A STUDY ON SLOPE STABILITY ANALYSIS OF GEOSYNTHETIC REINFORCED EMBANKMENTS

by

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TO MY GREAT PARENTS

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ABSTRACT

In this study, the design problem of a geosynthetic reinforced slope embankment is discussed. The method proposed by the Federal Highway Administration, FHWA is followed, and its adequacy is checked.

A computer program is developed which would design the slope of an embankment. The program has some searching routine to help to locate critical surfaces. The program prints the amount of reinforcements required as well as their distribution along the edge of the embankment.

ÖZET

Bu çalışmada, dik eğimli (şevli) geosentetik donatılı dolguların dizayn problemleri tartılışmıştır. "Federal Highway Administration, FHWA " tarafından önerilen metod kullanılmış ve yeterliliği kontrol edilmiştir.

Dolgunun şev dizaynı için bir bilgisayar programı geliştirilmiştir. Bu program, kritik yüzeylerin yerleşimini araştırmak için kullanılmıştır. Ayrıca, program dolgu kenarı boyunca gerekli olan donatı miktarını ve dağılımını da vermektedir.

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Symbol	Meaning
b	width of a slice
c	cohesion
CRF	creep reduction factor
D	moment arm
DM	driving moment
E	total interslice normal force
F	factor of safety
FC	construction damage factor of safety
FD	durability factor
FS	over all factor of safety
F.S.r	factor of safety of the unreinforced slope
F.S.s	sliding safety factor
F.S.u	factor of safety of the unreinforced slope
h	average height of a slice
H	slope height
n	number of slices
N	normal force acting on a segment of the base of a slice

Pr	resisting force
Psl	sliding force
q	surcharge
r	moment arm
R	radius of a circle
S	shear force on the base of a slice
T	tensile force of the reinforcement
Tmax	maximum tensile force used in design
Ts	sum of available or required tensile force per width of reinforcement for all reinforcement layers
Tu	ultimate or yield tensile strength
u	pore water pressure
W	weight of an individual slice
Y	location of the resultant force
α	angular measure
θ	angular measure
ϕ	angle of internal friction for a soil

CHAPTER I

INTRODUCTION

Reinforced Soil is a composite construction material in which the strength of engineering fill is enhanced by the addition of some reinforcements such as, fabrics,in the form of strips. The basic mechanism involves the generation of frictional forces between the soil and the reinforcement. Additionally, the reinforcement has the ability to unify a mass of soil that would otherwise part along a failure surface. The basic two components of reinforced soil are namely, engineering fill and reinforcement as well as some form of facing which prevents surface erosion and gives an aesthetically pleasing finish.

An aspect in the success of any reinforced soil is that the two materials should be compatible in terms of surface characteristics, geometry and adherence, so that the stresses can be transferred from one to the other. Existing ground and embankments for example, may be strengthened considerably by the installation of reinforcement elements, in the form of layers of strips or grids, made out of polymers, or plastics. For example, the inclusion of reinforcing elements into the

the edge of a slope, offers an outstanding potential for increasing strength in slope stability, for maintaining steep slopes in embankments.

Embankments, for instance are constructed for many different purposes including highways, railways, dams, levees and stockpiles. In each instance the embankment must be checked whether it has an adequate factor of safety against slope stability or not. Stability failure occurs when an outer portion of an embankment slides downward and outward with respect to the remaining part of the embankment.

A detailed investigation of slope stability includes in general a geological study, field observations, in site testing, test boring, laboratory testing, and detailed slope stability calculations. Several factors may affect the stability of the embankment. For example, type of external loading , change of water level, the quality of the backfill, foundation type. These several factors may produce shear stresses throughout the soil mass, and a movement will occur unless the shearing resistance on every possible failure surface throughout the mass is sufficiently larger than the shearing stresses. The shearing resistance depends on the shear strength of the soil and other natural factors, such as instant presence of water from seepage and/or rainfall infiltration as well as roots, ice lenses and frozen ground.

In many cases, the factor of safety against stability failure may not be adequate, so the need of some reinforcements become essentially required to produce stability, without of which a steep slope would not be possible. The use of this reinforcements is so well suited to the needs of highway construction where steep slopes of reinforced soil reduce the required width of new roads and are specially suitable for the widening of existing traffic lanes in constricted rights of way.

CHAPTER II

GEOSYNTHETIC REINFORCEMENT

2.1 INTRODUCTION

Geosynthetic products appeared two decades ago as new materials for civil engineering applications. Because of their unique properties as light weight reinforcements, the geosynthetics have become essential for use in geotechnical applications.

Geosynthetic materials can be divided into two categories, Extensible and Inextensible reinforcements. An example of extensible geosynthetics is geotextile, which has a fabric structure, while an example of inextensible geosynthetics is geogrid, which has a grid structure (non fabric) manufactured of synthetic polymers.

2.2 DEFINITION OF GEOTEXTILES

Geotextiles are thin, flexible, permeable sheets of synthetic material used to stabilize and improve the performance of soil associated with civil engineering works.

Correctly designed and installed, geotextiles have the ability to filter, drain, reinforce and separate soil. In many applications, geotextile may be designed and selected to perform a combination of these functions. For example, when installed at the base of a granular fill embankment constructed over soft clay all four functions might operate. Relationships between the functions of geotextiles and materials are show in Fig.2.1.

2.2.1 Classification of Geotextiles

The properties of a textile will be radically affected by the material of the textile and the structure of the textile imparted by the manufacturing process. Twenty types of geotextiles and related products are presented in Fig.2.2.

The main two groups are:

A) Woven Fabrics

As the name implies, woven fabrics are obtained by conventional weaving processes, using a mechanical loom. In this process, an array of parallel elements is beamed into the loom, and transverse elements are threaded over and then under alternate warp elements. This type of weaving described is plain weave, of which there are many variations, such as twill, satin and serge; however, plain weave is the most commonly used in geotextiles.

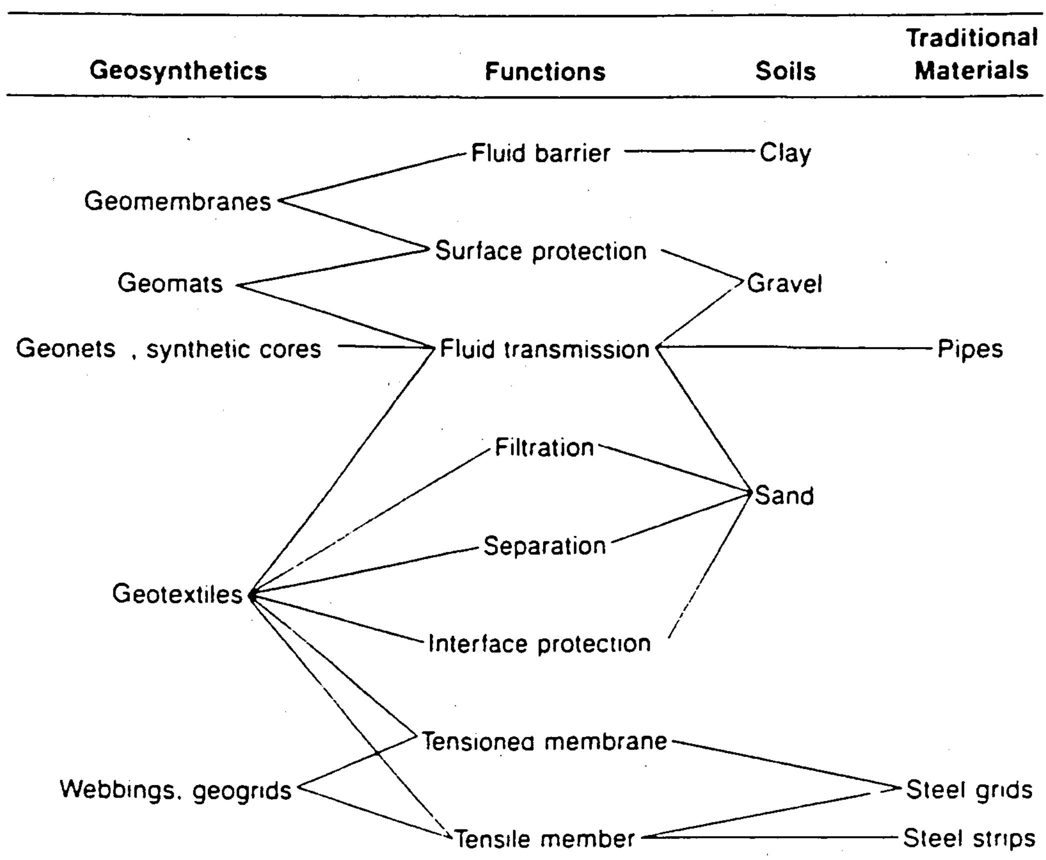


Fig.2.1 Relationships Between Functions of Geotextiles and Materials (Giroud,1986)

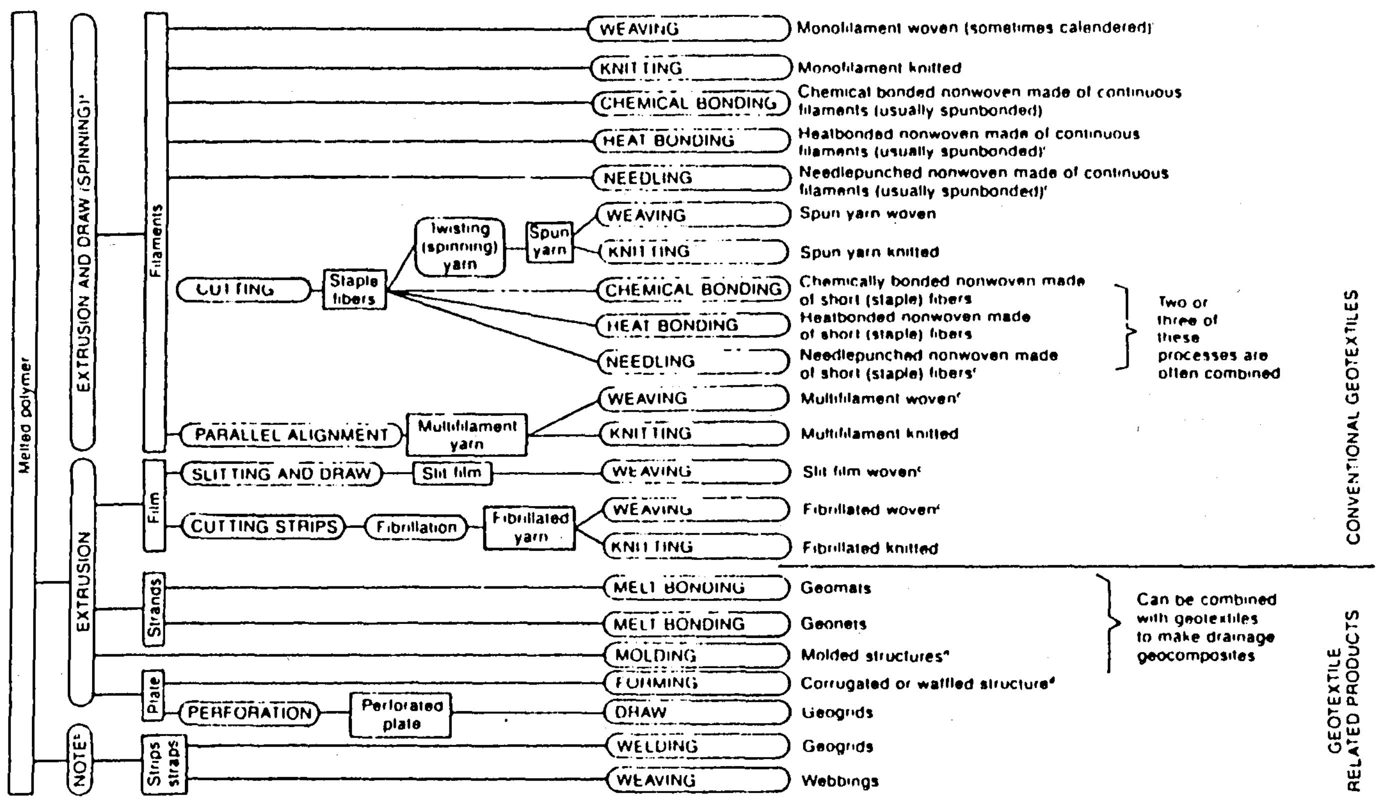


Fig.2.2 Production of Geotextiles and Related Products (Giroud,1986)

