Design & Behaviour of Reinforced Wall & Embankment

Design methodologies

- The design of a structure incorporating geosynthetics aims to ensure its strength, stability and serviceability over its intended life span. There are mainly four design methods for the geosynthetic-related structures or systems.

1. *Design-by-experience:*

- This method is based on one's past experience or that of other's. This is recommended if the application is not driven by a basic function or has a nonrealistic test method.

2. *Design-by-cost-and-availability*:

In this method, the maximum unit price of the geosynthetic is calculated by dividing the funds available by the area to be covered by the geosynthetic.

The geosynthetic with the best quality is then selected within this unit price limit according to its availability.

Being technically weak, this method is nowadays rarely recommended by the current standards of practice.

3. *Design-by-specification*:

This method often consists of a property matrix where common application areas are listed along with minimum (or sometimes maximum) property values.

Such a property matrix is usually prepared on the basis of local experiences and field conditions for routine applications by most of the governmental agencies and other large users of geosynthetics.

4. *Design-by-function*: This method is the preferred design approach for geosynthetics. The general approach of this method consists of the following steps:

a. Assessing the particular application, define the primary function of the geosynthetic, which can be reinforcement, separation, filtration, drainage, fluid barrier or protection.

b. Make the inventory of loads and constraints imposed by the application.

c. Define the design life of the geosynthetic.

d. Calculate, estimate or otherwise determine the required functional property of the geosynthetic (e.g. strength, permittivity, transmissivity, etc.) for the primary function.

e. Test for or otherwise obtain the allowable property (available property at the end of the design life) of the geosynthetic, as discussed.

F. Calculate the factor of safety, FS, reproduced as below:

$$FS = \frac{\text{Allowable (or test) functional property}}{\text{Required (or design) functional property}}$$

g. If this factor of safety is not acceptable, check into geosynthetics with more Appropriate properties.

h. If acceptable, check if any other function of the geosynthetic is also critical, and repeat the above steps.

i. If several geosynthetics are found to meet the required factor of safety, select the geosynthetic on the basis of cost–benefit ratio, including the value of available experience and product documentation.

- It should be noted that the design-by-function method bears heavily on identifying the primary function to be performed by the geosynthetic.

- For any given application, there will be one or more basic functions that the geosynthetic will be expected to perform during its design life.

- Accurate identification of the geosynthetic function as primary function(s) is essential. Hence, a special care is required while identifying the primary function(s).

Function	*Failure mode(s)*	*Possible cause(s)*
Reinforcement	Large deformation of the soil-geosynthetic structure	Excessive tensile creep of the geosynthetic
	Reduced tensile resisting force	Excessive stress relaxation of the geosynthetic
Separation/ filtration	Piping of soils through the geosynthetic	Openings in the geosynthetic may be incompatible with retained soil. Openings might have been enlarged as a result of in situ stress or mechanical damage
Filtration	Clogging of the geosynthetic	Permittivity of the geosynthetic might have been reduced as a result of particle buildup on the surface of or within the geosynthetic. Openings might have been compressed as a result of long-term loading
Drainage	Reduced in-plane flow capacity	Excessive compression creep of the geosynthetic
Fluid barrier	Leakage through the geosynthetic	Openings may be available in the geosynthetic as a result of puncture or seam failure
Protection	Reduced resistance to puncture	Excessive compression creep of the geosynthetic

- The design-by-function approach described above is basically the traditional *working stress design approach* that aims to select allowable geosynthetic properties so that a nominated minimum total (or global) factor of safety is achieved.

- In geosynthetic applications, particularly reinforcement applications (e.g. geosynthetic-reinforced earth retaining walls), it is now common to use the *limit state design approach*, rather than the working stress design involving global safety factors.

- For the purpose of geosynthetic-reinforced soil design, a limit state is deemed to be reached when one of the following occurs:

1. Collapse, major damage or other similar forms of structural failure;

2. Deformations in excess of acceptable limits;

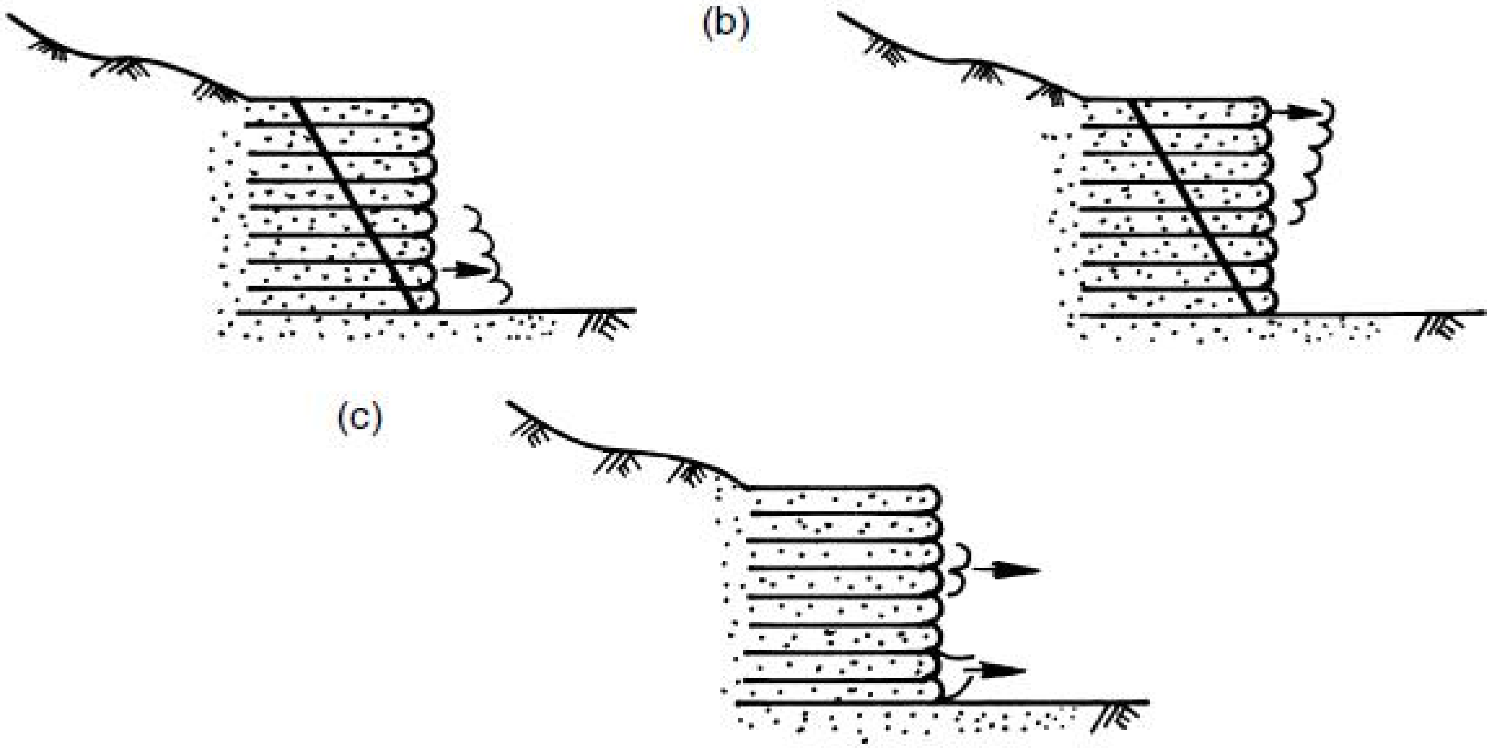
3. Other forms of distress or minor damage, which would render the structure unsightly, require unforeseen maintenance or shorten the expected life of the structure.

