, nominal or estimated levels, e. g. of ground, ground-water or free water

2.2.2 *Design values*

- of actions assessed directly or derived from representative values considering partial factors in accordance with EN 1990:2002
- of geotechnical parameters, assessed directly or derived from characteristic values considering partial factors
- of structural properties, there are strength properties of materials and resistances of structural elements, calculated in accordance with EN 1991 to 1996 and EN 1999

It should be considered that properties of soil and rock masses, as quantified for design calculations by geotechnical parameters, shall be obtained from test results, either directly or through correlation, theory or empiricism, and from other relevant data. The reliability of these parameters depends on the knowledge of the soil conditions as well as on the extent and quality of the geotechnical investigations.

2.3 *Design by prescriptive measures*

In design situations where calculation models are not available or not necessary, exceeding limit states may be avoided by the use of prescriptive measures. These involve conventional and generally conservative rules in the design, which may be given in national annexe (EC 7).

2.4 *Load tests and tests on experimental models*

When the results of load tests or tests on (large or small scale) models are used to justify a design, the following features shall be considered:

- differences in the ground conditions between the test and the actual construction
- time effects, especially if the duration of the test is much less than the duration of loading of the actual construction
- scale effects, especially if small models are used. The effects of stress levels shall be considered, together with the effects of particle size

2.5 *Observational method*

When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as "the observational method", in which the design is reviewed during construction.

3 GEOSYNTHETICS TERMINOLOGY, FUNCTIONS AND TESTING

3.1 *Terms related to products and principal functions*

The geosynthetics terminology may be based on the subdivisions by prEN ISO 10318. According to this standard **"Geosynthetic"** is a generic term describing a product, at least one of whose components is made from a synthetic or natural polymer, in the form of a sheet, a strip or a three dimensional structure, used in contact with soil and/or other materials in geotechnical and civil engineering applications. According to Figure 1 geosynthetics can be differentiated into permeable and impermeable products.

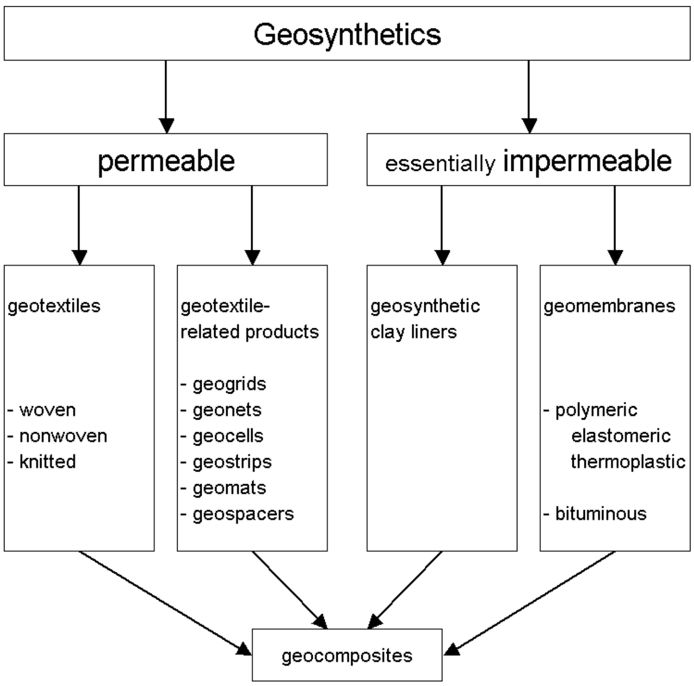

Figure 1: Geosynthetics subdivision (prEN ISO 10318)

The terms related to the principal functions of geosynthetics are also defined in prEN ISO 10318 and furthermore in the European standard CEN Item 7 "Terms and their definition". These terms have regard to the use of geosynthetics for:

- **Drainage**, to collect and transport fluids
- **Filtration**, to allow passage of fluids while preventing passage of soil particles
- **Protection**, to prevent damage of a layer
- **Reinforcement**, to improve the shear resistance of a soil
- **Separation**, to maintain the integrity of a soil layer
- **Erosion control**, to prevent soil erosion by water or wind forces
- **Barrier**, to prevent the migration of liquids or gases

The principal use of a geosynthetic material requires sometimes combined functions. For instance there are potential advantages in combining the separation and reinforcement function of geosynthetics in construction over poor ground.

3.2 *Concepts of testing*

Three basic levels of testing are considered for geosynthetics:

- **Index testing**. Testing carried out under standardized conditions used to compare the basic properties of products.
- **Quality control testing**. Rapid testing to assure continuity of quality.
- **Performance testing**. Testing of geosynthetics in contact with a soil under standardized conditions in the laboratory, to provide a better simulation of site conditions than index testing. Performance testing may also be carried out at full-scale on site.

A number of test methods presently available have been published in the ISO and EN series besides various national standards (e.g. BS, ASTM, DIN, NF) and these will be supplemented or superseded. The majority of these tests will relate to index or quality control testing:

The tests must be in conformity with the requirements of the specific application and with the problem oriented design. The behaviour of polymer materials depends on time and temperature. Exemplary for polymeric reinforcement base strength at a selected design life knowledge of the stress and strain properties is essential. Thus the base strength of a polymeric reinforcement should be lower than the base strength with respect to tensile creep rupture or creep strain. In the case of cohesive soil reinforcement where the gain in strength and consolidation is slow consideration may need to the stress relaxation.

The use of polymer materials in the ground possibly causes changes in the material behaviour because of mechanical damage and the soil chemical and biological environment. The definition of durability is the ability to maintain requisite properties over the selected design life. That means for geosynthetics: the ageing effects of UV exposure or ozone degradation or the combined effects of temperature and stress, and secondary effects due to chemical degradation. In respect of tensile creep rupture, all of these variables will interact. Depending on site specific aspects it may be not necessary to consider all of the possible environmental hazards which could affect the performance of geosynthectis. For instance the risk of attack of aggressive fluids can often be dealt with by using preventative design measures such as the installation of impermeable barriers and effective drainage systems.

4 GEOSYNTHETIC REINFORCED SOIL TECHNIQUE

4.1 *General design principles*

- The soil reinforcement by geosynthetics generates a mechanical improvement of the soil by supporting tensile forces. The reinforcing elements are flexible and, due to their low bending stiffness, can only absorb axial tensile loads. The improvement acts to reduce the shear force that has to be carried by the soil, and to enhance the shearing resistance in the soil by increasing the normal stress acting on potential shear surfaces. (Figure 2)