B) Non Woven Fabrics

In the case of non wovens, continuous monofilaments are usually employed; these may, however, be cut into short staple fibres before processing. The first step in processing involves continuous laying of the fibres or filaments on to a moving conveyor belt to form a loose web slightly wider than finished product. This passes along the conveyor to be bonded. The bonding process used falls into one of the three broad categories:

i) Chemical Bonding : A chemical substance is added to the web to fix the fibers together.

ii) Thermal Bonding : The web is heated and compressed, which cause partial melting of the fibers and makes them adhere together.

iii) Mechanical Bonding : The web is subjected to alternate runs by thousands of small needles of special shapes, which entangle the fibers by needle punching.

2.2.2 Functions and Applications of Geotextiles

In general, the functions and applications of geotextile vary from site to site and from application to application. However, the common use of them is illustrated in Fig.2.3, and can be grouped into the following categories (Giroud,1986) namely:

1) Fluid transmission (removes excess water)
2) Filtration (prevents piping)
3) Separation (prevents mixing)
4) Protection (prevents damage)
5) Tensioned membrane (provides reinforcement)
6) Tensile member (provides reinforcement)

While the general application of geotextiles may by grouped into the following categories , presented in Table 2.1 and Fig.2.4 ;

a) Hydraulic applications (drainage, erosion control)
b) Geosynthetic construction (containers, geomembrane)
c) Geotechnical structures (roadways, soil reinforcement)

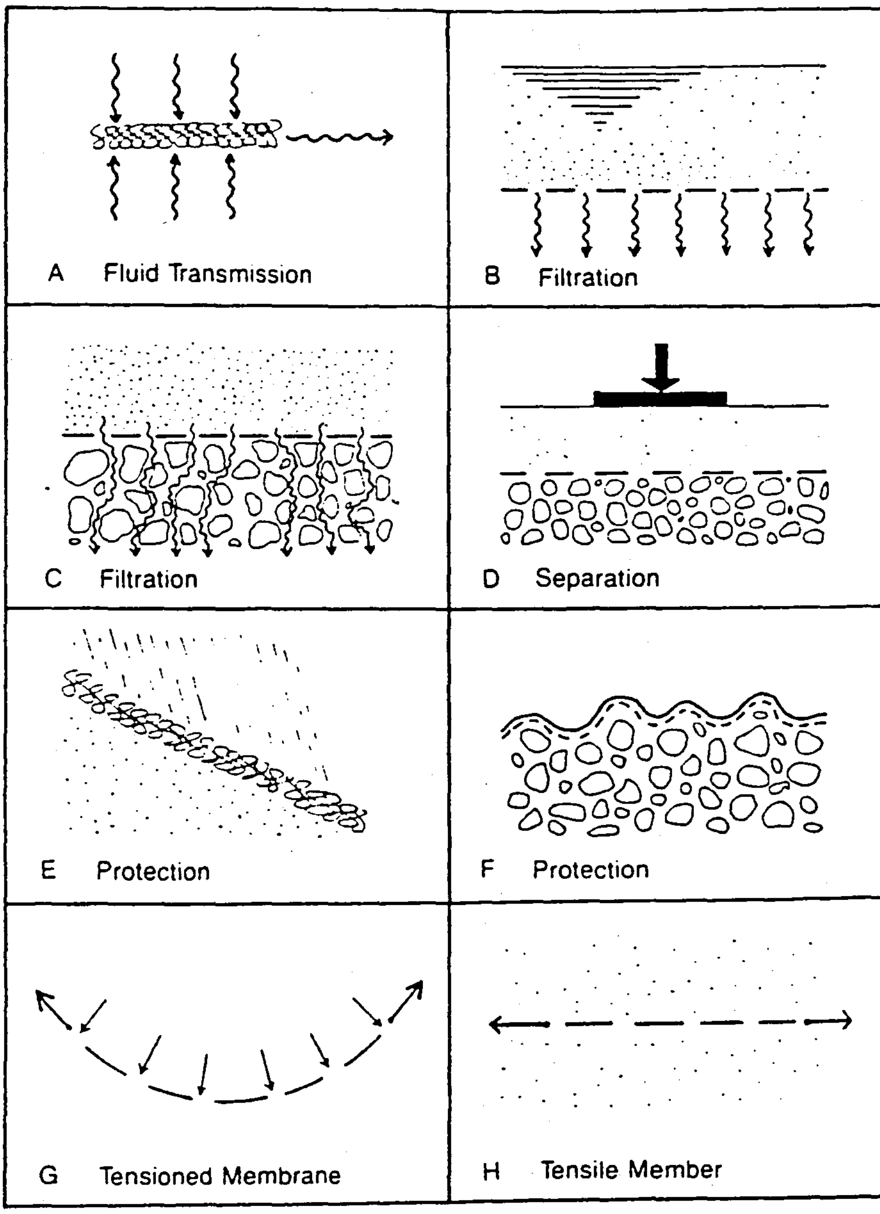


Fig.2.3 Functions of Geotextiles and their Related Products (Giroud,1986)

Table 2.1 Relationships Between Applications and Functions of Geotextiles (Giroud,1986)

Application Category	Application Area	Application Type	Fluid Transmission	Filtration	Protection	Separation	Tensioned Membrane	Tensile Member
Hydraulic Applications	Drainage and Ground Water	a Geosynthetic drains without filter (thick nonwoven)	x					
		b Geosynthetic drains with filter (geocomposites)	x	x				
		c Gravel drains		x				
		d Pipes		x				
		e Ground water recharge		x				
	Erosion Control	f Bank revetments		x				
		g Erosion mats			x			
		h Silt fences		x			x	
		i Retaining structures		x			x	
Geosynthetic Construction	Containers	j Concrete forming		x			x	
		k Sand tubes (hydraulic fill)		x			x	
		l Gabions					x	
		m Sand bags					x	
	Geomembrane Support	n Bridging					x	
		o Cushion			x			
		p Slip surface			x			
Geotechnical Structures	Roadways	q Landing mats			x			
		r Asphalt overlay			x			
		s Unpaved roads (large deflection)				x	x	
		t Base courses (small deflection)				x		x
		u Ballast				x		x
		v Asphalt pavement reinforcement				x		x
	Soil Reinforcement	w Faced reinforced walls						x
		x Unfaced reinforced walls						x
		y Slopes						x
		z Embankments						x

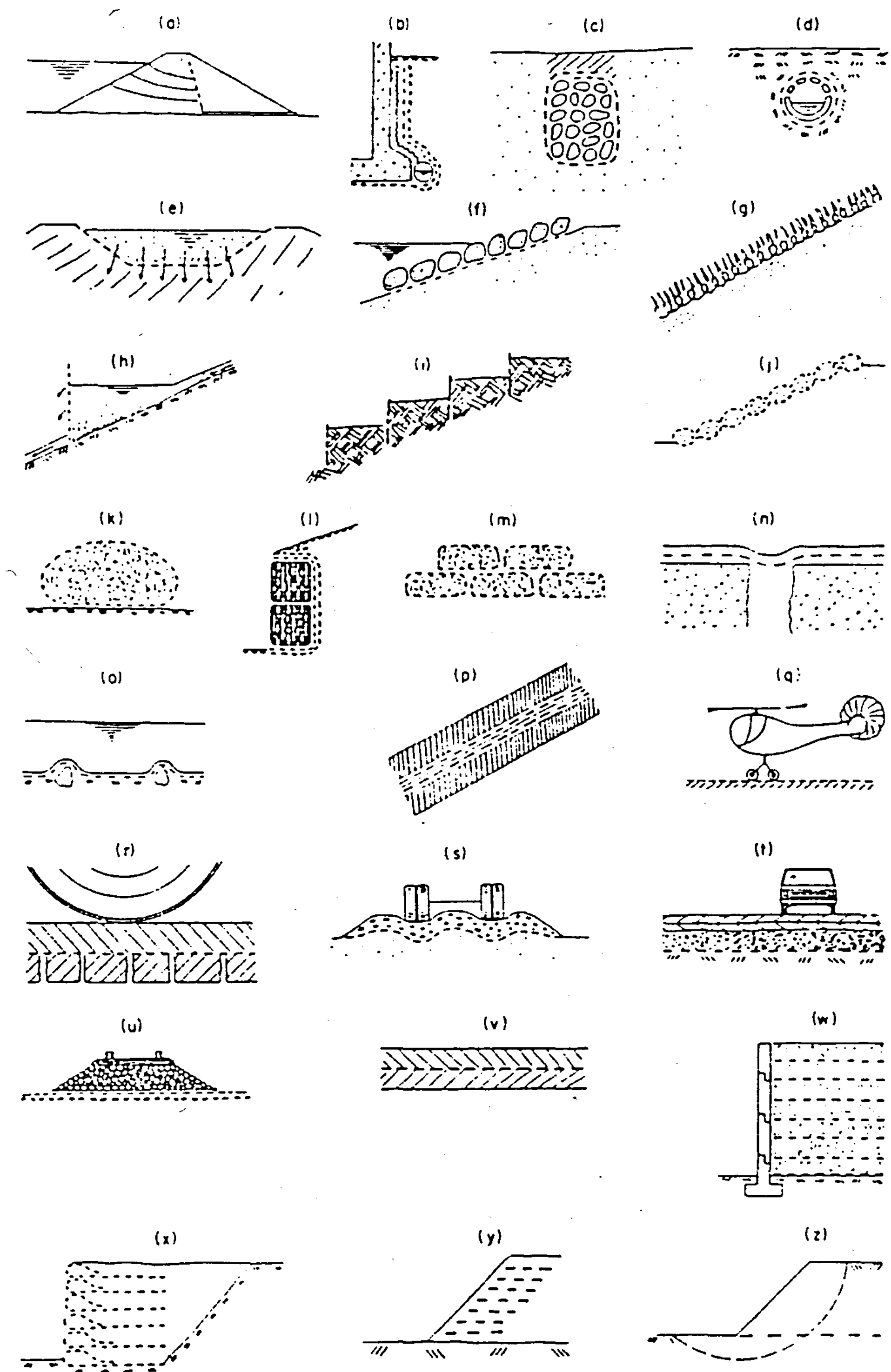


Fig.2.4 Examples of Applications of Geotextiles and Their related Products (Giroud,1986)

2.3 GEOGRIDS

Geogrids are characterized by opening which can be larger in dimension than the sets of members making up the solid component of the grid. Textile grid structures can be formed using special weaving techniques such as leon weave, which produces large orthogonal pores, or by heat bonding two orthogonal sets of strands or tapes. The method employed for the production of Tensar grids involves a patented method of processing sheet polymer. Two or three stages are involved in the manufacturing process, which is illustrated diagrammatically in Fig.2.5. The first stage involves feeding a sheet of polymer, several millimeters thick, into a punching machine, which punches out holes on a grid pattern. Following this, the punched sheet is heated and stretched, or drawn, in the machine direction. This distends the holes to form an elongated grid opening, In addition to changing the initial geometry of the holes, the drawing process orients the polymer molecules in the direction of drawing. The degree of orientation will vary along the length of the grid; however, the overall effect is an enhancement of tensile strength and stiffness. The process may be halted at this stage, in which case the end product is a uniaxially orientated grid. Typical examples are illustrated in Fig.2.6.