- The condition defined in (1) is the ultimate limit state, and (2) and (3) are serviceability limit states.

Retaining walls

- A number of design approaches have been proposed; however, the most commonly used design approach is based on limit equilibrium analysis.
- The analysis consists of three parts:

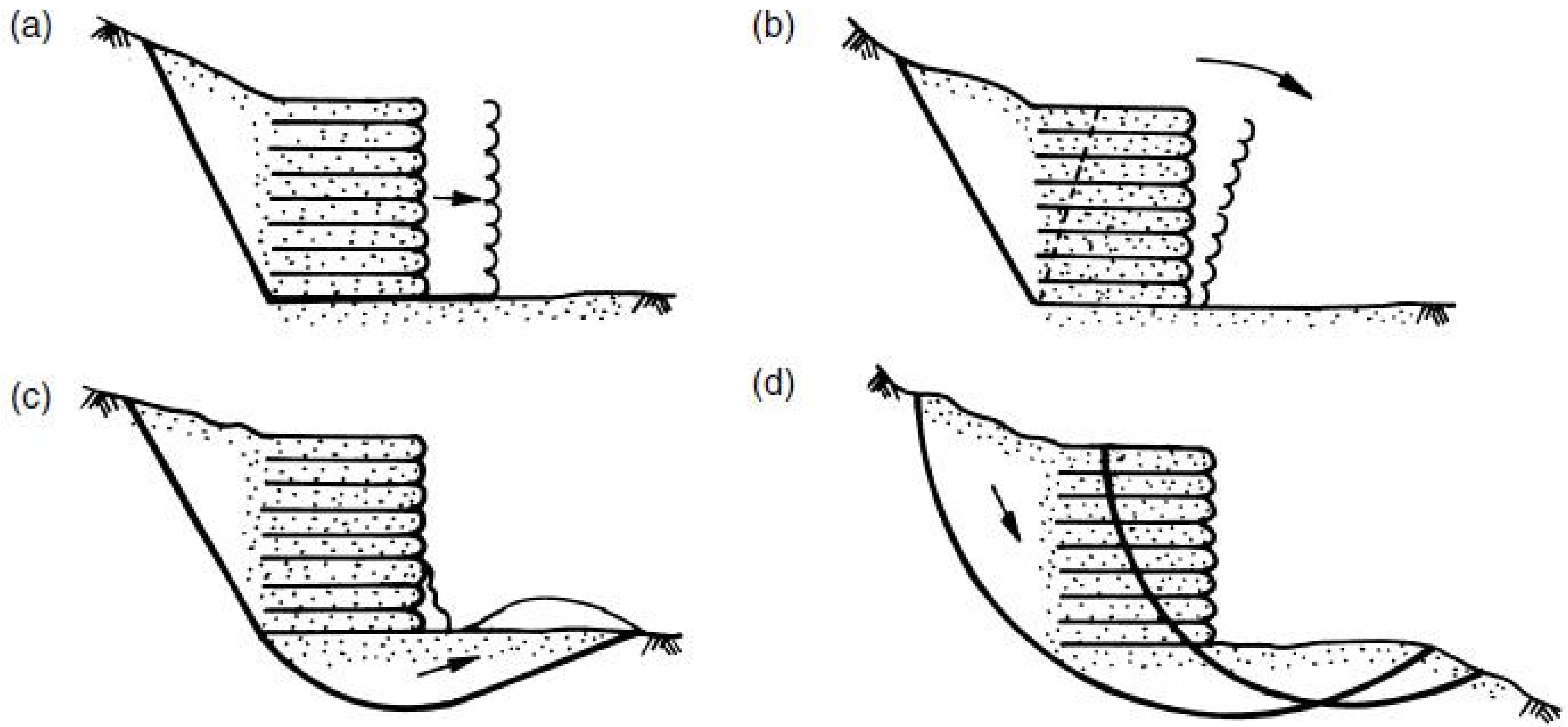
1. **Internal stability analysis** : An assumed Rankine failure surface is used, with consideration of possible failure modes of geosynthetic-reinforced soil mass, such as geosynthetic rupture, geosynthetic pullout, connection (and/or facing elements) failure and excessive geosynthetic creep. The analysis is mainly aimed at determining tension and pullout resistance in the geosynthetic reinforcement, length of reinforcement, and integrity of the facing elements.



Internal failure modes of geosynthetic–reinforced soil retaining walls: (a) geosynthetic rupture; (b) geosynthetic pullout; (c) connection (and/or facing elements) failure.