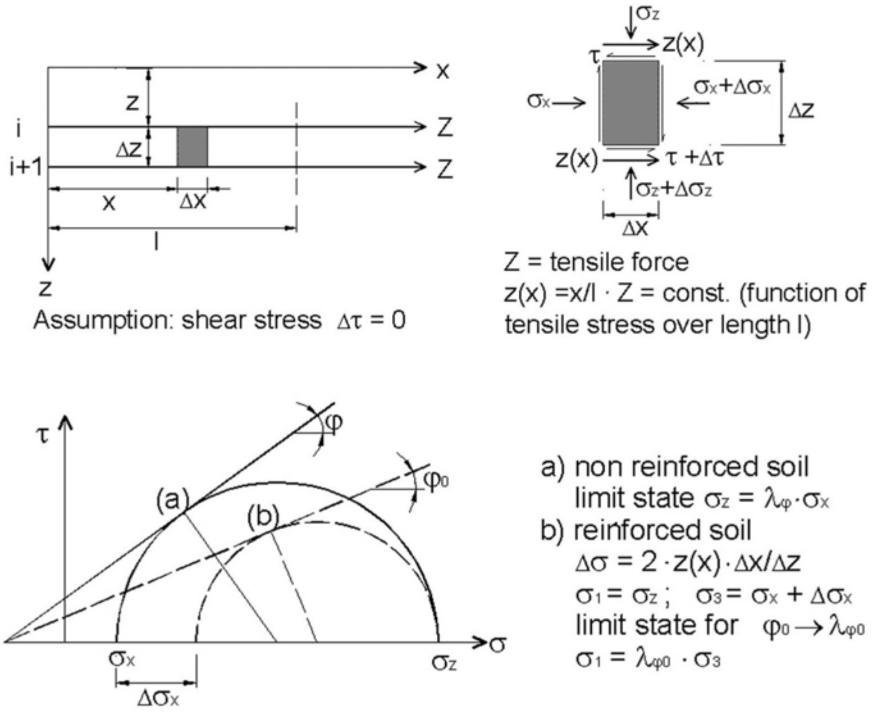

Figure 2: Interactive forces between reinforcement and subsoil, influence on the limit state (assumption: $\Delta\tau = 0$). Ref. [3]

- The design of geosynthetic reinforced soil structures shall be based on the fundamentals of the Eurocodes EC 1/ EC 7 as outlined in sect. 2. That means: The soil reinforcement design may be governed by an ultimate limit state of collapse or a serviceability limit state. These should be considered in terms of both external and internal stability in the case of all reinforced soil applications. A fundamental principle of limit state design is that the design strength should be equal to or greater than the design load.

  In the case of external stability the design load may be resisted by forces generated in the soil including pore water pressure and soil shear strength. For each failure mode, prescribed load factors and material factors are appropriately applied to ensure that the factored restoring force equals or exceeds the factored disturbing force.

  The internal stability of a reinforced soil mass is governed by the interaction between soil and reinforcement. This interaction occurs by friction or adhesion. In terms of this interaction the ultimate limit state can be brought about by either rupture of the reinforcement or failure of the bond between the soil and the reinforcement. The two properties of interaction, the coefficient of direct sliding and the bond coefficient (pull out resistance) are needed for design.

  In considering the ultimate limit states of collapse of the reinforced soil the resisting forces generated by reinforcement will be reduced by a material factor. The design strength may be determined by dividing the unfactored reinforcement base strength by a prescribed value of the partial material factor.
- The design strength employed may be dictated by considerations of a serviceability limit state, whereby the concept depends on the end use of the structure as a rule. Normally serviceability limits for reinforced soil are prescribed in terms of acceptable deformations considering the creep properties of the material. Ref. BS 8006:1995 / prEN 14475.
- The variation over time of the required reinforcement effect is an important factor governing the selection of suitable geosynthetic material. In the case of embankments or foundation layers it may be only required to support stability during the initial critical phase of construction and consolidation up to the ground has increased in strength. Against it in the case of walls, abutments and slopes the reinforcement has to maintain stability throughout the life of the structure, so that creep characteristics of a geosynthetic usually govern the selection. Ref.: Jewell 1996 [13].

4.2 *Geosynthetic reinforced embankment foundations*

4.2.1 *Basal reinforced embankments*

In an embankment foundation constructed over soft soil the principal tensile strain is horizontal directed, so that the mode of potential failure is characterized by lateral spreading and extrusion. This mode of failure can be prevented by the inclusion of horizontally inclined reinforcement at the interface of the embankment fill and the foundation soil. The reinforcement absorbs the outward shear stresses of the embankment slopes and imparts an inward shear stress onto the surface of the soft foundation due to its bond and stiffness characteristics.

The design strength of the reinforcement will be governed by either the tension needed to provide lateral stability of both the fill and the ground, or by the tension necessary to provide rotational stability of both the fill and the foundation ground.

For design analysis technique plasticity solutions or equilibrium methods or continuum methods, i.e. finite element and finite difference methods can be used. As examples for limit equilibrium methods Figure 3 shows a disc model and Figure 4 a block model both for mode of failures involving the embankment fill and the foundation ground.

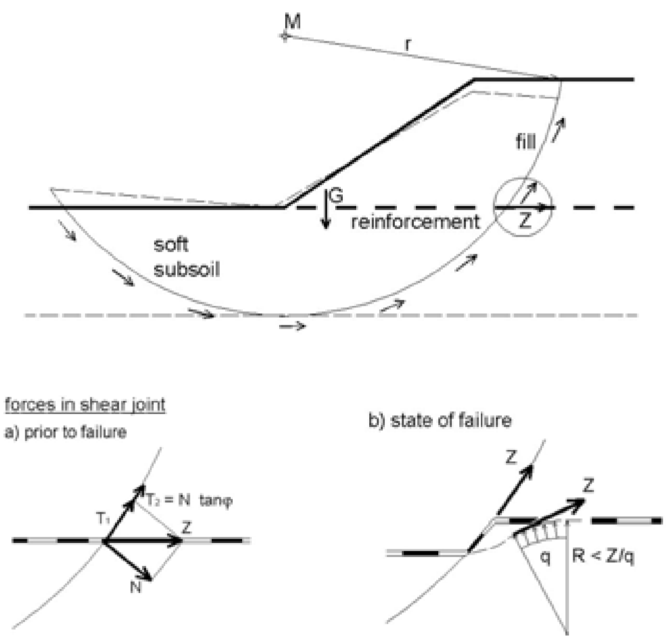

Figure 3: Disc-model for slope foundation failure with local application of tensile force of the reinforcement at foundation level. Ref. [3].

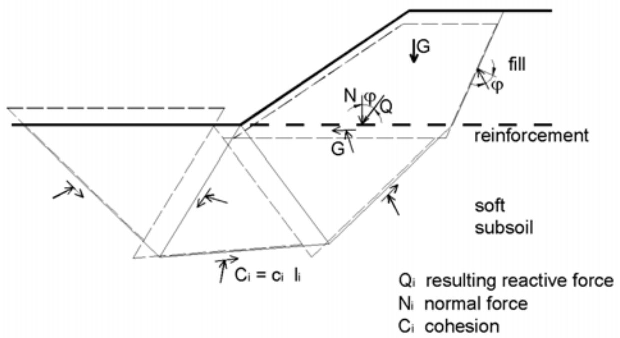

Figure 4: Block model consisting of several displaced elements for slope failure with the approach of global displacement. Ref. [3]

The experience with the models in Figure 3 and 4 can be summarized as follows: Ref. [3]:

- The model with local application of tensile force (Figure 3) neglect the changes in direction of forces and failure geometry resulting from system displacements parallel to the reinforcement. However, the obtained solution yields results which are on the safe side. The permissible tensile force has to be sufficiently high and comply with the given safety margin of the design. The approach on the basis of this conventional failure method can only be applied in cases where the soft subsoil extends to great depth and the failure can develop freely.
- The model consisting of displaceable elements (Figure 4) makes allowances for the flow of forces and considers the displacements of the soil along the reinforcement level. Its application is advisable as well in cases where the soft subsoil extends far below the potential failure zone and where the boundary of the bed is shallow. When the failure zone reaches the lower boundary of the soft layer this leads to a compulsory slip joint. In this case, the system fails mainly because the soft soil is squeezed out.