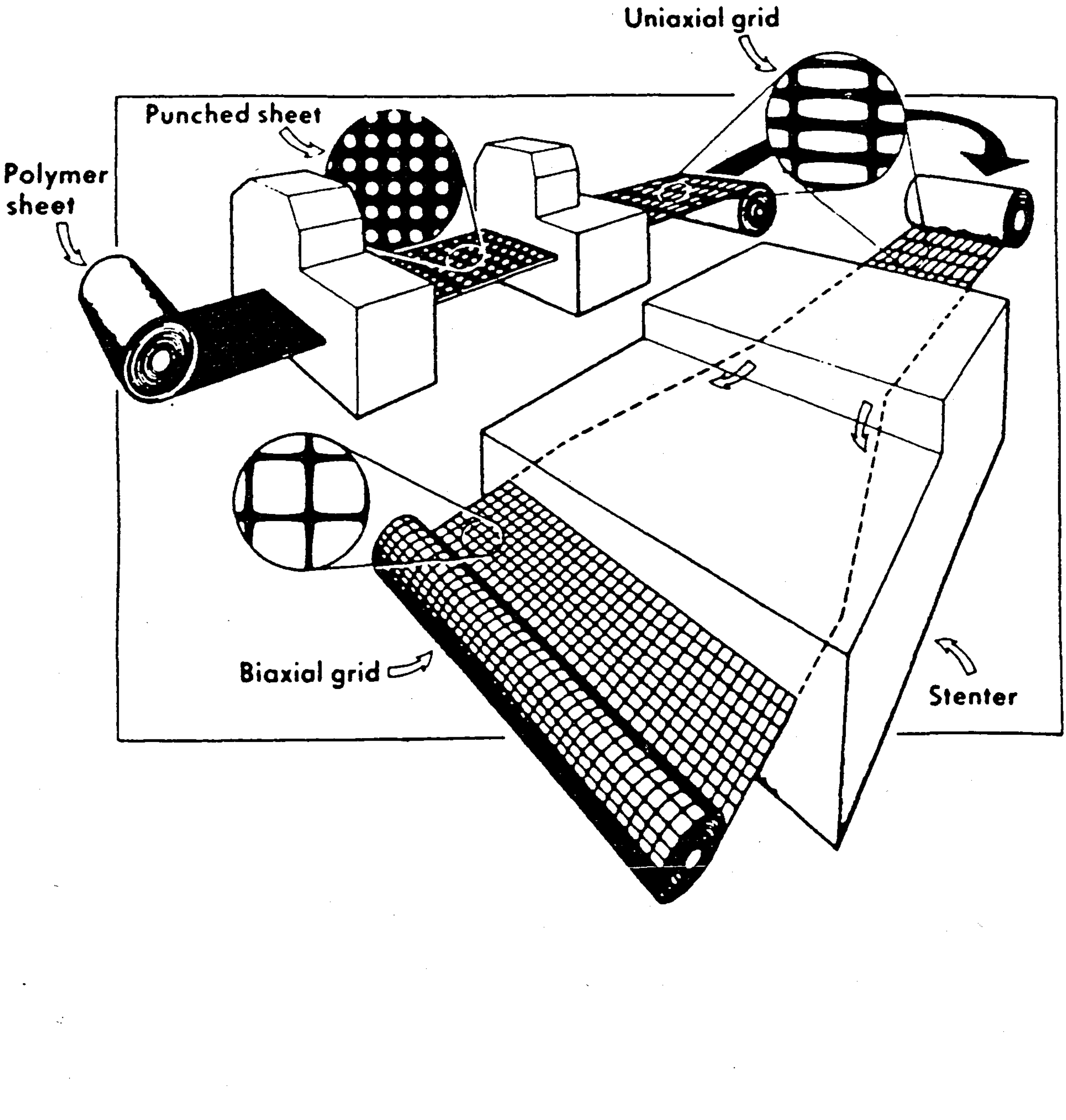
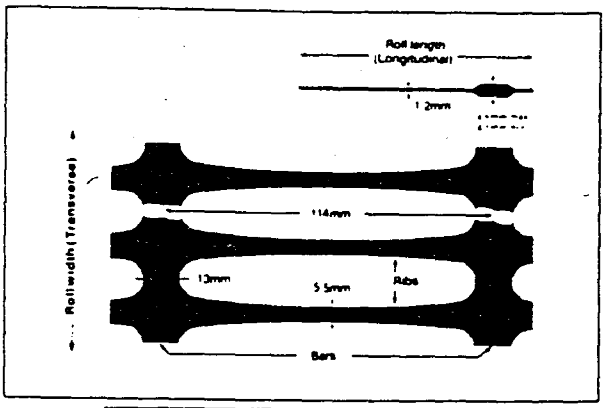


Fig.2.5 Tensar Manufacturing Process (Netlon,1986)

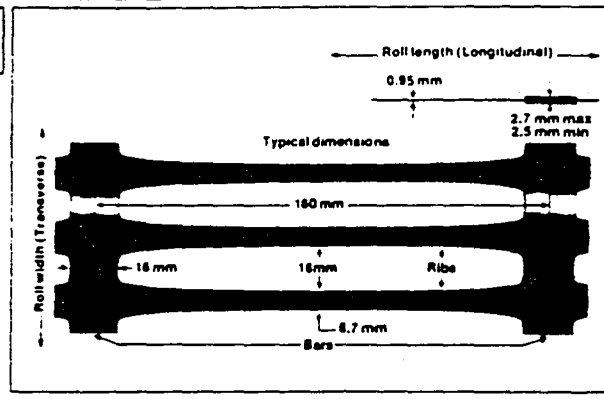


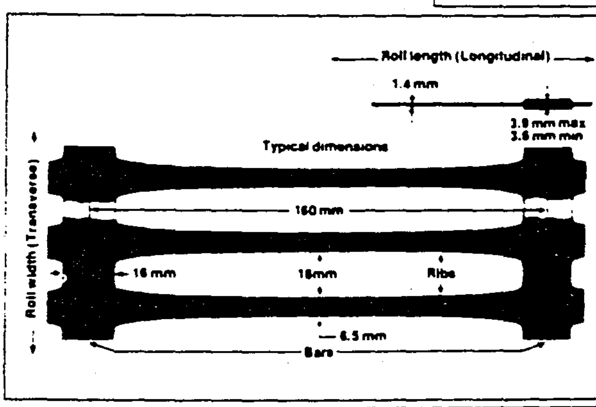
'Tensar' SR2 geogrid

Polymer = High density polyethylene
Weight = 0.85 kg/m
Quality Control Strength 80 kN/m
Characteristic Strength (120 year design life) 29.0 kN/m
Roll dimensions 30m × 1m

'Tensar' SR55 geogrid

Polymer = High density polyethylene
Weight = 0.5 kg/m
Quality Control Strength 55 kN/m
Characteristic Strength (120 year design life) 20.5 kN/m
Roll dimensions 30m × 1m





'Tensar' SR80 geogrid

Polymer = High density polyethylene
Weight = 0.7 kg/m
Quality Control Strength 80 kN/m
Characteristic Strength (120 year design life) 30.5 kN/m
Roll dimensions 30m × 1m

'Tensar' SR110 geogrid

Polymer = High density polyethylene
Weight = 1.1 kg/m
Quality Control Strength 110 kN/m
Characteristic Strength (120 year design life) 42.0 kN/m
Roll dimensions 30m × 1m

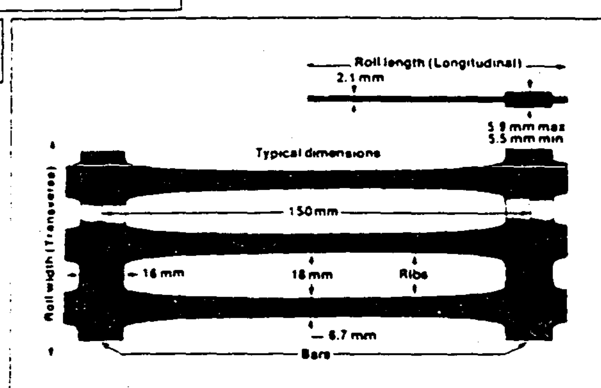


Fig.2.6 Typical Examples of Tensar Uniaxial Grids (Netlon,1986)

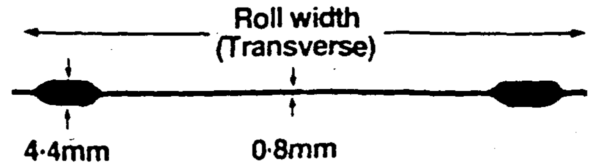
Alternatively, the uniaxially orientated grid may proceed to a third stage of processing to be warn in the transverse direction, in which case a biaxially orientated grid is obtained. In this structures the grid opening is very nearly square, as illustrated in Fig.2.7. Although the temperatures used in the drawing process are above ambient, this is effectively a clod drawing process, as the temperatures are significantly below the melting point of the polymer.