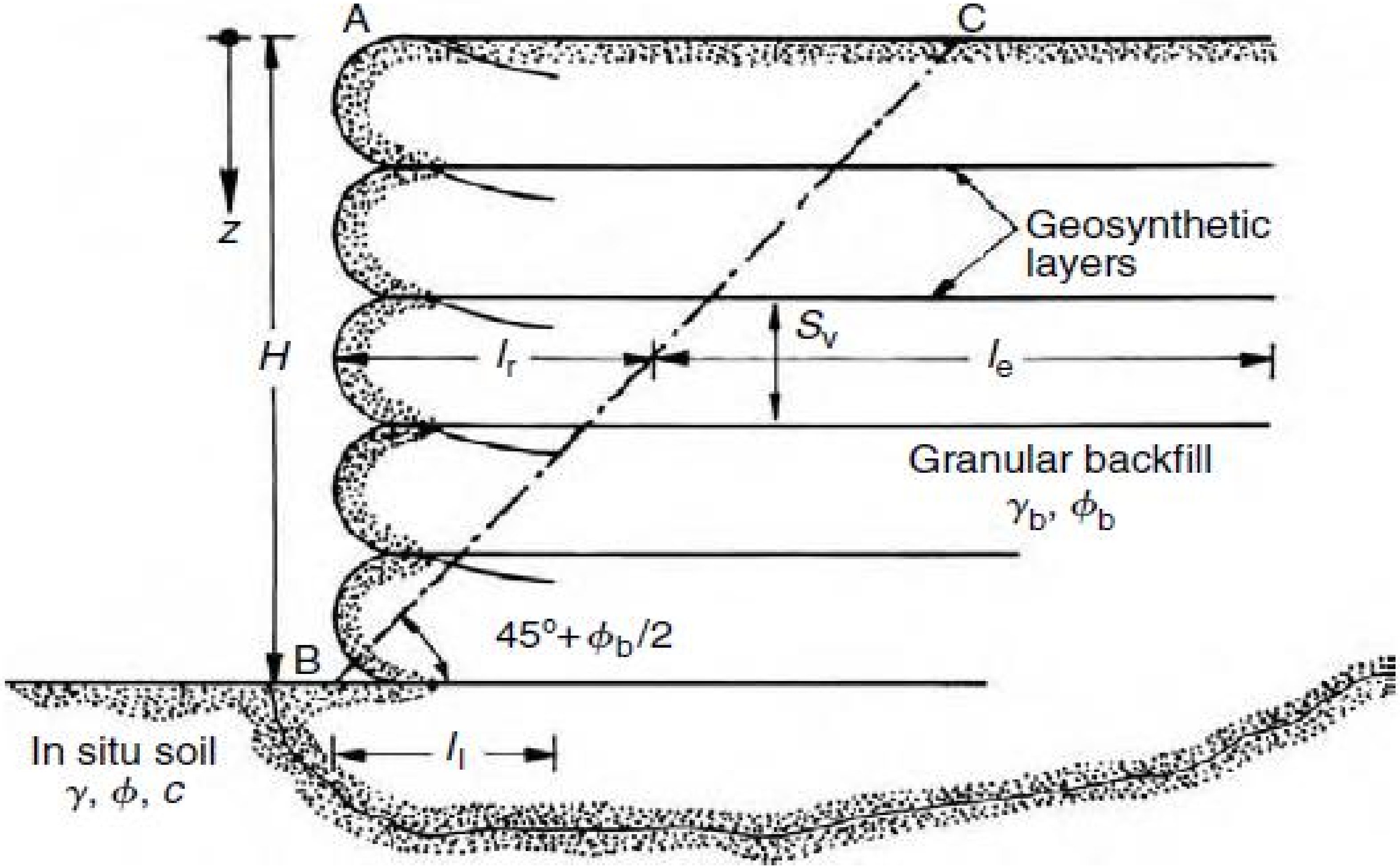
2. External stability analysis : The overall stability of the geosynthetic reinforced soil mass is checked including sliding, overturning, load-bearing capacity failure, and deep-seated slope failure

3. Analysis for the facing system, including its attachment to the reinforcement



External failure modes of geosynthetic-reinforced soil retaining walls: (a) sliding; (b) overturning; (c) load-bearing capacity failure; (d) deep-seated slope failure.

- Figure shows a geotextile-reinforced retaining wall with geotextile wraparound facing without any surcharge and live load. The backfill is a homogeneous granular soil.



- According to Rankine active earth pressure theory, the active earth pressure, a, at any depth *z* is given by:

$$\sigma_a = K_a \sigma_v = K_a \gamma_b z$$

where, K_a is the Rankine earth pressure coefficient, is the unit weight of the granular backfill and The value of *K*a can be estimated from

$$K_a = \tan^2\left(45^\circ - \frac{\phi_b}{2}\right),$$

Where$\emptyset_b$ is the angle of shearing resistance of the granular backfill

- The factor of safety against the geotextile rupture at any depth z may be expressed as

$$FS_{(R)} = \frac{\sigma_G}{\sigma_a S_v},$$

where σ_G is the allowable geotextile strength in kN/m, and S_v is the vertical spacing of thegeotextile layers at any depth z in metre.

The magnitude of the FS(R) is generally taken to be 1.3–1.5

- The geotextile layer at any depth, z, will fail by pullout if the frictional resistance developed along its surfaces is less than the force to which it is being subjected.

- This type of failure occurs when the length of geotextile reinforcement is not sufficient to prevent its slippage with respect to the soil. The effective length, l_e, of a geotextile layer along which the frictional resistance is developed, may be conservatively taken as the length that extends beyond the limits of the Rankine active failure zone.

The factor of safety against the geosynthetic pullout at any depth *z* may be expressed as

$$FS_{(P)} = \frac{2l_e\sigma_v \tan\phi_r}{S_v\sigma_a},$$

where ϕ_r is the angle of shearing resistance of soil–geosynthetic interface and it isapproximately equal to **$2\phi_b/3$.**

The magnitude of the FS(P) is generally taken to be 1.3–1.5.

$$l_e = \frac{S_v K_a[FS_{(P)}]}{2\tan\phi_r}.$$

The length, l_r, of geotextile layer within the Rankine failure zone can be calculated as:

$$l_r = \frac{H - z}{\tan(45^\circ + \phi_b/2)},$$

where *H* is the height of the retaining wall

The total length of the geotextile layer at any depth *z* is

$$l = l_e + l_r = \frac{S_v K_a [FS_{(P)}]}{2 \tan \phi_r} + \frac{H - z}{\tan(45^\circ + \phi_b/2)}.$$

If the wraparound facing is to be provided, then the lap length can be determined using the following expression:

$$l_1 = \frac{S_v K_a [FS_{(P)}]}{4 \tan \phi_r}.$$

The design procedure for geosynthetic-reinforced retaining walls with wraparound vertical face and without any surcharge is given in the following steps:

Step 1*:* Establish wall height (H).