  Design charts based on plasticity solutions enable a reinforcement soil bond coefficient to be chosen, thus enabling a limit to be placed on the magnitude of the resulting reinforcement tension. Limit equilibrium methods based on the slip circle approach always assume that full bond is realised. Continuum methods provide the most accurate approach however, good reinforcement/soil interaction models are required within the software. Ref. Jewell 1996 [13], Lawson 2001 [16].

  For the design of stiffness and tensile strength of the reinforcement it is essential that the reinforcement acts stiffer than the adjoining soil so as to activate the shear forces. Assuming that the deformation of the reinforced and non-reinforced system at failure is approximately the same, it follows that the strain of the reinforcement, when activating the assumed tensile forces, must be less than the critical deformation of the soil.

  The design life of the basal reinforcement is only the time needed for the foundation soil to attain a definite degree of consolidation. As the soil consolidates the reinforcement becomes more and more redundant.

4.2.2 *Basal reinforced piled embankments*

Piled embankment foundations combined with basal geosynthetic reinforcement are used to control both initial stability and settlement, respectively differential settlement, of the embankment. The complex foundation interaction problem is created by the difference in compressibility between the incompressible pile caps and the compressible soft foundation soil. This difference causes an arching effect in the embankment fill between adjacent pile caps. Examples of principal failure mechanisms in ultimate and serviceability states are shown in Figure 5 and 6.

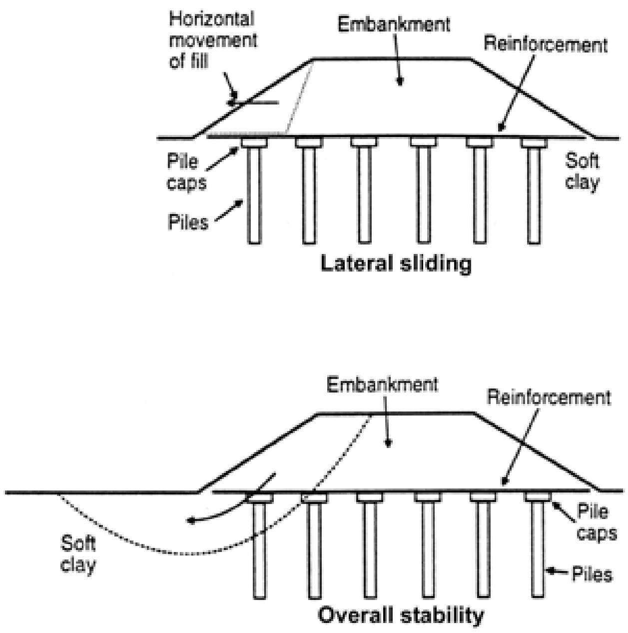

Figure 5: Ultimate limit states for basal reinforced piled embankments. Examples according to BS 8006:1995

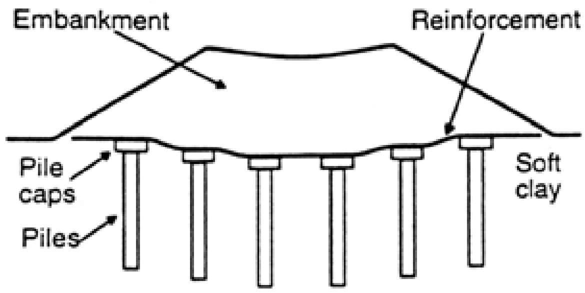

Figure 6: Serviceability limit states for basal reinforced piled embankments. Example for reinforcement strain and foundation settlement according to BS 8006:1995

The design methods promoted range from formalised methods, such as BS 8006:1995, to simplified hybrid 2-dimensional methods and 3-dimensional methods, depending on the placement of the piled foundation and the pile cap spacing. Current design procedures disregard the support of the soft foundation between the pile caps because it is wide unknown at what point in time an equilibrium condition is reached, where the foundation soil supports the unarched embankment loads transferred to the geosynthetic reinforcement. Therefore the current safe design calculations generate relatively high tensile loads in the reinforcement. Considering the serviceability limit state critical requirements should be measured in terms of acceptable differential deformation. In particular for low-height piled embankments the requirement must be to ensure the differential deformation in allowable limits by optimisation the design of minimum embankment height, maximum pile cap spacing and minimum geosynthetic reinforced tensile strength and stiffness. Lawson (2001), Ref. [16].

Foundation support beneath the reinforcement has a marked effect on reducing the loads carried by the reinforcement, Jones et al. (1990), Ref. [14].

4.3 *Geosynthetic reinforced fill slopes and walls*

4.3.1 *Mechanism and interaction features*

For reinforced fill walls and steep slopes there is a common mark that the design loads will be transferred to the reinforcement from the soil in the active zone near the face of the wall or slope. To effect internal stability of the reinforced soil mass these loads will be transferred by the reinforcement into the stable, resistant zone of soil behind the active zone, Figure 7,8.

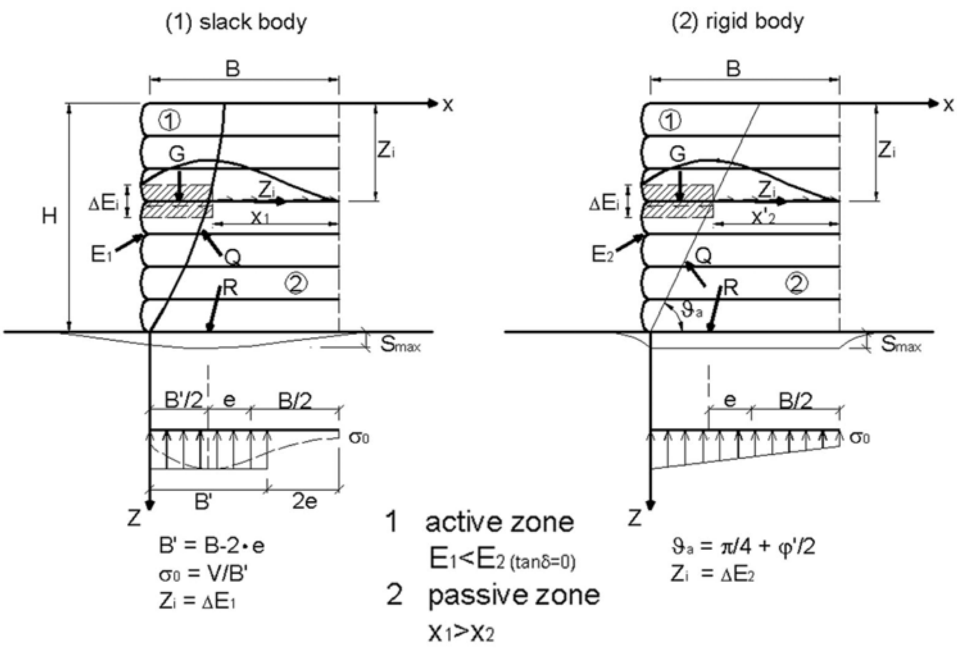

Figure 7: Comparison of models: (1) slack body and (2) quasi-monolithic earth body with regard to their settlements, base pressure σ_0, earth pressure E, and tensile force of reinforcement Z_i, Ref. [3].