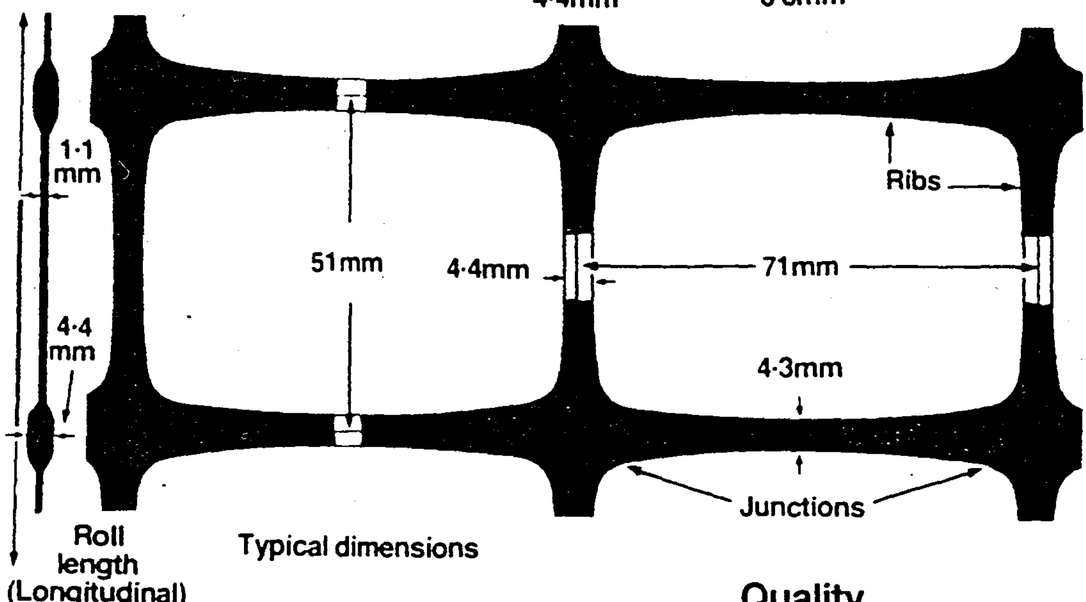
2.4 TENSILE BEHAVIOR OF GEOSYNTHETICS

The tensile behavior of geotextiles and geogrids can be "characterized by the plot of the force per unit width (expressed in kn/m), versus strain Fig.2.8. This tension elongation curve is obtained by subjecting a rectangular specimen of geosynthetic to an increasing elongation in one direction and recording the resulting tensile force until failure occurs" (Giroud,1986). Table 2.2. shows typical values of tensile characteristics of geotextiles and their related products.

Specification

'Tensar' AR1 polymer grids were developed for reinforcing asphalt roads and pavements to minimise rutting and reflective cracking.





Roll dimensions

Length: 50m
Width: upto 4·0m
Approx diameter 0·5m
Approx weight 54kg

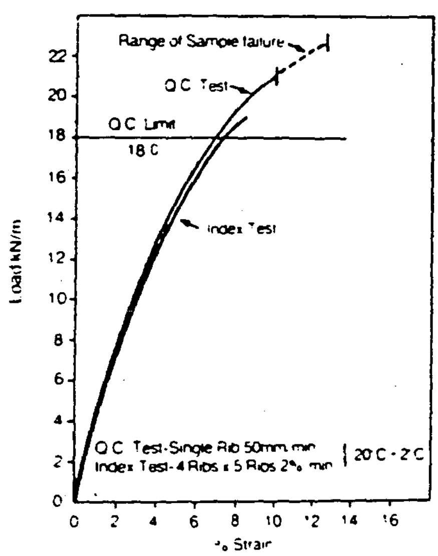
Physical properties of the grids

Weight: 0·24 kg/m²
Colour: Black

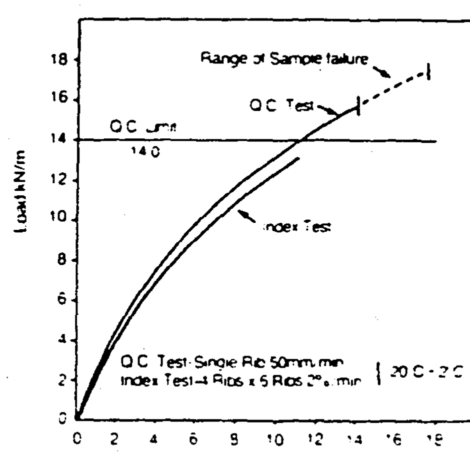
Quality Control Properties

	*Quality Control Strength (kN/m)	Approx Peak Strain (%)	**Maximum Shrinkage (%)
Transverse	18·0	10·0	4·0
Longitudinal	14·0	14·0	4·0

*Determined as a 95% lower confidence limit
**Determined as the free relaxation in a forced circulation hot air oven at 140°C for 30 mins



Typical tensile results for 'Tensar' AR1 polymer grids (Transverse direction)



Typical tensile results for 'Tensar' AR1 polymer grids (Longitudinal direction)

Fig.2.7 A Typical Sample of Tensar Biaxial Grid

(Netlon,1986)

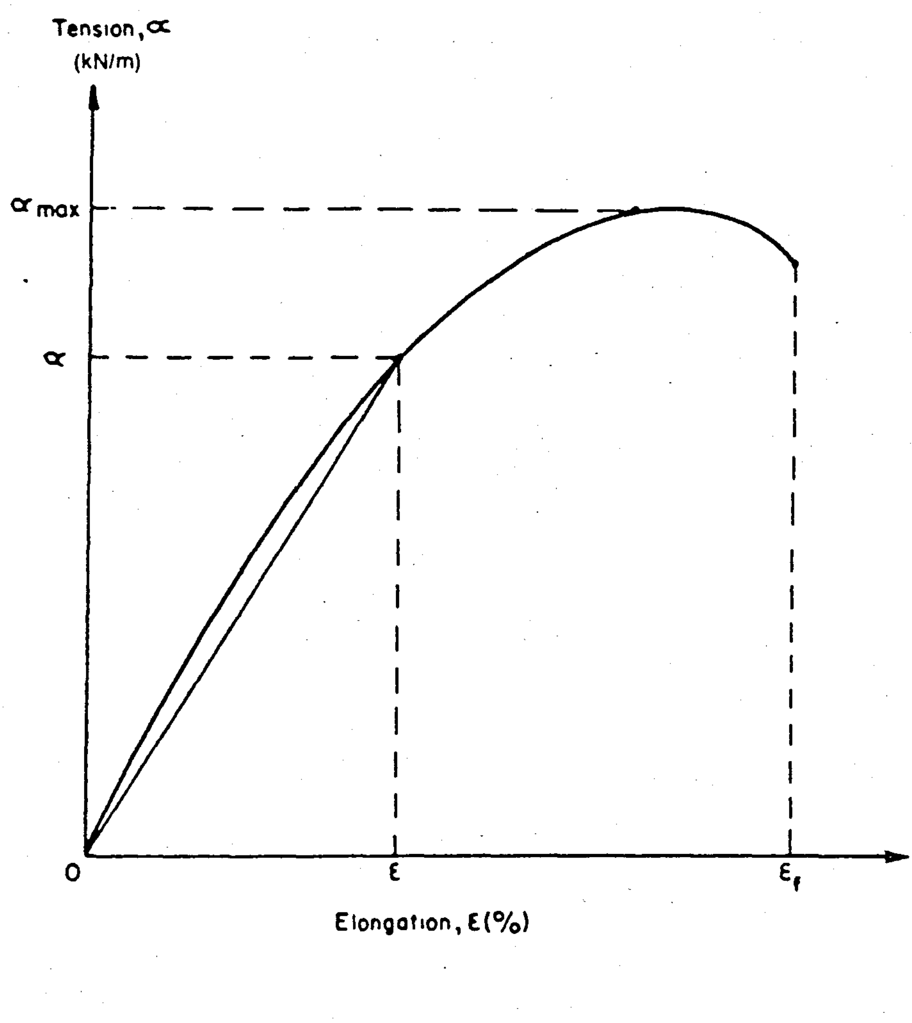


Fig.2.8 Typical Tension-Elongation Curve

Table 2.2 Typical Values of Tensile Characteristics of Geotextiles and Their Related Products (Giroud, 1986)

Type of Geotextile or Geotextile-Related Product	Elongation at Failure ϵ_f %	Level of Tensile Characteristics	Strength α_{max} kN/m (lb/in.)	Secant Modulus at ϵ = 5% J_5 kN/m (lb/in.)
Heatbonded nonwoven geotextile	50–100	Typical	20 (120)	50 (300)
Needlepunched nonwoven geotextile	50–100	Typical	20 (120)	20 (120)
		High	100 (600)	100 (600)
Woven geotextile	10–25	Typical	25 (150)	300 (1.800)
		High	80 (500)	1.000 (6.000)
		Very High	500 (3.000)	5.000 (30.000)
Geogrid	10–15	Low	20 (120)	150 (900)
		High	100 (600)	1.000 (6.000)
		Very high	200 (1.200)	2.000 (12.000)
Webbing	10	Typical	100 (600)	1.000 (6.000)
Geonets	> 100	Typical	5 (30)	
Geomats	> 100	Typical	1 (5)	

2.5 ADVANTAGES

Geosynthetics reinforcement have numerous advantages. Mainly ;

a. Ease of transportation

b. Construction by unskilled labor

c. Limited heavy equipment required

d. Minimal excavation required

e. No corrosion problem

f. Drainage of backfill

g. Low cost and weight

h. Resistance to chemical attack

i. Speedy construction

j. An improved composite construction material

k. The use of a Lower quality backfill materials

2.6 DISADVANTAGES

Geosynthetic reinforcements have also some limitations :

a. Susceptibility to damage during construction;

b. Creep (Large deformation may develop with time

c. Lack of proven theories and tests for analysis

2.6.1 General Creep Considerations

The time dependent stress deformation behavior of geosynthetics is of concern, because the reinforcement may undergo excessive deformation due to creep even though adequate factors of safety are provided against rupture or pullout. Apparently, fastening or interlocking of the geotextile fibers by heat or resin bounding or woven structures can also produce creep deformation. Creep is a function of stress level, temperature, and obviously material type.

2.7 SUMMARY

Geosynthetic products have transformed geotechnical engineering to the point that it is no longer possible to do geotechnical engineering without them. Moreover, they have progressively pervaded all branches of geotechnical engineering in what may be one of the most important means of soil reinforcement. They are used as a practical means to solve construction problems and at the same time, have open up a new opportunities for creativity for the geotechnical engineer.

CHAPTER III

MECHANICS OF SLOPE STABILITY ANALYSIS

3.1 INTRODUCTION

The stability of earth masses against sliding, or gravity effects, is a serious problem. It must be routinely solved in most earthwork construction. This is because the ground is not being level, which results in gravity components of the weight tending to move the soil mass from a higher to a lower elevation.

Every mass of soil located beneath a sloping ground surface or beneath the sloping sides has the tendency to move downward and outward under the influence of gravity. If this tendency is counteracted by shearing resistance of the soil, or by some other means e.g., some reinforcements, the slope is stable, otherwise a slide occurs.

3.2 LITERATURE REVIEW

The literature subdivides slope stability analysis into several methods. The limit equilibrium evaluates the overall stability of the sliding mass just on failure surface, using some or all of the three equations of statics equilibrium. The soil stress strain relationships are not considered. This is the procedure believed to have been first proposed by Fellenius (1936), defined by Bishop (1955), and later used by Morgenstern and Price(1965).

The development of limit equilibrium methods based on the plastic equilibrium of trial failure surfaces began in Sweden in 1916, following the failure of a number of quay walls. Petterson (1955) and Hultin (1916) in separate publications reported that the failure surfaces in the soft clays of closely resembled arcs of circles. Over the next few years the friction circle method of analysis was devised, results from simple undrained shear tests were used with reasonable success in predicting stability, and the method of slices was introduced by Fellenius (1936). The concept of pore water pressure and the effective stress method of analysis was introduced by Terzaghi (1936). Improved soil strength measurements resulted from better sampling techniques, the development of the triaxial shear test, and the measurement of pore water pressure.

Improved methods of analysis that included the side forces between slices were developed, beginning with Fellenius

(1936) and Bishop (1955). More rigorous analytical methods usually involving the use of digital computers are available (Morgenstern and Price, 1965; Janbu, 1973; Bailey and Christian, 1969). However, despite the use of more rigorous methods of analysis and improved soil-testing techniques, many uncertainties remain in predicting the stability of slopes. These uncertainties are primarily associated with the measurement of soil strength (Johnson, 1975) and the prediction of pore pressure.