Step 2*:* Determine the properties of granular backfill soil, such as unit weight (γ_b) and angle of shearing resistance ($\emptyset_b$).

Step 3*:* Determine the properties of foundation soil, such as unit weight (γ) and shear strength parameters (c and $\emptyset$).

Step 4*:* Determine the angle of shearing resistance of the soil–geosynthetic interface ($\emptyset$r).

Step 5*:* Estimate the Rankine earth pressure coefficient from Equation (5.7).

Step 6*:* Select a geotextile that has allowable fabric strength of σ_G.

Step 7*:* Determine the vertical spacing of the geotextile layers at various levels from Equation (5.9).

Step 8*:* Determine the length of geotextile layer, *l*, at various levels from Equation (5.13).

Step 9*:* Determine the lap length, L_l, at any depth z from Equation (5.14).

Step 10*:* Check the factors of safety against external stability

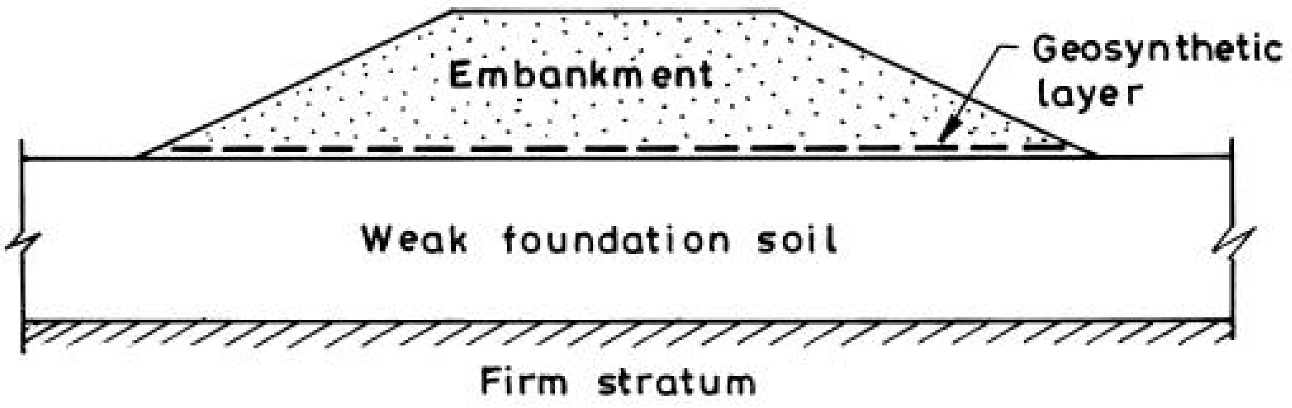
Step 11*:* Check the requirements for backfill drainage and surface runoff control.

Step 12*:* Check both total and differential settlements of the retaining wall along the wall length. This can be carried out as per the conventional methods of settlement analysis.

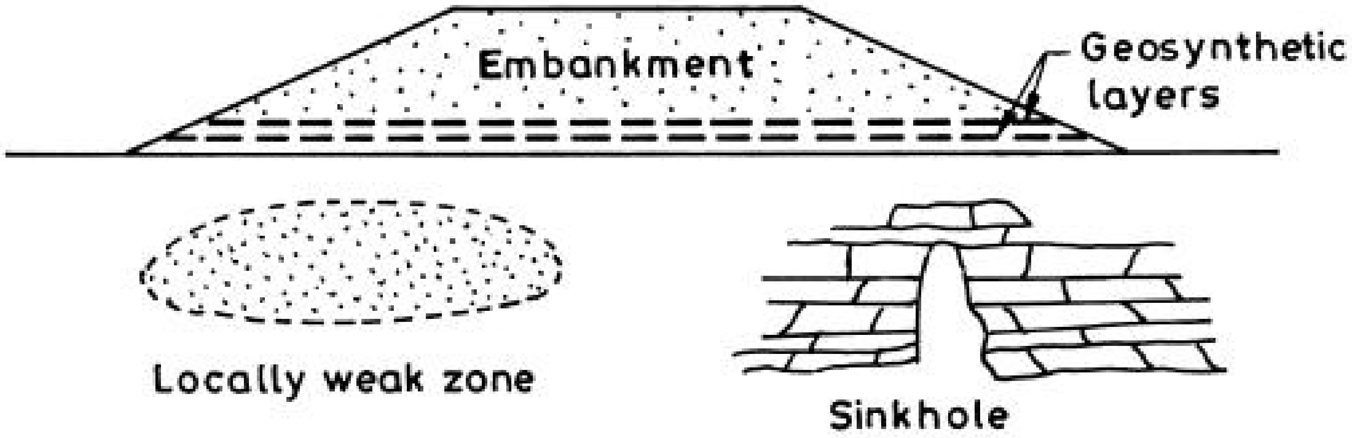
Embankments

- The construction of embankments over weak/soft foundation soils is a challenge for geotechnical engineers.
- In the conventional method of construction, the soft soil is replaced by a suitable soil or it is improved (by preloading, dynamic consolidation, lime/cement mixing or grouting) prior to the placement of the embankment.
- Other options such as staged construction with sand drains, the use of stabilizing berms and piled foundations are also available for application.

- These options can be either time consuming, expensive, or both. The alternate option is to place a geosynthetic (geotextile, geogrid, or geocomposite) layer over the soft foundation soil and construct the embankment directly over it



- More than one geosynthetic layer may be required, if the foundation soil has voids or weak zones caused by sinkholes, thawing ice, old streams, or weak pockets of silt, clay or peat In such situations, the geosynthetic layer is often called a *basal geosynthetic layer*.