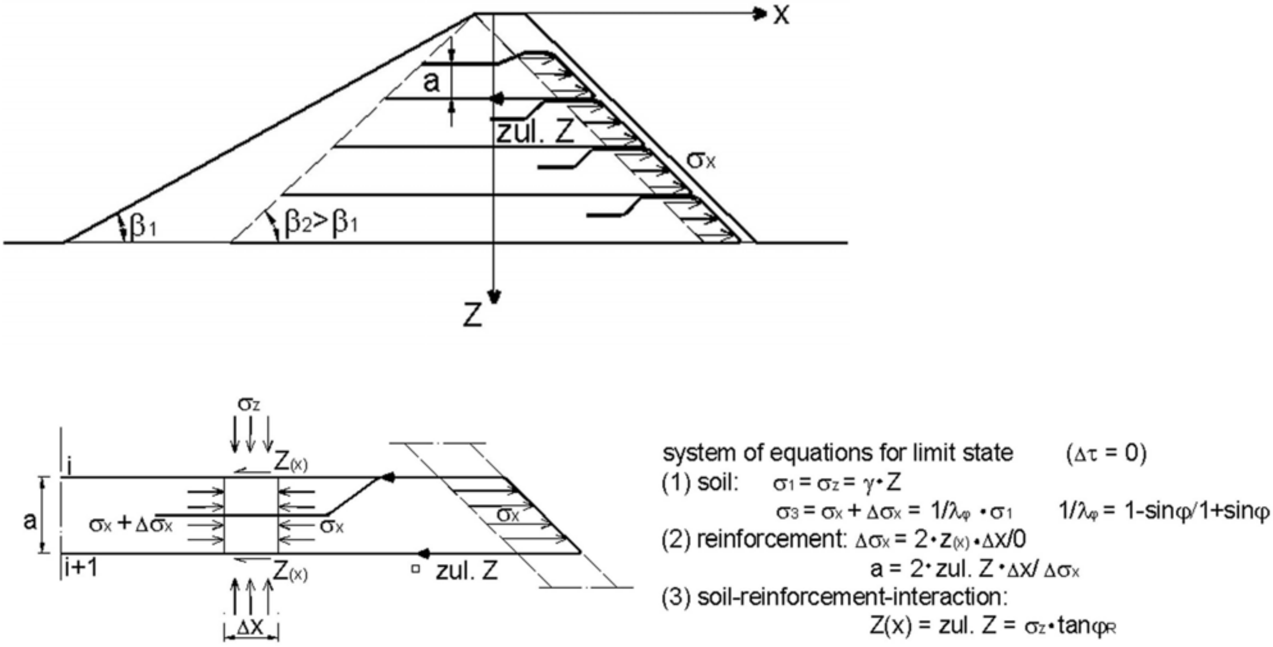

Figure 8: Interactive forces for the limit state of a steep fill slope constructed according to the principle of the so-called bolster dam, Ref. [3].

The load transfer will absorb tensile strains developed in the soil in the active zone. These tensile strains are transferred from the soil to the reinforcement by interaction of soil / reinforcement bond. The tensile strains generate in their turn corresponding tensile forces in the reinforcement in the active zone.

4.3.2 *Classification*

Reinforced fill slopes and walls are constructed using successive layers of compacted, selected fill incorporating intervening layers of horizontal or sub-horizontal fill reinforcement placed at spacings required by the design.

Geosynthetic reinforced slopes can be classified as being steep or shallow depending on their slope inclination. Classifications with the usual types of facings are given for example in BS 8006:1995 and rather similar in prEN 14475, Figure 9 and 10.

Geosynthetic reinforced soil walls act as earth retaining structures, based on Eurocode EC 7, in which the reinforced elements transfer forces imposed by the loads of the reinforced fill, the backfill, the surcharge and external loading actions. According to the systems shown in Figure 10 walls can be classified in vertical, battered an incline types. Standard types are marked by a level crest and particularly foundation.

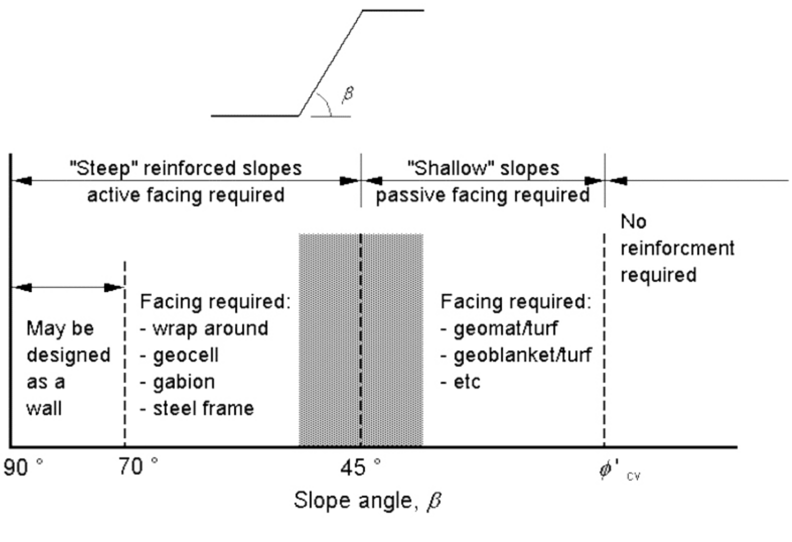

Figure 9: Classification of reinforced fill slopes according to BS 8006:1995.

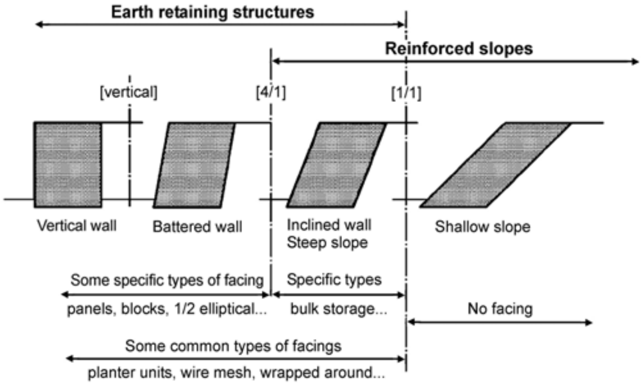

Figure 10: Classification of reinforced fill slopes and walls according to prEN 14475

4.3.3 *Slope and wall facing*

Facings are an integral component of reinforced design. As shown in Figure 10 reinforced fill earth retaining structures require an active facing to retain the fill between the reinforcing layers.

The facing can be constituted of either hard units (typically made of concrete), or deformable units (typically made from metal, steel grid or mesh, or gabion baskets), or soft units (typically made from geosynthetics sheets or grids, or woven wire mesh). Alternatively, the facing units may be formed as fabric containers filled with soil. Examples of facing systems are described in prEN 14475, Annex C.

The wall facings are structural components, however the standard design assumption is, that the facing panels do not contribute to the stability of the retaining system. Typical facing systems for reinforced soil walls are for example partial and full height panels, segmental concrete blocks, semi elliptical steel faces, steel wire grids, gabion baskets and, more for shallow inclined walls, formeworked wrapped around or bagged faces.

The facing system should enable construction within specified tolerances of vertical and horizontal alignment and should perform within specified tolerances of vertical and horizontal alignment over the design life, as defined in prEN 14475. The system should be able to sustain differential settlements required by the design without structural damage to the facing.