3.3 FACTORS CAUSING INSTABILITY

Factors leading to in stability can be classified as:

1) Those causing increased stress;

2) Those causing a reduction in strength.

Factors causing stress include increased unit weight of soil by wetting, added external loads such as building, traffic loads on embankments, steepened slopes either by natural erosion or by excavation. Loss of strength may occur by adsorption of water, increased pore pressures, freezing and thawing action, loss of cementing materials, and weathering processes.

The presence of water is a factor in most slope failures, since it causes both increased stresses and reduced strength. The rate of slide movement in a slope failure may vary from a few millimeters per hour to very rapid slides in which large movements take place in a few seconds. Slow slides occur in soils having a plastic stress-strain characteristic where there is no loss of strength with increasing strain. Rapid slides occur in situations where there is an abrupt loss of strength, as in liquefaction of fine sand or a sensitive clay.

These several factors produce shear stresses throughout the soil mass, and a movement will occur unless the shearing resistance on every possible failure surface throughout the mass is sufficiently larger than the shearing stresses.

3.4 METHODS OF ANALYSIS

The most common methods of slope stability analysis are based on limit equilibrium. In this type of analysis the factor of safety with regard to the slope's stability is estimated by examining the conditions of equilibrium when incipient failure is postulated along a pre-defined failure plane, and then comparing the strength necessary to maintain equilibrium with the available strength of soil. All limit equilibrium problems are statically indeterminate and, since the stress-strain relationship along the assumed failure surface is not known, it is necessary to make enough assumptions so that a solution using only the equations of equilibrium is possible. The number and type of assumptions that are made leads to the major difference in the various limit equilibrium methods of analysis.

Other methods of slope analysis are based on use of the theory of elasticity or plasticity to determine the shearing stresses at critical places within a slope for comparison with the strength. Recently developed finite element computer techniques are an example of this type of analysis.

In general, slope stability is a plane strain problem, i.e., the length compared to cross section is very large. It is usual to investigate a typical cross section which is one unit thick with plane strain, ignoring the perpendicular strains and stresses.

3.5 BISHOP'S PROCEDURE

In this method the potential failure surface is assumed to be a circular arc with center O and radius R. The soil mass above trial failure surface is divided by vertical planes into a series of slices of width b, as shown in Fig.3.1. The base of each slice is assumed to be a straight line. For any slice the inclination of the base to the horizontal is α and the height, measured on the center line, is h.

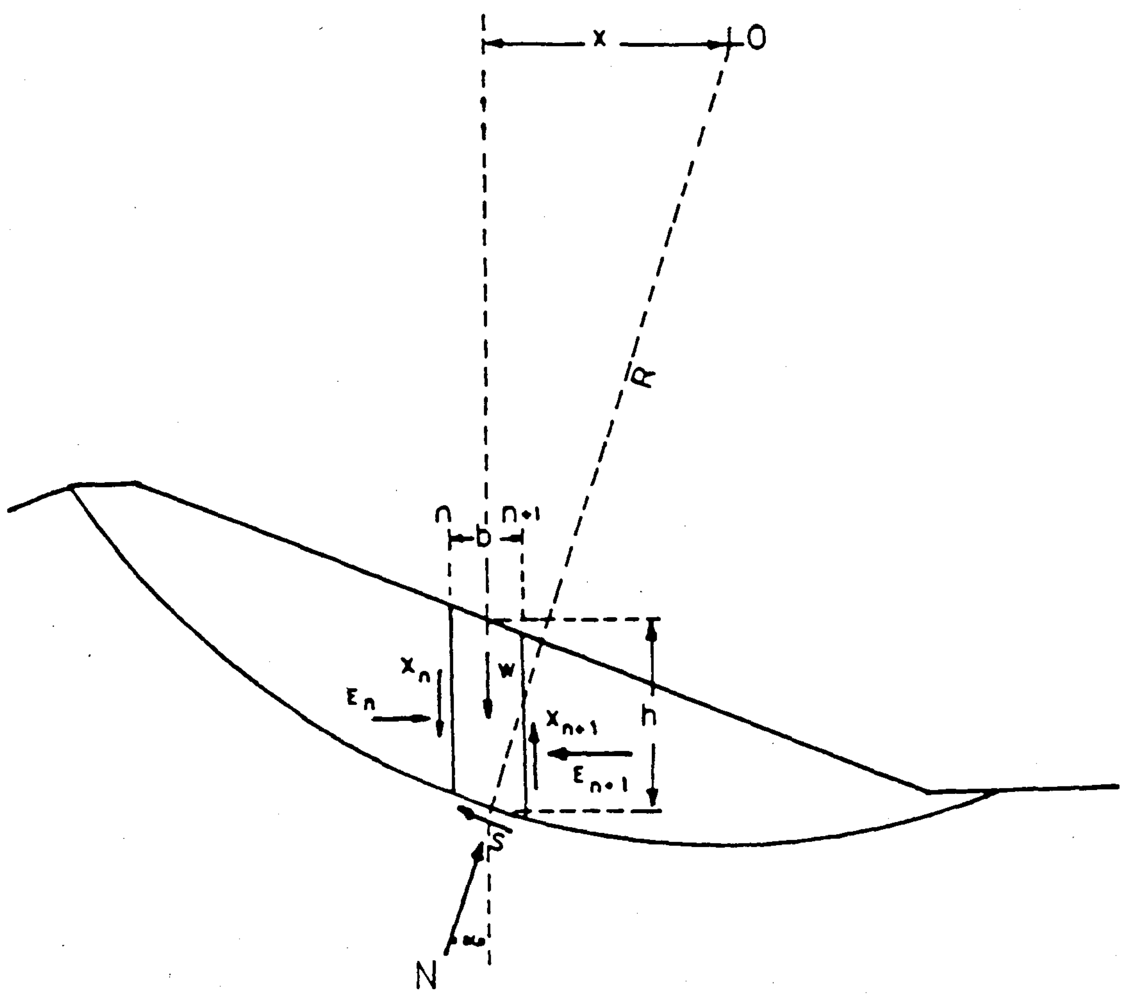


Fig. 3.1 Forces and Locations Involved in the Equilibrium of an Individual Slice

The equations of static equilibrium on each slice which must be satisfied are :

1. Moment equilibrium
2. Horizontal force equilibrium
3. Vertical force equilibrium

The forces (per unit dimension normal to the section) acting on individual slice, are:

a) The total weight of each slice, W
b) The total normal force on the base, N
c) The shear force on the base, S
d) The total normal forces on the sides, E
e) The shear forces on the sides, X

Any external forces must be included in the analysis. Because the problem is statically indeterminate and in order to obtain a solution, Bishop(1955) proposed some assumptions regarding the inter slice forces, their inclinations, and the forces applied at the base.

Assumptions proposed by Bishop are :

1) Normal force acting concentrically on the base
2) The sum of shear forces on each slice is zero
3) The weight of each slice is acting in the middle
4) The sum of horizontal forces on each slice is zero

After lengthy derivations and substitutions, the equation for the factor of safety which is defined as the ratio of the resisting moment to the disturbing (overturning) moment predicted by Bishop's method is

$$F = \frac{A}{B} \tag{3.1}$$

in which,

$$A = \Sigma \left\{ [cb + (W - u\,b) \tan \phi] \frac{\sec \alpha}{1 + (\tan \phi \tan \alpha / F)} \right\}$$

$$B = \Sigma \{ W \sin \alpha \}$$

b = width of the slice

c = apparent cohesion

W = weight of the slice

u = pore water pressure

α = angle of tangent to the slope slip circle

where effective or total stress parameters may be used in this equation.

3.6 SUMMARY

The solution of any slope stability problem is highly sensitive to the shear strength parameters, rather than the method used in analysis, and the shear strength is generally the most difficult parameter in the analysis to predict which may:

1) Be undrained for some cases of loading
2) Be effective for some cases of loading
3) Increase with time (as consolidation) or with depth
4) Decrease with time due to later saturation or due to dissipation of excess pore water pressure.

Furthermore, the shear strength is sensitive to disturbance and testing procedures, and it is also difficult to predict changed soil water conditions.

This shows that the calculated factor of safety is not exact, due to the many uncertainties involved in the parameters and analysis. However, due to its simplicity, and since Bishop's method was found to compare well with other rigorous methods,it is used in most slope stability analysis.

CHAPTER IV

GLOBAL STABILITY

4.1 INTRODUCTION

Extremely soft soils are characterized by high water content and fine grained soil, thus both compressibility and low shear strength are to be expected. When embankments are constructed over weak soils such as soft clays, there can be problems with instability in the form of rotational slipping or transverse spreading of the embankment or large deformation of the soil. Before the advent of geosynthetics, these problems were overcome by building the embankment with very flat side slopes, or berms Fig.4.1, in extreme cases, embankments have been constructed on piled foundations. In any of these solutions extra cost will be involved due to right of way, ground treatment, excavations, materials ,and transportation.

A much more economical and practical solution can be achieved by the use of several layers of geosynthetic reinforcement, placed over the original soft foundation before placing of embankment fill Fig.4.2a or place them