The geosynthetic as the basal layer in the embankment over soft foundation soil can serve one of the following basic functions or a combination:

1. reinforcement

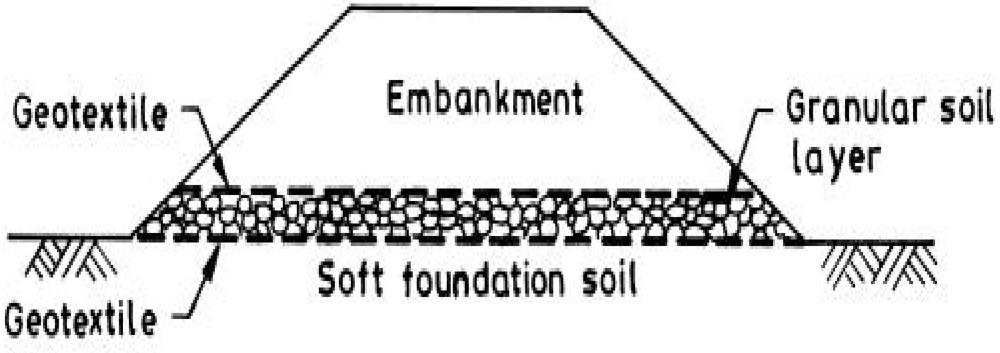
2. drainage

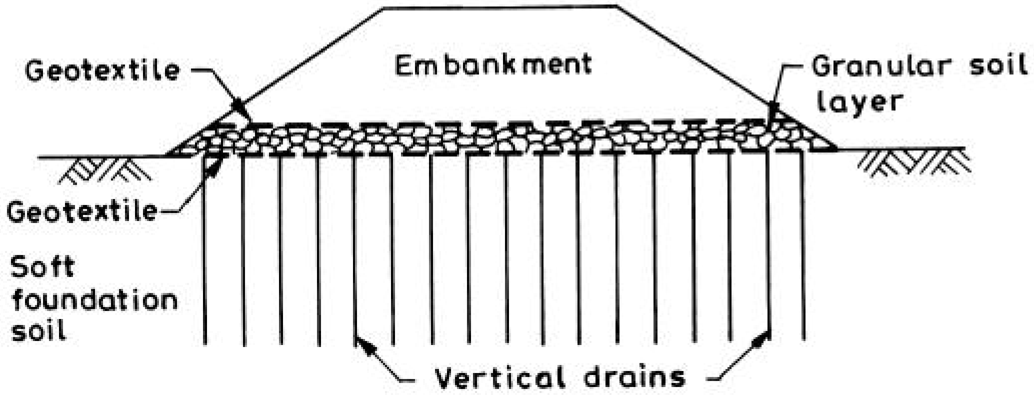
3. separation/filtration

The reinforcement function usually aims at a temporary increase in the FS of embankment, which is associated with a faster rate of construction or the use of steeper slopes that would not be possible in the absence of reinforcement.

- Geosynthetics used to provide reinforcement function include woven geotextiles and/or geogrids. The following factors may be of major concern when choosing the basal geosynthetic to function as a reinforcement:
- tensile strength and stiffness
- soil–reinforcement bond characteristics
- creep characteristics
- geosynthetic resistance to mechanical damage
- durability.

- The drainage function is associated with the increase in the rate of consolidation to have a more stable embankment or staged construction.
- In fact, the geosynthetic allows for free drainage of the foundation soils to reduce pore pressure buildup below the embankment.
- The consolidation of soft foundation soil can be further accelerated by installing vertical drains along with the basal drainage blanket.





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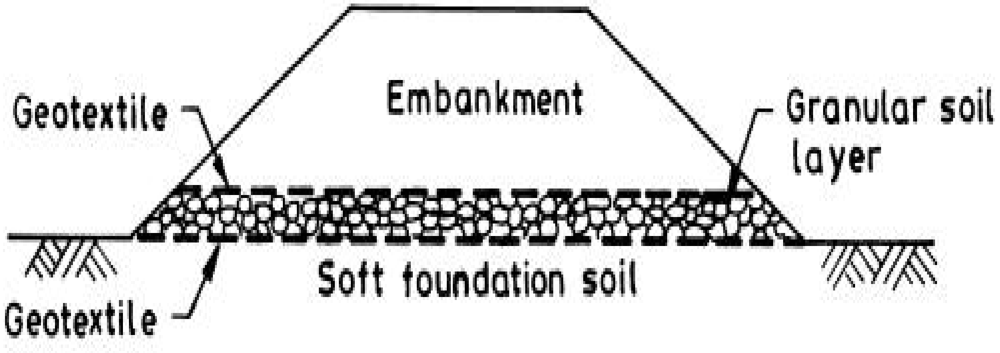
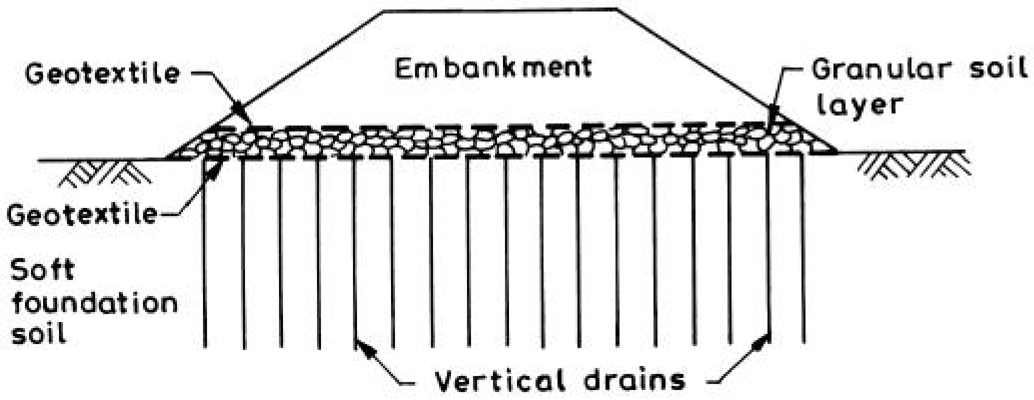