4.3.4 *Design procedures*

4.3.4.1 *Reinforced steep fill slopes*

The internal equilibrium in a steep fill slope determines the maximum required stresses which govern the reinforcement strength and spacing. The analytical methods have been formalised in a number of national design codes. The most common techniques are the two-part wedge (Figure 11) and log-spiral analysis methods.

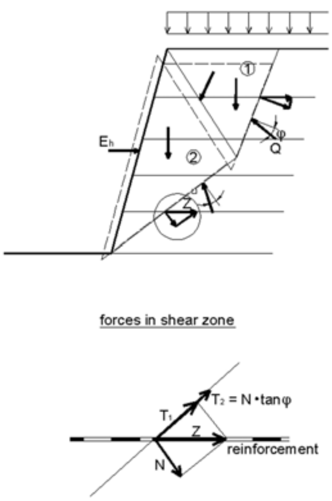

Figure 11 Block model for steep slope with two elements showing the approach of tensile force distribution in the failure zone. Ref. [3]

The block element model in Figure 11 considers the tangential component of the tensile force T_1 as retaining force as well as also with component T_2 the retaining shear force resulting from the normal stress which is increased by reinforcement in the failure zones.

Other design procedure for standard geometries using design charts has been described, for example by Jewell (1990), Ref. [12], based on the two-part wedge analysis for steep reinforced slopes. More complex slope geometric requires special stability analysis considering realistic assumptions on the action of the geosynthetics forces in the slope and on individual safety factors.

4.3.4.2 *Reinforced fill walls*

Design follows the limit state concept and the sequence presented for steep reinforced slopes in sect. 4.3.4.1. It's usual to consider first the ultimate limit state calculation, after which the serviceability limit deformations can be assessed.

The ultimate limit analyse has to include the ability of the foundation soil to support the inclined and eccentric loading at the base of the reinforced zone. In any inadequate case, the reinforced zone may be embedded deeper into the soil and / or the reinforced length increased.

After the ultimate limit analyse the serviceability limit deformations have to be assessed. The deflections at the wall can be caused by

- deformation in the reinforced zone by elongation in the reinforcement
- deflections by alignments during construction
- foundation displacement and settlement in the foundation soil caused by the loading from the reinforced fill and the backfill

The design of reinforced soil walls comprehends calculations on the internal, overall and external equilibrium as shown in Figure 12, Jewell (1996), Ref. [13].

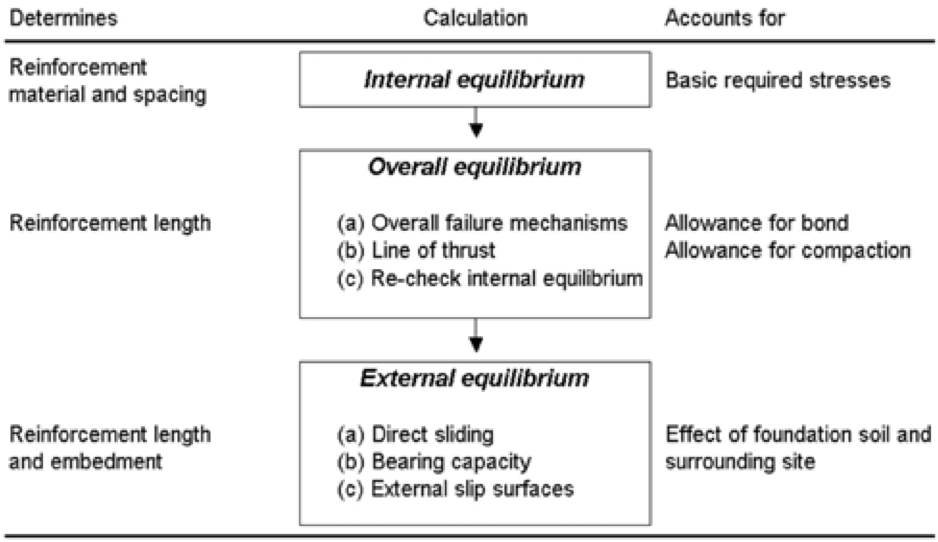

Figure 12: Steps in the design of reinforced soil walls, Ref. [13]

The internal equilibrium governs the maximum required stress to be resisted by the reinforcement in terms of strength and spacing of the reinforcement. In this context also external constructed loads, applying the reinforced zone, shall be considered.

The overall equilibrium determines the required reinforcement length, whereby the two-part wedge analyse is a mostly suitable proof. The analysis by failure mechanism passing through the toe of the wall as a rule yields the most critical state, however failure passing through the face of the wall of other elevations shall also be proofed.

Failure mechanisms passing behind and below the reinforced zone are examined by an external equilibrium analysis, whereby such failure modes can be caused by

- outward sliding of the reinforced zone at or over the foundation level
- eccentric loading of the foundation
- bearing capacity failure beneath the reinforced zone
- external failure passing around the reinforced zone

4.3.4.3 *Polymeric reinforcement*

All geosynthetic fill reinforcement shall comply with the requirements of the design and EN 13251. As required by the design, polymeric fill reinforcement shall be provided with certified values of design strength and isochronous load-strain characteristics pertaining to the specified design life and operating temperature of the reinforced fill structure.

Certification of design strength of polymeric fill reinforcement shall be based on tensile creep (and creep rupture) as EN ISO 13431, construction induced damage as ENV 12224 and fill-reinforcement interaction as EN ISO 12957-1. Design strength will also be affected by a consideration of biological and chemical attack per ENV 12225, ENV ISO 12960, ENV ISO 12447 and EN ISO 1213438, resistance to weathering per ENV 12224.

4.3.5 *Drainage*

A fundamental design component for reinforced slopes and soil walls is to drain the structure effective made to last during the life of the structure.

According to the recommendations of prEN 14475 should be considered:

- In the case of reinforced soil slopes surface drainage is required to protect against erosion and slope softening. Subsurface drainage is required to ensure that groundwater is removed from reinforced zone, thus preventing a possible build-up of water pressure.

  In combining the functions of reinforcement with in-plane drainage both by geosynthetics it should be considered that the drainage material may remove local build-up in pore water pressure within the compacted fill only.
- In the case of reinforced fill walls the following features have to be regarded in drainage design:
  a) If the foundation of the wall is not free draining a longitudinal drainage trench of suitable size, or a geocomposite should be placed at the back of the structure to collect water and bring it into the site drainage system. Any facing should allow water to pass through to this drainage system.
  b) Where water flow is expected from the retained soil drainage trenches, or geocomposite drains should be placed at intervals along the wall.
  c) In cases of significant water flows a drainage blanket of sufficient thickness should be executed below the reinforced fill wall and discharged beyond the toe.

4.4 *Geosynthetic reinforced bearing layers*

4.4.1 *Mechanism features*

As a sheme the considered two-layered foundation system comprises a base course of granular fill overlying a subgrade of low subsoil stiffness. Such a system shall be stressed by outward shear stress applied to the subgrade, together with the vertical stress, and this results in a low bearing capacity of the whole base course–subsoil system. The bearing capacity and the deformability are governed by the shear resistance and compression stiffness of the base course-subsoil system. In this system the thickness, quality, and density of the base course have the greatest influence on its load-distributing capability. Ref. [4], [5].