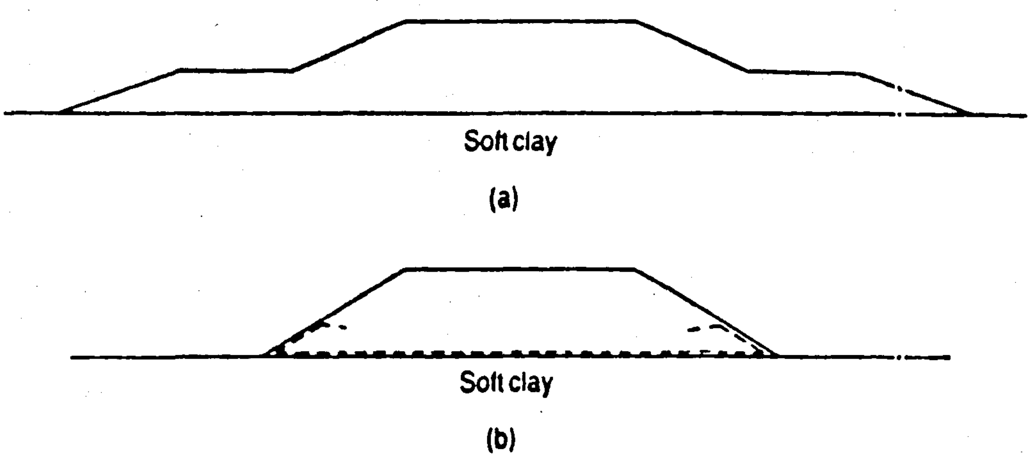


Fig.4.1 Comparison of Embankment Construction

a) With Berms

b) With Geosynthetic Reinforcement

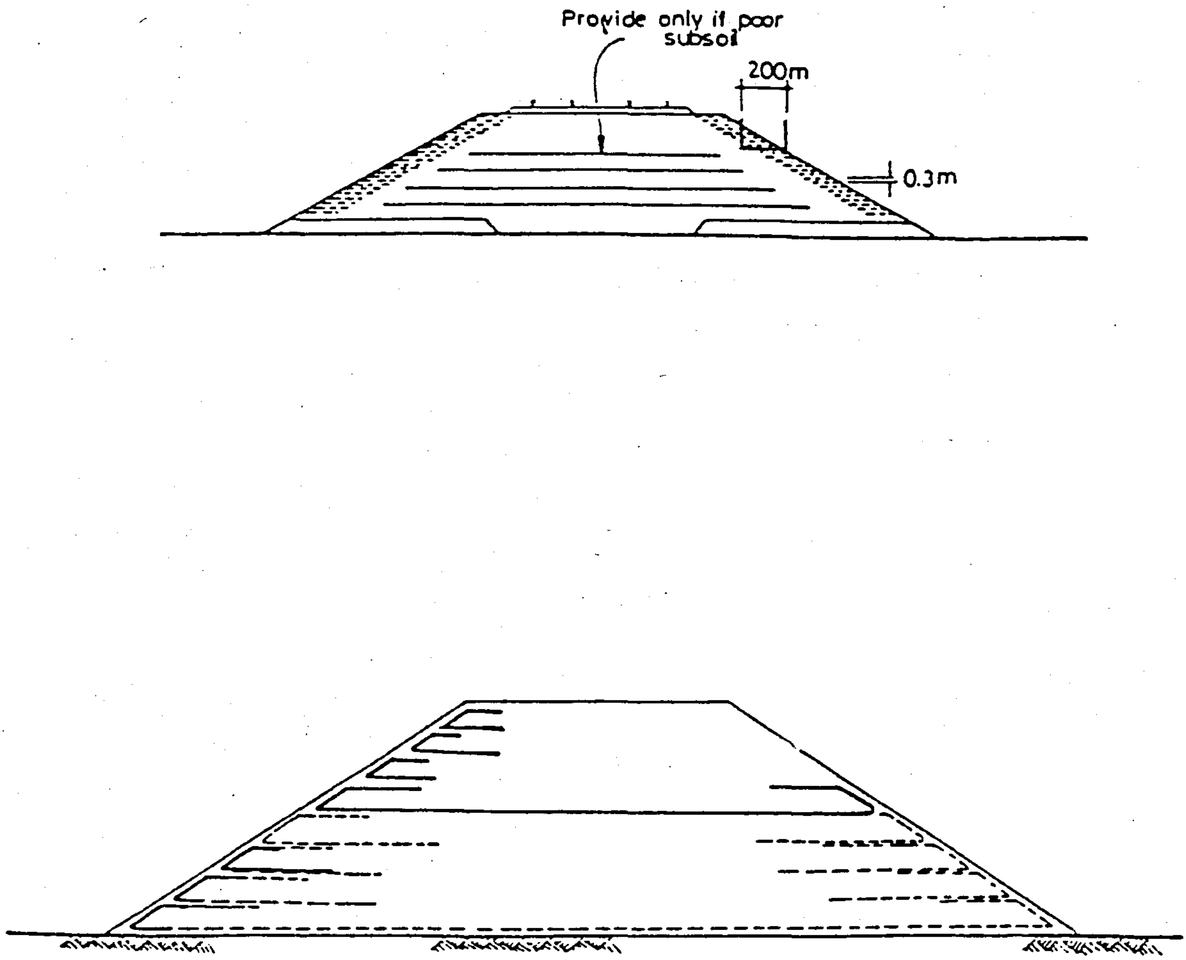


Fig.4.2 Reinforcement of Embankments

a) In Case of Poor Subsoil Conditions

b) To Produce Stability

towards the edge of the embankment so that the stability of slope will be increased, Fig.4.2b. If correctly designed and installed, the geosynthetics will transfer the tensile forces to the base of the fill, thereby resisting lateral spreading, rotational failure or extrusion of the underlying soft ground.

4.2 SOIL REINFORCEMENT INTERACTION

Geosynthetic reinforced soil is a composite material. The mechanical and physical properties of soil that affect interaction with the sheet reinforcement are a function of:

a) Particle size distribution
b) Particle angularity
c) Effective unit weight
d) Location of ground water table
e) Angle of internal friction
f) Cohesion of the soil
g) Reinforcement surface roughness and its opening size
h) Reinforcement deformation capability

The particle angularity and size distribution influence how the soil interlocks with the geosynthetic structure. In other words, interlocking in geogrids is only possible if soil particles are smaller than the geosynthetic opening. Fig.4.3. This mechanical interlock creates a flexurally stiff platform which distributes load evenly, reduces rutting and minimizes differential settlement. The stress deformation properties control how much the soil deforms under applied stresses. The friction mobilized between the soil and geosynthetic reinforcement is controlled by the angle of internal friction of the soil, the effective stress and location of the ground water table. In turn, it must be pointed out that, geosynthetics confined in a soil generally have higher strength than unconfined ones, due to soil particles inter locking with the fabric openings.

4.3 GEOTECHNICAL CRITERIA

If available, free draining granular backfill is preferred, because of its high frictional characteristics, high permeability and limited compaction requirements. However, in some cases, granular backfill was not available, and cohesive backfill was used successfully. The major criterion for selection of backfill is that it must be able to mobilize friction or adhesion between the reinforcement sheets and the soil. In the case of granular soil, the higher the friction angle is, the higher the geosynthetic to soil friction angle while in the case of cohesive soil, the greater the compacted density is, the higher the geosynthetic adhesion.

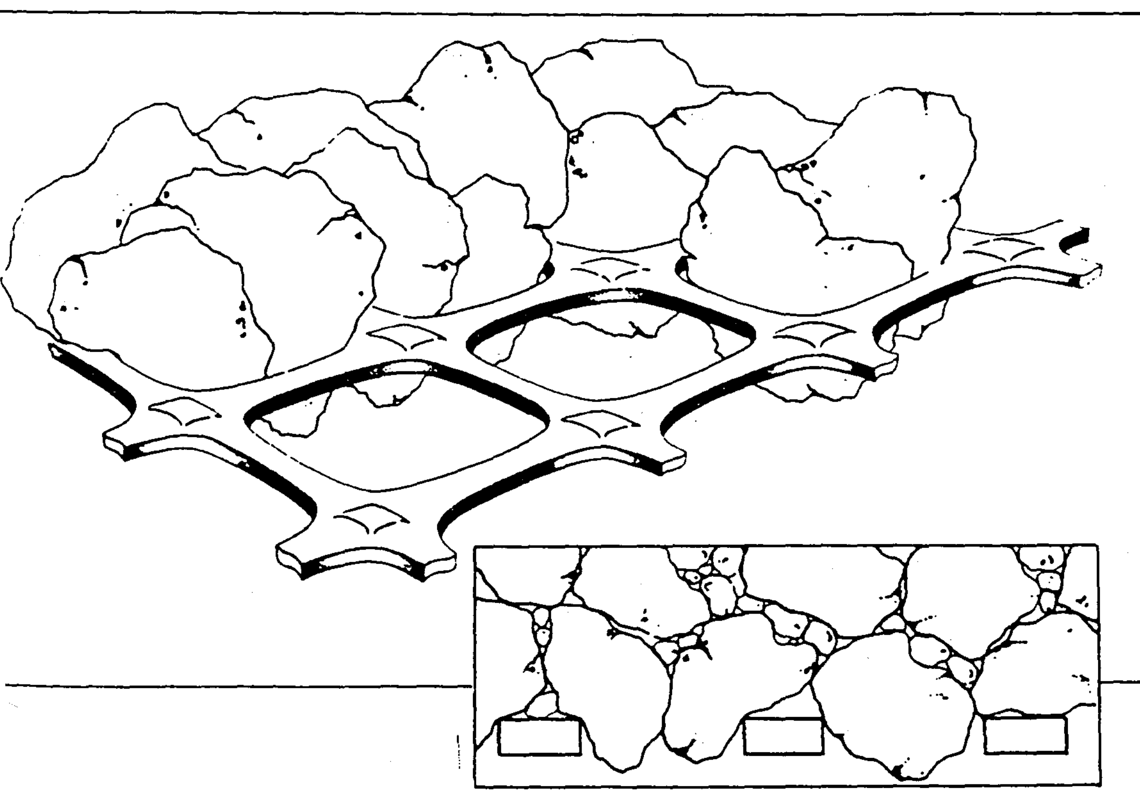


Fig.4.3 Interlocking Action Between the Soil and the Grid (Netlon,1990)

In comparison to cases where obtaining high quality material is difficult and more likely to be expensive, the selection of a poorer material is possible. It is, however, well established, that the use of soils with poorer strength, gradation, and plasticity characteristics will generally lead to more massive, more heavily reinforced, more deformable, and possibly more costly embankments for the following reasons :

a) The lower the soil friction angle, the higher will be the internal horizontal earth pressure to be restrained by the reinforcements
b) The lower the soil friction angle, the lower will be the apparent friction coefficient for frictional reinforcing systems, and the lower the bearing value for passive reinforcement systems
c) The higher the plasticity of the backfill, the greater will be the possibility of creep deformations, especially when the backfill is wet
d) The greater the percentage of fines in the backfill, the poorer will be the drainage and the more sever will be potential problems from high water pressures.

Thus, when high quality backfill is readily available, it should be used. When it is not, the cost of importing good quality backfill must be weighed against the higher cost and potentially poorer performance of a larger, more heavily reinforced embankment constructed using the lower quality but available soil.

4.4 SOIL PARAMETERS USED IN DESIGN

The Determinations of soil parameters which will be used in the analytic design and preliminary calculations should be chosen carefully corresponding to the proper conditions of the foundation soil.

When a slope is formed, by the construction of an embankment, the changes in total stress result in changes in pore water pressure in the vicinity of the slope and, in particular, along a potential failure surface. Prior to the construction the initial pore water pressure at any point is governed by the static water table level.

If the permeability of the soil is low, a considerable time will elapse before any significant dissipation of excess pore water pressure will have taken place. In the short term, at the end of construction the soil will be virtually in the undrained condition and a total stress analysis will be relevant. In principle, an effective stress analysis is also possible for the end of construction condition using the pore water pressure measurements. However, in the long term, the fully drained condition will be reached and only an effective stress analysis will be appropriate.

If, on the other hand, the permeability of the soil is high, dissipation of excess pore water pressure will be largely complete by the end of construction. An effective stress analysis is relevant for all conditions with values of pore water pressure being obtained from the static water table level.

4.5 THE EFFECT OF WATER TABLE

The construction of an embankment results in an increase in total stress, both within the embankment itself as successive layers of soil are placed and on the foundation soil.

If the permeability of the compacted fill is low, no significant dissipation of pore water pressure is likely to take place during the construction. Dissipation proceeds after the end of construction with the pore water pressure decreasing to the final value in the long term . The factor of safety of an embankment at the end of construction is therefore lower than in the long term Fig.4.4. Thus, it is very important to get rid of this water during and after the construction.

In order to minimize this porewater pressures induced during the embankment construction, the base of the fill should be furnished with a granular drainage blanket and/or using horizontal drainage geotextiles.