Design approach for an embankment

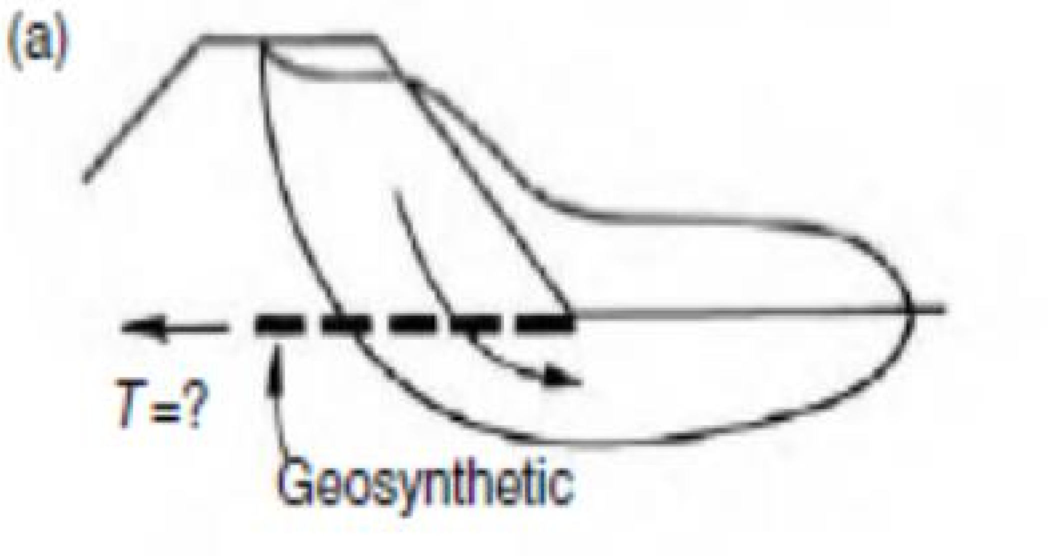
- The basic design approach for an embankment over the soft foundation soil with a basal geosynthetic layer is to design against the mode (or mechanism) of failure.

- These failure modes indicate the types of analysis that are required. In fact, each failure mode generates required or design value for the embankment geometry or the tensile strength of the geosynthetic.

- The potential failure modes are as follows:

Overall slope stability failure:

This is the most commonly considered failure mechanism, where the failure mechanism is characterized by a well defined failure surface cutting the embankment fill, the geosynthetic layer and the soft foundation soil.



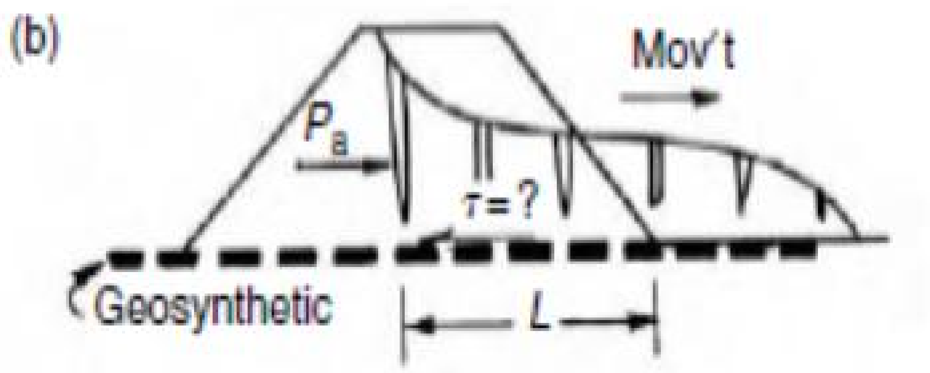
- This mechanism can involve tensile failure of the geosynthetic layer or bond failure due to insufficient anchorage of the geosynthetic extremity beyond the failure surface.

- The analysis proceeds along the usual steps of conventional slope stability analysis with the geosynthetic providing an additional stabilizing force, *T*, at the point of intersection with the failure surface being considered.

- The geosynthetic thus provides the additional resisting moment required to obtain the minimum required factor of safety

Lateral spreading

The presence of a tension crack through the embankment isolates a block of soil, which can slide outward on the geosynthetic layer.

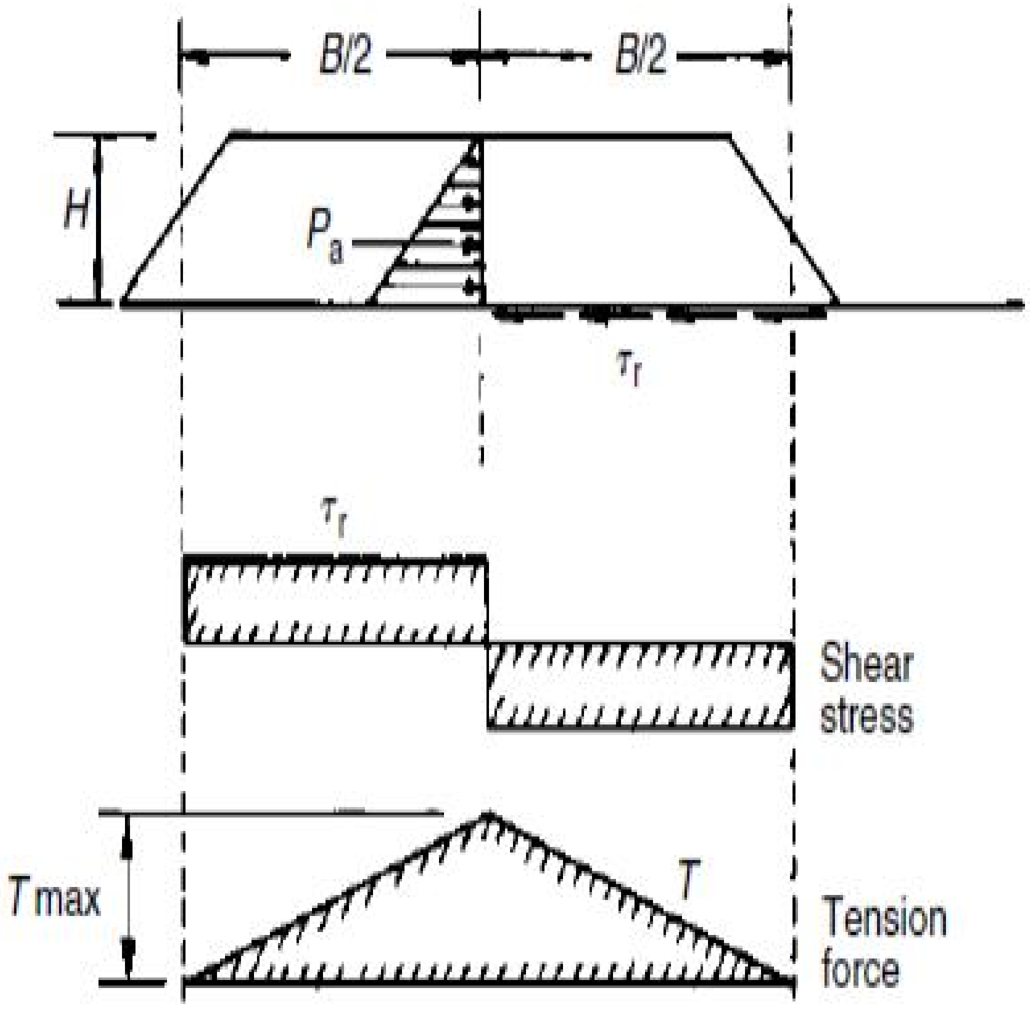


- The horizontal earth pressures acting within the embankment mainly cause the lateral spreading.