The inclusion of horizontally inclined geosynthetic reinforcement in the foundation level acts as a strengthening element as well as this prevents migration of the subsoil into the base course in particular by dynamic actions. A reinforcement with effective performance in the foundation level reduces the outward shear stress thereby increasing the bearing capacity of the system. The prevention of subsoil migration improves the serviceability state and thus extends the life time of the base course.

4.4.2 *Design principles*

The design of bearing layers on subgrade has been based on semi-empirical methods used to the dimensioning of unpaved roads, railway tracks, working platforms and pads for structure foundations.

In the analysis it is difficult to assess characteristic loading and reliable load distribution because as a rule static and life loads are simultaneously in action. The dynamic loading may be a temporary or slowly moving life load or a vibration load or a three-dimensional action of a wheel load. Therefore in the design of such bearing layers the life loads shall mostly be reduced to quasi-static loads and the fatigue of the bearing system, for instance caused by repeated loading from traffic, shall be assessed by empirical relations. In this context has been considered the distinction in loading mode, for instance the loading is divided for an axi-symmetric mode in the dimensioning of unpaved roads and for plane-strain mode in the case of tracked vehicles on working platforms.

There are similarities between the action of reinforcement in a above mentioned two-layered bearing system and in an embankment on weak subsoil (sect. 4.2.1).

Thus ultimate and serviceability limit states are investigated in design. The maximum reinforcement force is limited by the design strength in the ultimate limit state analysis, and by the allowable force in the serviceability limit state and analysis. The allowable force is mostly governed by the maximum allowable elongation of the reinforcement, according to experience in the range less than 5 %.

Typical ultimate limit states shall be characterized either by shear failure or at extreme load by punching failure according to Figure 13.

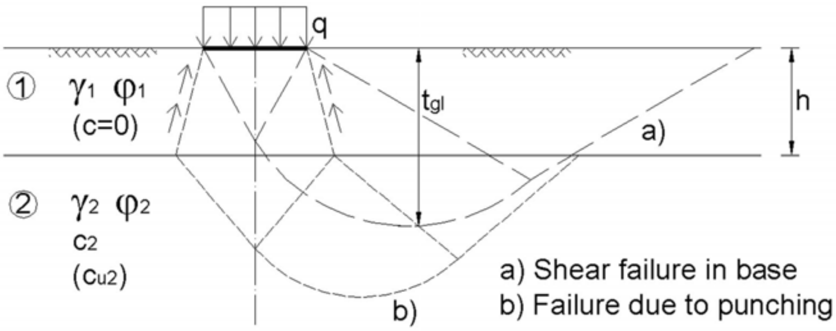

Figure 13: Failure mechanism of a unreinforced two-layer system, for (a) shear failure and (b) punching failure. Ref. [10]

The failure kinematic is influenced mainly by the ratios of stiffness of the base course to the subsoil and base course thickness h to width b of the loaded area. In general, the danger of punching failure of the base course exists where the ratio h/b becomes smaller than 1.5, Gudehus (1985), Ref. [10].

A geosynthetic reinforcement in the foundation level, acting like a membrane at the bottom of the base course, stabilizes the system against shear or punching failure. The bearing capacity of the reinforced system exceeds however once the subsoil has fully plasticized and the reinforcement either fails or is pushed out. In summary the following modes of ultimate limit states have to be considered in design:

- punching and shear failure of the base course
- uplift at the foundation and reinforced level, if so required
- pull-out of the reinforcement
- tensile failure of the reinforcement

The kinematic modes for stability analysis are based either on

- a membrane model, considering consolidation settlement, subgrade reaction and shear failure reaction or
- a deformed block model consisting of different movable elements, with or without considering membrane effects

These kinematic modes are presented e.g. by Giroud (1981) Ref. [9], Floss (1986) Ref. [3].

Theoretical design of the base course thickness and the geosynthetic reinforcement, based on models, formulae or nomographs, is not generally sufficient, because these approaches do not consider the variety of local site influences and the interactions between subsoil, base course and geosynthetic reinforcement in an adequate manner. Thus the dynamic actions during construction causes the strongest stressing of the geosynthetics in many cases. Therefore, the required mechanical resistance of the geosynthetics has to be selected in accordance with this fact and the interaction influences.

Especially in the case of insufficient base course quality or decreased subsoil strength, the interactive behaviour becomes a critical state. Under such conditions, the geosynthetics are stressed primarily by punch and scrub effects, which reduce the durability of the fabric structure and surface texture. Furthermore, the geosynthetics are stressed by punching and bursting, when sharp-edged base course material is thrown over and compacted. In some cases it may be necessary to provide a protection layer above the reinforcement.

In the case of subsoils with low bearing capacity and high water content, only high-grade geosynthetics with good mechanical and filter characteristics perform well. For extremely bad conditions, the application of combined geosynthetics consisting of a filter and a strengthening element may be a useful solution.

In conclusion, regarding all mentioned design influences and interactions, it may be more practical to work with a reliable simplified classification scheme than with a theoretical approach in the design of reinforced bearing layer systems. For example such a scheme, divided to categories for the traffic loading, reinforcement stressing and consistency of subsoil, used for the selection of the base course thickness of unpaved roads, was proposed by Floss (1987), Ref. [7].

5 GEOSYNTHETIC SOIL TECHNIQUE FOR WATERWAYS AND COASTAL PROTECTION

5.1 *Waterway engineering*

For the use of geosynthetics in hydraulic engineering there is sufficient experience leading to uniform rules for the design lay out as well as for material requirements, testing of material properties and definite requirements for construction methods. Ref. EN 13253/54/55, [1], [2], [11], [17], [18].

The geosynthetic soil technique has to be realized with regard to mechanical and hydraulic efficiency, durability and tensile strength of geosynthetics as well as to installation requirements. Geosynthetics are used in the form of woven fabrics, nonwoven fabrics and composite materials for the stabilization of banks and inverts.

Standard construction methods for revetments are shown in Figure 14, Ref. [1].

5.1.1 *Permeable revetments*

For permeable revetments geotextiles are used as filter and protection layers. Permeable rubble or rip-rap revetments are installed on waterfront embankments, if the surface water level can be lower than the existing groundwater table behind the revetment or if the natural ongoing seepage loss of surface water into the subsoil can be tolerated. The revetment toe must be configured in such a way that scour action is unable to adversely affect the stability of the revetment.