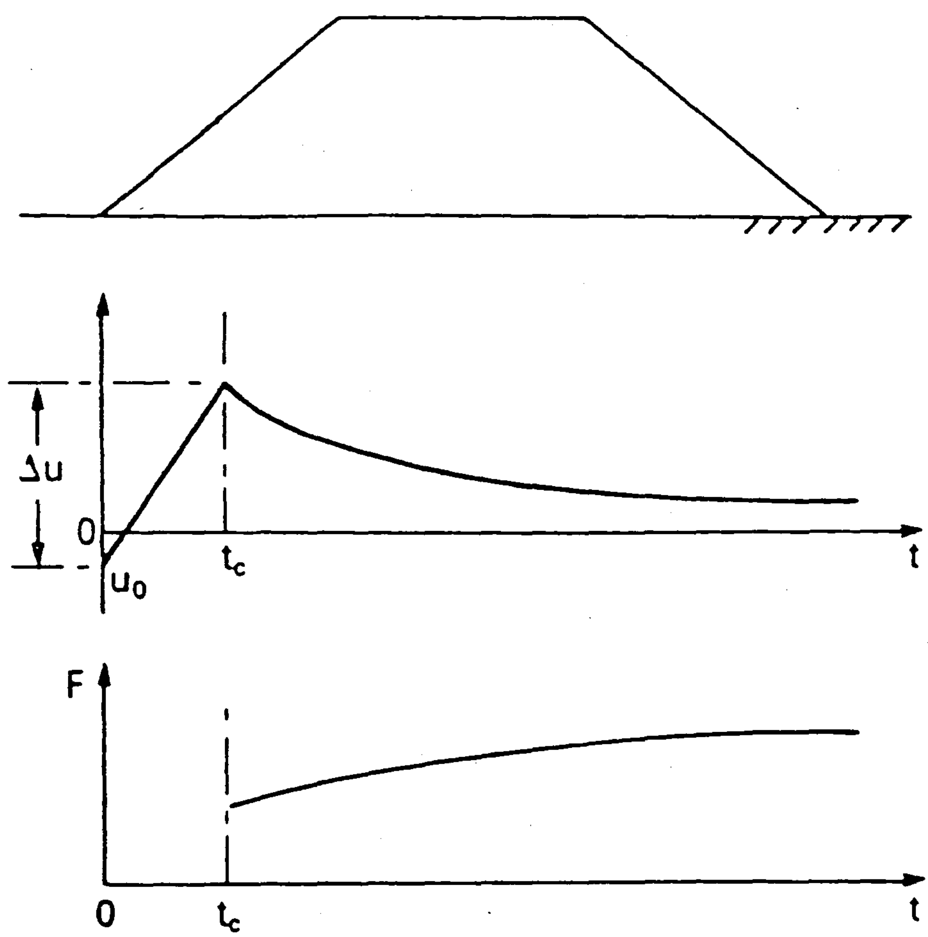


Fig4.4 Pore Water Pressure Dissipation and Factor of Safety in the Foundation Soil

Moreover, to further aid drainage and dissipation of excess porewater pressure a vertical granular drainage blanket (or sand drains) should be constructed during the placement of the main body of fill while constructing the embankment, Fig.4.5.

Furthermore, temporary loads(usually removed towards the end of the construction period) and constructing in stages can produce more stability of the embankment. The use of gradually increasing surcharge fill, which will result in the dissipation of pore water pressure where closely spaced vertical drains are provided and consequently, an increase in the shear strength. In addition, as the rate of consolidation (settlement) proceeds, the soil gains in shear strength allowing yet greater surcharge load to be placed, and thus sufficient surcharge will be carried as an equivalent permanent load, and then the surcharge load (or portion of it) is removed and the permanent system is built.

4.6 SOIL IMPROVEMENT METHODS

It is sometimes more likely required to build an embankment over very poor foundation where on other alternative route is possible. Thus, the foundation soil must be stabilized by one or a combination of those soil improvement methods.

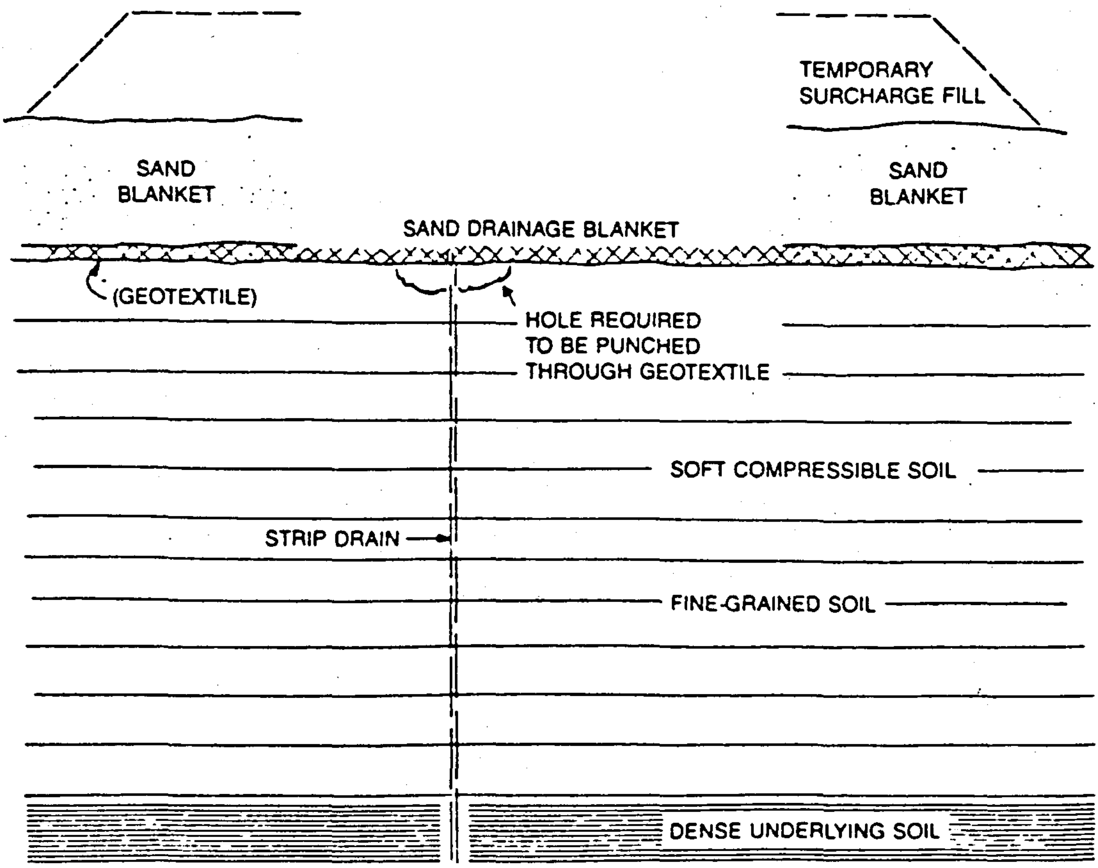


Fig4.5 Typical Cross Section Showing Reinforcing Fabric and Strip Drain

A) Geogrid Mattress

It may not be sufficient or economical to satisfy the ultimate bearing capacity criteria simply by widening the base width of the embankment, when the foundation soil is very poor. In such case the base support may be strengthened by placing several layers of geogrids.

B) Jet Grouted Inclusions

Injection of materials into the ground is one of the recent technology for soil stabilization and ground improvement. With this process it is possible to solidify the soil, using a narrow pipe. Injections by Jet Grouting, involves controlling a method of displacing and instantaneously replacing unstable soils with a special formulated mortar grout to increase the stability.

C) Compaction Grouting Inclusions

Another method of injection, called Compaction Grouting involves the injection through a grout pipe inserted into the soil, of very stiff soil cement mortar under high pressure, so as to displace and thus compact the adjacent soils.

D) In Site Lime Stabilization

Also, in recent years, lime has been used extensively to modify the engineering characteristics of fine grained soils. Generally, the plasticity, workability and strength are improved by lime treatment. Lime stabilized columns produced by mixing the agent with the soil in site, are effective in increasing the stability and the permeability of the foundation.

4.7 SUMMARY

Attention and enough care must be given to the system as a whole. In order to have a stable reinforced embankment, it is not enough to reinforce it arbitrary, failure criteria must be checked to have a global stability. Choosing good quality backfill, improving the foundation soil, making enough tests on the reinforcement to ensure their physical properties, careful handling and placement of reinforcement are all very important factors during the construction.

It is clear that the applications of geosynthetics in geotechnical engineering is almost essential in all phases of construction if they are correctly designed and placed. They can support the slope of the unreniforced steep slope, without of which it is not stable, increase the bearing capacity of foundation soil, and accelerate the consolidation of the foundations which will result in a speedy construction and reduction in differential settlement.

Their wide application are due to their light weight, ease of insulation, and effectiveness of cost reduction compared to conventional classical methods.

CHAPTER V

DESIGN PHILOSOPHY

5.1 INTRODUCTION

There are two main purposes for using reinforcement in engineered slopes:

a) To increase the stability of the slope, particularly after a failure has occurred or to widen an embankment in a constrained right of way Fig.5.1.

b) To provide improved compaction to the edge of a slope, thus decreasing the tendency for surface sloughing.

For the second application, Fig.5.2, reinforcement placed at the edges of the embankment slope have been found to provide lateral resistance during compaction, thus allowing for an increase in compacted soil density over that normally achieved. Edge reinforcement also allows compaction equipment to more safely operate near the edge of the slope. Even modest amounts of reinforcement in compacted slopes have been found to reduce sloughing and slope erosion. For this application, the design is simple: place a geotextile, geogrid, or wire mesh reinforcement that will survive

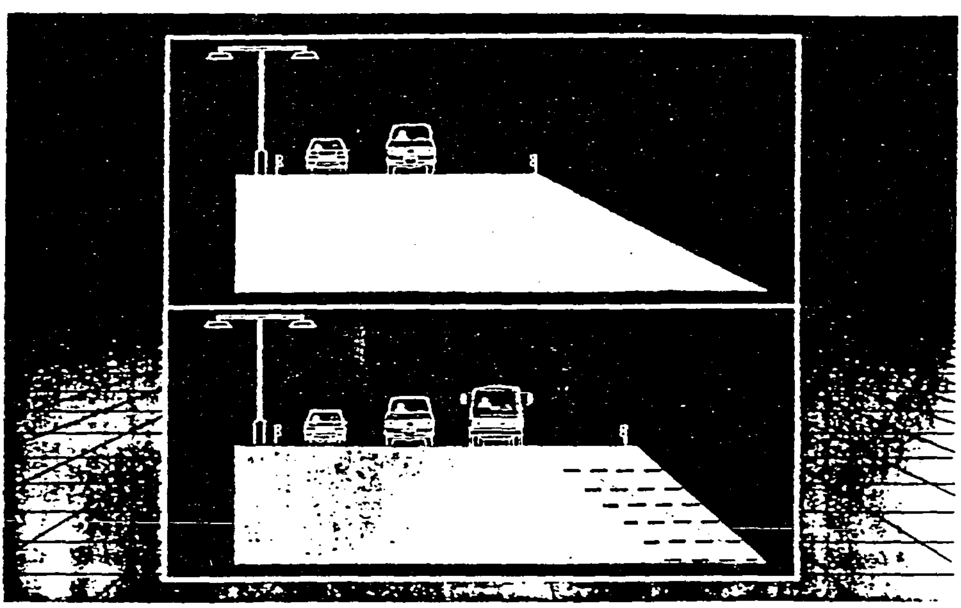


Fig.5.1 Widening an Embankment in Constrained
Right of Way (Netlon,1990)