- In fact, the horizontal earth pressures cause the horizontal shear stresses at the base of the embankment, which must be resisted by the foundation soil.

- If the foundation soil does not have adequate shear resistance, it can result in failure.

- The lateral spreading can therefore be prevented if the restraint provided by the frictional bond between the embankment and the geosynthetic exceeds the driving force resulting from active soil pressures within the embankment.



For the conditions as sketched in Figure, the resultant active earth pressure P_a and the corresponding maximum tensile force T_{max} are calculated as follows:

$$P_a = \frac{1}{2}\gamma H^2 K_a$$

$$T_{max} = \frac{\tau_r B}{2} = \frac{(\gamma H \tan \phi_r)B}{2},$$

- For no lateral spreading, one can get

$$\frac{T_{\max}}{P_a} \geq 1$$

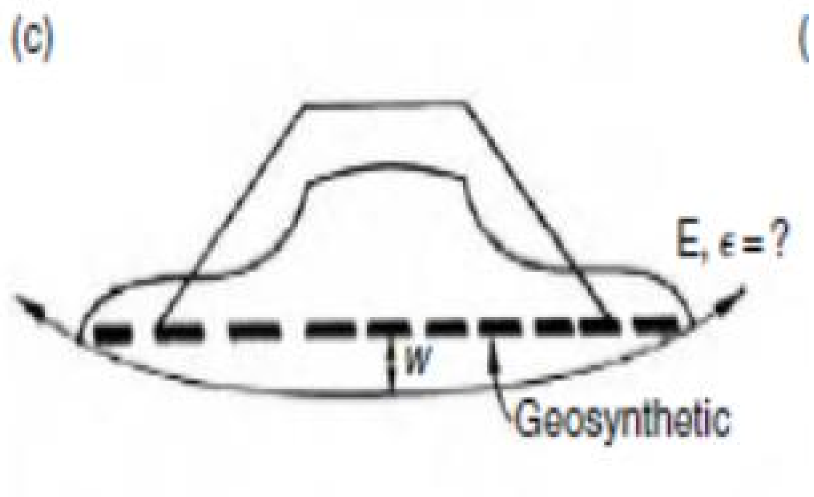
It is general practice to consider a minimum safety factor of 1.5 with respect to strength and a geosynthetic strain limited to 10%. The required geosynthetic strength T_{req} and modulus E_{req} therefore are

$$T_{req} = 1.5T_{\max} \qquad E_{req} = \frac{T_{\max}}{\varepsilon_{\max}} = 10T_{\max}.$$

The lateral spreading failure mechanism becomes important only for steep embankment slopes on reasonably strong subgrades and very smooth geosynthetic surfaces. Thus, it is not the most critical failure mechanism for soft foundation soils.

Embankment settlement

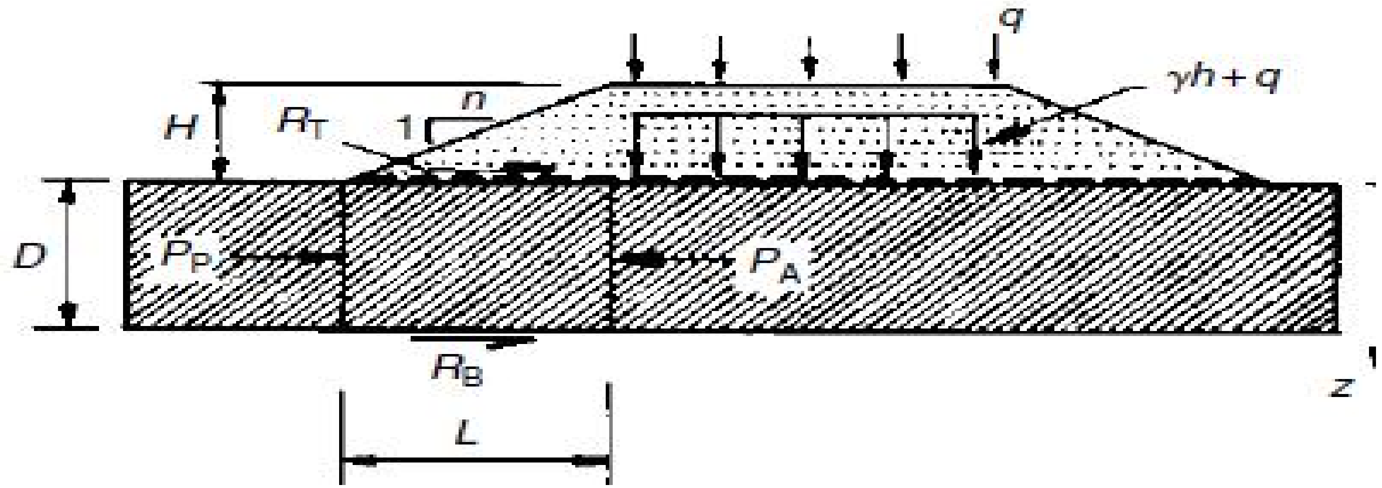
The embankment settlement takes place because of the consolidation of the foundation soil. The settlement can also occur due to the expulsion of the foundation soil laterally.



- This mechanism may occur for heavily reinforced embankments on thin soft foundation soil layers. The factor of safety against soil expulsion, *F*e, can be estimated from

$$F_e = \frac{P_P + R_B + R_T}{P_A},$$

where P_p is the passive reaction force against block movement, R_T is the force at the top of the soil block, R_B is the force at the base of the soil block, and P_A is the active thrust on the soil block.