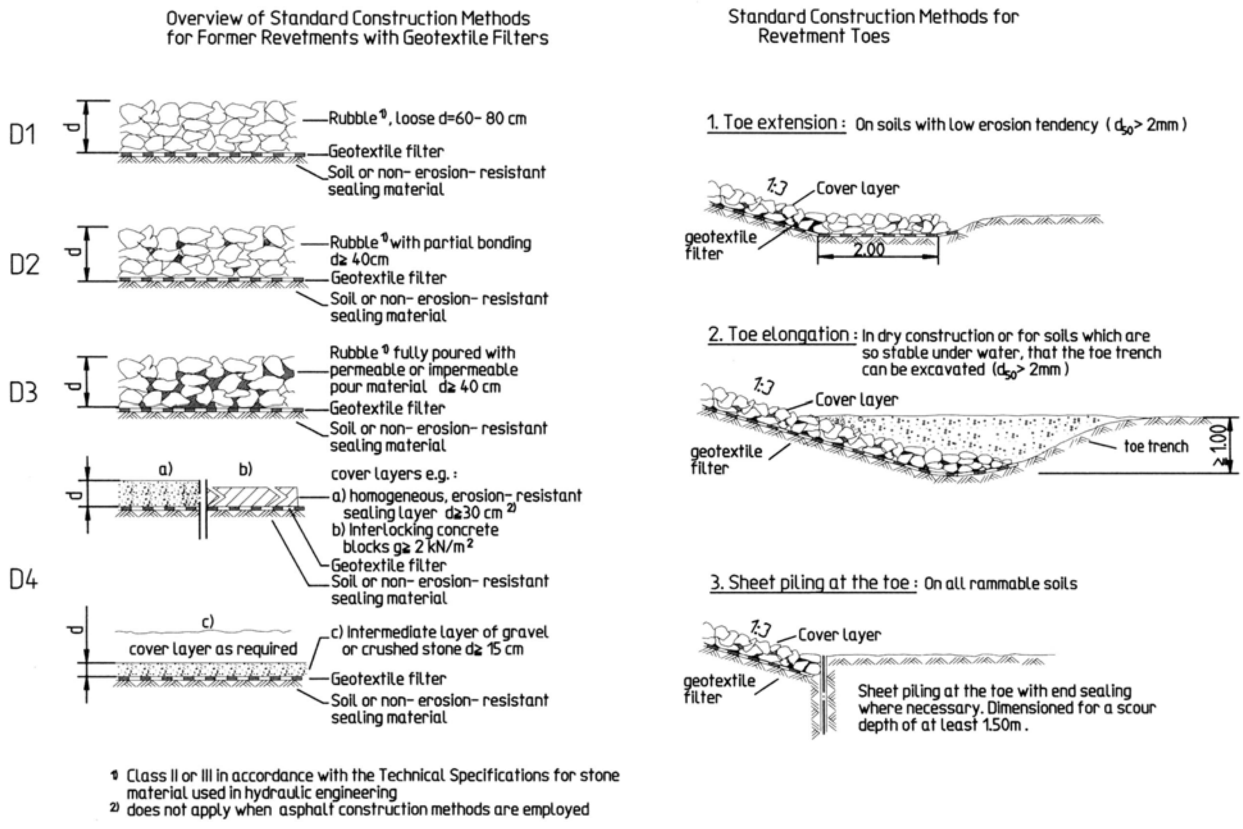

Figure 14: Standard construction methods for revetments and their toe configuration. Ref. [1]

The requirements for geotextile filters must guarantee long-term erosion protection of channel banks and beds and at the same time preserve mechanical and hydraulic filter effectiveness, Ref. [17]. In addition to the normal filter design the geotextile and the soil/geotextile friction behaviour as part of a revetment for slope protection have to be designed in a way that migration of soil particles down the slope underneath the geotextile are avoided.

Furthermore, the geotextile filters must be robust to withstand the mechanical loads exerted during installation and service. Additional loads associated with shipping traffic and wave size have also be taken into consideration. To ensure the transfer of shear stresses between the cover layer and the geotextile and between the geotextile and subgrade large frictional forces must be effective. Impact and abrasion resistance are further design parameters to be considered during installation and service.

In conclusion the design and selection of suitable geotextile filters depend on various boundary conditions.

5.1.2 *Impermeable revetments*

Impermeable revetments are required in case the surface water level of waterways rises higher than the existing groundwater level behind the revetment. These impermeable constructions must be dimensioned to be resistant to the magnitude and frequency of ship induced water level fluctuations (swell and sunk).

The design requirements have to ensure sufficient impermeable efficiency and stable long-term impermeability for both the lining elements and sealing layers placed in the side of waterway embankments. Such sealing elements, made from mineral clay, geosynthetic clay liners (GCL) or geomembranes, have to be protected against loads resulting from ship traffic. As a general rule a conventional type of revetment placed above the installed impermeable sealing element is normally required.

5.2 *Coastal protection*

In the design of coastal protection in particular, the following loads should be taken into consideration:

- wave and circulate forces which cause through flow and abrasion of geosynthetics
- loads due to seepage flow
- loads due to erosion and sedimentation

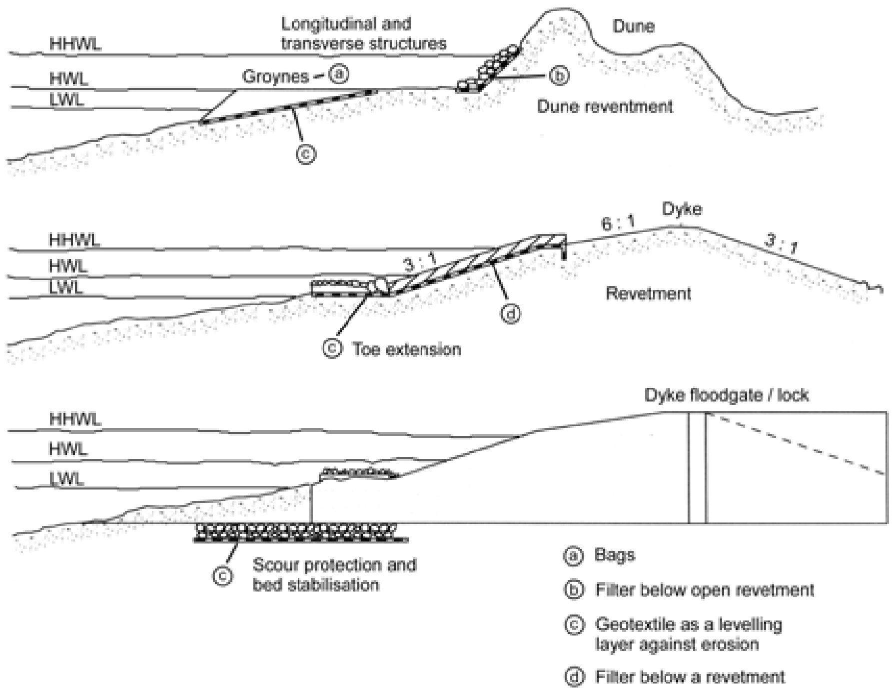

Figure 15: Overview of the application of geosynthetics in coastal protection. Ref. [1]

A broad outline of the application of geosynthetics in coastal protection is provided by the examples in Figure 15, Ref. [11], [18]:

- filter layers in dyke and foreshore revetments and as bed protection, e. g. dyke floodgates and storm tide barrages
- separation and filter layers at foundation level of groynes and breakwaters
- flexible construction elements in the form of sand-filled tubes, bags and mats
- flexible bed stabilisation mattresses for offshore and coastal protection

The following design and use considerations shall be regarded:

- If geotextiles are subjected to intensive UV radiation or chemical and biological attack in the marine environment, it is especially important to ensure the proper structural design and long-term durability of the materials used.
- For underwater installations the required woven tensile strength must be calculated according to the loads resulting from the process of placement into the water and sinking at the proposed installation position.
- Geotextile filters must possess sufficient mechanical strength, especially for resisting the forces imposed during the installation of rip-raps. To prevent loads on the filter due to tumbling of the revetment stones due to current, wave and ice forces, a protection layer may be installed between the filter and the revetment layer.
- The use of sandfilled geotextile composites like sandmats can be an alternative stabilisation and filtration measure providing also accurate placing underwater.
- The application of geotextile containers in form of sand-filled bags and tubes permits the use as flexible construction elements or entire structures, e. g. in the case of erosion control, scour fill, reefs, groynes and jetties, dams, breakwaters and dune revetments.

In conclusion the geosynthetic soil-technique in coastal protection applications is based upon experience and requires geosynthetic materials of highest performance respectively robustness according to the guidelines and established references.

6 GEOSYNTHETIC SOIL-TECHNIQUE FOR LANDFILL STRUCTURES

6.1 *Design principles*

The design concept for landfills presumes accurate knowledge on the distribution of groundwater flow paths and barriers, their hydraulic properties, the structure and deformation behaviour of the subsoil and the potential for improving the sealing effect of the subsoil. Besides the mechanical and biological effects the chemical loads, including highly concentrated or undiluted fluid matters, diluted fluid matters, leachate, landfill gas and gas condensate are of major importance for the selection of resistant construction materials used in landfills.

In order to assess the suitable function of a landfill structure the design of the base and capping sealing systems requires high performance. A base sealing system must securely separate the potentials of groundwater and leachate, accumulating inside the waste body. The landfill capping system prevents or minimises both the in-flow of surface water into the waste body and the uncontrolled escape of landfill gas. Generally, landfill capping sealing systems are designed with components made of mineral or composite liners in conjunction with components for degasification, drainage and vegetation.

The following design principles have to be considered, Ref. EN 13257/65, [8]:

- For sealing systems on slopes, the inner and outer stability must be proven. The inner stability is substantially determined by the shear behaviour of the single layers of the system. The outer stability can be improved by the absorption of tensile forces from the single layers. The interlocking between the single layers is decisive for the transmission of forces between the layers and therefore for the absorption of tensile forces.
- Load dependent deformations, affecting the function of the sealing system, have to be avoid.
- Resistance to sliding shall be ensured for all interfaces and boundary surfaces, for all loading conditions due to the intrinsic weight of the waste and also external loads. These calculations should consider the construction, operational and post-closure phases of the landfill.
- In addition shear resistance should be confirmed for each interface between the individual sealing components that the maximum transferable shear strength is capable of taking the tension from downslope stresses with the required factor of safety, Ref. [6]. The sealing elements should be designed to transfer shear stresses only. The development of unacceptable tensile stresses can be eliminated by geosynthetic reinforcing.

6.2 *Use of geosynthetics*

Generally, geosynthetics can be specified for the following functions in landfills:

- sealing in base or capping sealing systems
- protection of geomembranes or other liners
- filtration in drainage systems
- drainage of fluids (liquids or gases)
- soil or waste reinforcement

Figures 16, 17 and 18 show examples of base and capping sealing systems for a domestic waste deposit, Ref. [18].

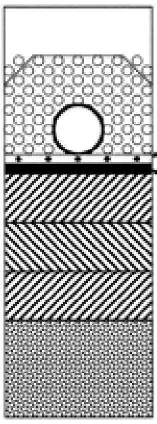

Figure 16: Base sealing system

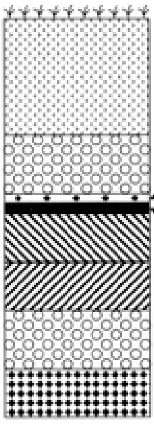

Figure 17: Capping sealing system of a domestic landfill

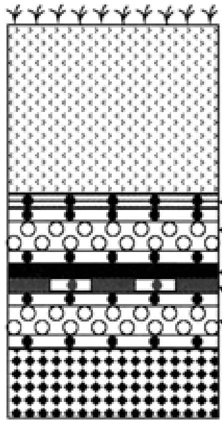

Figure 18: Example of an alternative capping sealing system for a steep slope

The following considerations should be regarded for the design and use of geosynthetics in landfill structures, Ref. [8]:

- The design can be based either on an analytical (reinforcement, drainage) or a semiempirical (filtration, protection) approach. There is a need to guarantee the long-term performance of geosynthetics. The properties of geosynthetics may be affected by induced mechanical stresses, radiation, temperature, chemicals and micro-organisms.
- Geomembranes are used as structural components, either in composite basal lining or capping systems, in connection with their function as fluid (liquids or gases) barrier. The integrity of geomembranes is related to requirements, which can be specified by design calculations or empirical rules. The geomembrane has to be protected against load dependent damages by a protection layer.
- Geosynthetic clay liners (GCL) are alternative sealing elements in particular for capping sealing systems.

  When using geosynthetic clay liners on slopes a sufficient factor of safety for stability must be taken into account, Ref. [6]. The internal shear strength relating to the type of bentonite encapsulation and the given contact interface shear strength have to be checked.
- In all cases where geotextiles are used as drainage layers, adequate transmissivity must be guaranteed under the imposed load at every stage of the landfill operation and after closure. A high factor of safety on the transmissivity should be incorporated into the design required as long term performance.
- In landfill sealing systems geotextile filters can be dimensioned using known rules. For a depth filtration the pore structure of the geotextile should be chosen to be as open as possible. The requirements must be set up for the specific filtration length and the thickness of the geotextile.

  The function and effective operation of geotextile filters can be complicated by the nature of the material to be filtered, the liquids and the gases. Rapid clogging as a result of the growth of microorganism is possible. Therefore a specific study and testing on the clogging susceptibility may be necessary.

  For geotextile filter layers in landfill capping systems in particular, a safe filtration effect even in deformed condition must be proven. A high thickness together with a high mass per unit area and a high elongation has, in all cases, a favourable effect on the mechanical filter effectiveness of elongated geotextiles.
- Reinforcement geosynthetics in landfill design can perform numerous requirements. The following applications can be emphasized:
  a) horizontal reinforcement of slopes and dykes
  b) inclined reinforcement of slopes to ensure the stability of mineral drainage layers
  c) inclined reinforcement of the capping system to ensure stability of the drainage system and restoration profile
  d) horizontal reinforcement of the waste body to increase the internal and/or external stability of the waste body

In conclusion the geosynthetic engineering in landfill construction requires in all cases an analytical study which must be undertaken to prove the stability of the structure. Depending on the required service life of the structure, the variation of hydraulic, mechanical, chemical and/or biological parameters must be considered when assessing the long-term behaviour of the waste as well as all construction materials used in the landfill.

7 FINAL REMARKS

In conclusion of the discoursed survey it should be evident that geosynthetic soil techniques enable not only well and safe designed earth structures but nearly all applications can be seen in close relation to objectives considering environmental protection and careful treatment of raw-materials.

The methods of design and analysis for geosynthetic soil techniques have been developed and used over a considerable long period of time. Much experience has been gained on various applications. These methods which were established in different national design codes and have lead to different design approaches are now mostly replaced by harmonized European codes.

However while a bright future for geosynthetic applications is expected it should not be disregarded that a number of issues still need to be resolved regarding namely some conservative methods of design and analysis. For this reason further development and research shall be necessary, if possible in an international cooperation, straightened on issues such as:

- further development in the execution of special geosynthetic work
- improvement of limit states design and analysis by use of numerical methods, tests on experimental models and observations
- evaluation of long-term effectiveness and strengthening of earth structures by geosynthetics
- evaluation of ecological suitability and benefit of geosynthetic soil techniques
- improvement of quality control testing by rational and economical methods

Finally it should be remembered that the worldwide action of the national construction industries forces to intensify the correlations regarding the exchange of experience and scientific knowledge as well as the further harmonization of European and other international standards on geosynthetic soil techniques.

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