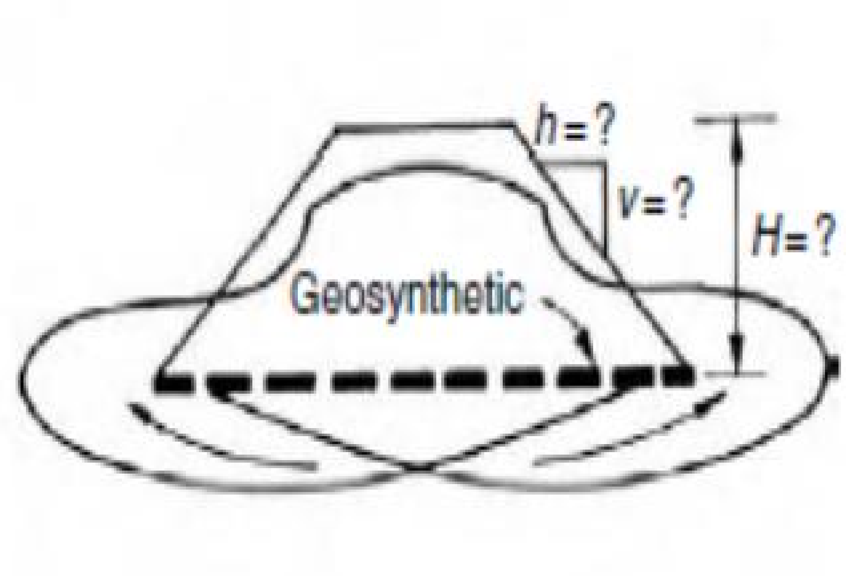
- The active and passive forces can be evaluated by earth pressure theories, while the forces at the base and top of the soil block can be estimated as a function of the undrained strength S_u at the bottom of the foundation soil and adherence between the reinforcement layer and the surface of the foundation soil, respectively.

- The geosynthetic layer may reduce differential settlement of the embankment somewhat, but little reduction of the magnitude of its total final settlement can be expected, since the compressibility of the foundation soils is not altered by the geosynthetic, although the stress distribution may be somewhat different.

Overall bearing failure

- The bearing capacity of an embankment foundation soil is essentially unaffected by the presence of a geosynthetic layer within or just below the Embankment.

- Therefore, if the foundation soil cannot support the weight of the embankment, then the embankment cannot be built.



- Overall bearing capacity can only be improved if a mattress like reinforced surface layer of larger extent than the base of the embankment will be provided.

- The overall bearing failure is usually analysed using classical soil mechanics bearing capacity methods.

- These analyses may not be appropriate if the soft foundation soil is of limited depth, that is, its depth is small compared to the width of the embankment.

- In such a situation, a lateral squeeze analysis should be performed

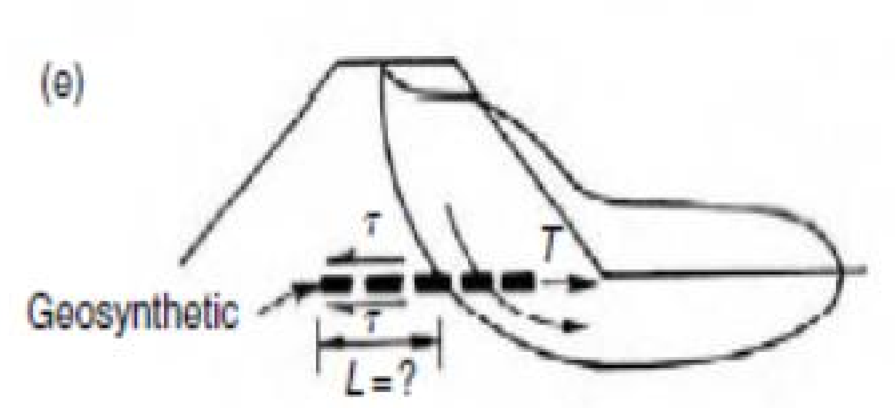
- This analysis compares the shear forces developed under the embankment with the shear strength of the corresponding soil.

- The overall bearing failure check helps in knowing the height of the embankment as well as the side-slope angles that can be adopted on a given foundation soil.

- Construction of an embankment higher than the estimated value would require using staged construction that allows the underlying soft soils time to consolidate and gain strength.

Pullout failure

Forces transferred to the geosynthetic layer to resist a deep-seated circular failure, that is, the overall stability failure must be transferred to the soil behind the slip zone.



- The pullout capacity of a geosynthetic is a function of its embedment length behind the slip zone. The minimum embedment length, *L*, can be calculated as follows:

$$L = \frac{T_a}{2(c_a + \sigma_v \tan \phi_r)}$$

If the high strength geosynthetic is used, then embedment length required is typically very large. However, in confined construction areas, this length can be reduced by folding back the edges of the geosynthetic similar to ‘wraparound’ in retaining walls or anchored in trenches properly or weighted down by berms.

The design procedure for embankment with basal geosynthetic layer(s) is given in the following steps:

- *Step 1:* Define geometrical dimensions of the embankment (embankment height, H; width of crest, b; side slope, vertical to horizontal as 1:n)

- *Step 2:* Define loading conditions (surcharge, traffic load, dynamic load). If there is possibility of frost action, swelling and shrinkage, and erosion and scour, then loading caused by these processes must be considered in the design.

- *Step 3:* Determine the engineering properties of the foundation soil (shear strength parameters, consolidation parameters). Chemical and biological factors that may deteriorate the geosynthetic must be determined.

- *Step 4:* Determine the engineering properties of embankment fill materials (compaction characteristics, shear strength parameters, biological and chemical factors that may deteriorate the geosynthetic). The first few lifts of fill material just above the geosynthetic layer should be free draining granular materials. This requirement provides the best frictional interaction between the geosynthetic and fill, as well as providing a drainage layer for excess pore water to dissipate from the underlying soils.

- *Step 5:* Establish geosynthetic properties (strength and modulus, soil–geosynthetic friction). Also establish tolerable geosynthetic deformation requirements. The geosynthetic strain can be allowed up to 2–10%. The selection of geosynthetic should also consider drainage, constructability (survivability) and environmental requirements.

- *Step 6:* Check against the modes of failure, as described earlier. If the factors of safety are sufficient, then the design is satisfactory, otherwise the steps should be repeated by making appropriate changes, wherever possible.