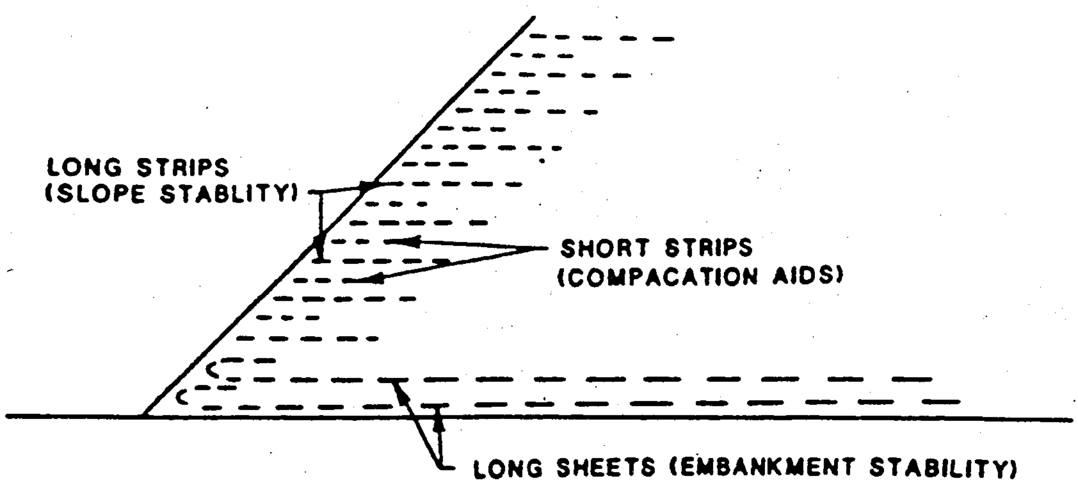


Fig.5.2 Slope Reinforcement Using Geosynthetics to Increase Slope Stability

construction at every lift or every other lift along the slope. Only narrow strips about 1.2 to 1.8 m in length are required and have to be placed in a continuous plane along the edge of the slope.

5.2 DESIGN CONCEPT OF FHWA

Reinforced slopes are currently analyzed using modified versions of the classical limit equilibrium slope stability methods. A circular or wedge type potential surface is assumed, and the relationship between driving and resisting forces or moments determine the slope factor of safety. Reinforcement layers intersecting the potential failure surface are assumed to increase the resisting force or moment based on their tensile capacity and orientation.

The tensile capacity of a reinforcement layer is taken as the minimum of its allowable pullout resistance behind the potential failure surface and its allowable design strength. A wide variety of potential failure surfaces must be considered, including deep seated surfaces through or behind the reinforced zone. The slope stability factor of safety is taken from the critical surface requiring the maximum reinforcement (FHWA,1990)

The assumed orientation of the reinforcement tensile force influences the calculated slope safety factor. In a conservative approach, the deformability of the reinforcements is not taken into account, and thus, the tensile forces per unit width of reinforcement Ts are assumed to be always in the horizontal direction of the reinforcements as illustrated in Fig.5.3. However, close to failure, the reinforcements may elongate along the failure surface, and an inclination from the horizontal can be considered. Tensile force direction is therefore dependent on the extensibility of the reinforcements used, and the following inclination is recommended:

i) Inextensible Reinforcements : T parallel to the reinforcements

ii) Extensible Reinforcements : T tangent to the sliding surface

5.3 REINFORCED SLOPE DESIGN STEPS

The steps for design of a reinforced soil slope Fig.5.4, are :

a. Establish the geometric and loading requirements for design
b. Determine engineering properties of the natural soil
c. Determine properties of available fill

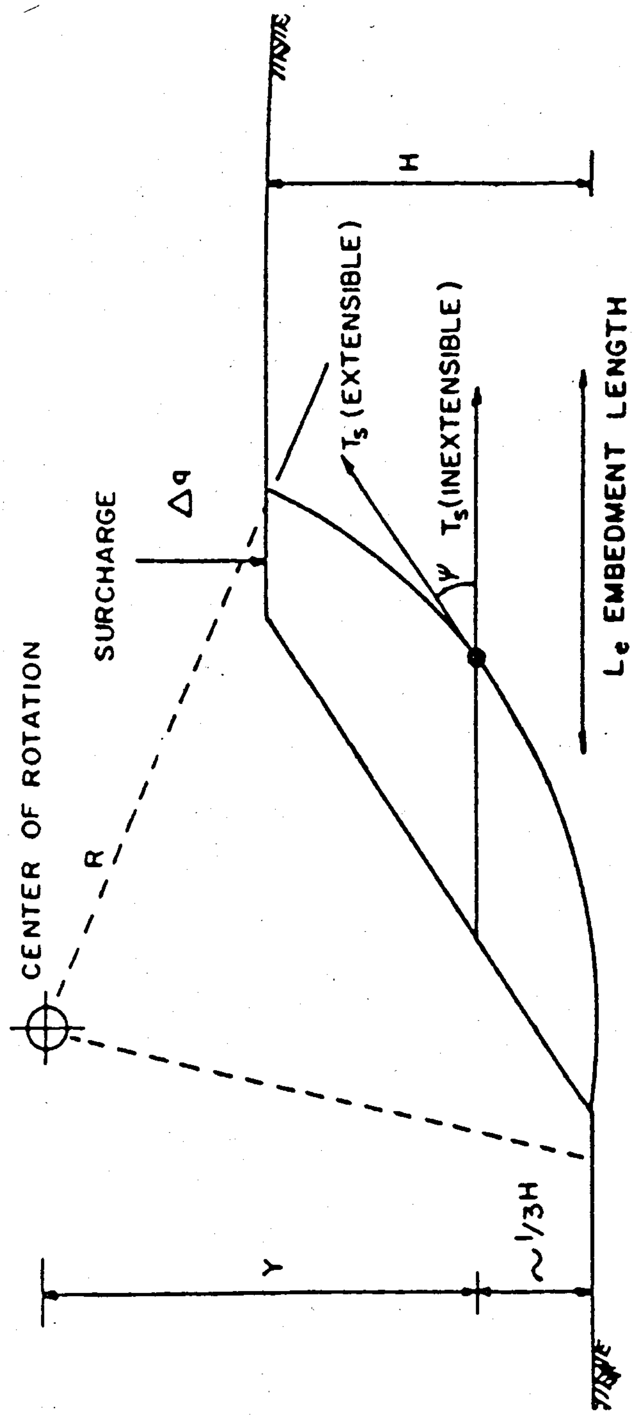


Fig.5.3 Orientation of the Tensile Forces

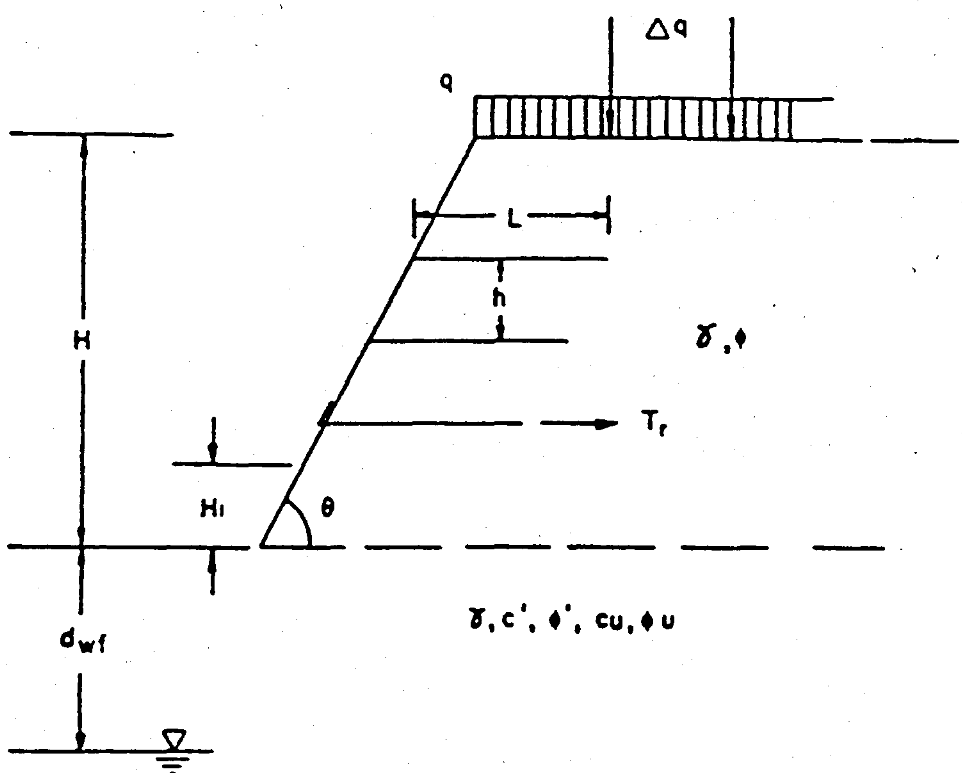


Fig.5.4 Requirements for Design of Reinforced Slope

d. Establish performance requirements (safety factor values, allowable reinforcement strength, durability criteria)

e. Check unreinforced stability of the slope

f. Design reinforcement to provide stable slope

g. Check external stability

The procedure assumes that the slope is to be constructed on a stable foundation. It does not include recommendations for deep seated failure analysis.

5.4 INTERNAL STABILITY

The following design steps and calculations are necessary for the rotational slip surface method using continuous reinforcement layers:

5.4.1 Check Unreinforced Stability

The slope without reinforcement must be analyzed using any conventional stability method e.g., Bishop's method, to determine safety factors and driving moments for potential failure surfaces.

The factor of safety of unreinforced slope :

$$F.S.u = F = \frac{A}{B} \tag{5.1}$$

in which,

$$A = \Sigma \left\{ [cb + (W - u\,b) \tan \phi] \frac{\sec \alpha}{1 + (\tan \phi \tan \alpha / F)} \right\}$$

$$B = \Sigma \{ W \sin \alpha \}$$

b = width of the slice

c = apparent cohesion

W = weight of the slice

u = pore water pressure

α = angle of tangent to the slope slip circle

Factor of safety of the reinforced slope :

$$F.S.r = F.S.u + \frac{Ts\,.\,D}{DM} \tag{5.2}$$

where :

Ts = sum of available tensile force per width of reinforcement for all reinforcement layers

D = moment arm of Ts about the center of rotation
= R for extensible reinforcement
= Y for inextensible reinforcement, Fig.5.3

DM = driving moment

To determine the size of the critical zone to be reinforced, the full range of potential failure surfaces found to have safety factors less than or equal to the target safety factor must be examined. Plot all of these surfaces on the cross-section of the slope. The surfaces that just meet the target factor of safety roughly envelope the limits of the critical zone to be reinforced.

Critical failure surfaces extending below the toe of the slope are indications of deep foundation and edge bearing capacity problems that must be addressed prior to completing the design. For such cases, a more extensive foundation analysis is warranted and foundation improvement measures should be considered.

5.4.2 Determine the Maximum Tensile Force

The total reinforcement tension Ts required to obtain the required target factor of safety F.S.r for each potential failure circle inside the critical zone that extends through or below the toe of the slope must be calculated using the following equation:

$$Ts = (F.S.r - F.S.u) \frac{DM}{D} \qquad (5.3)$$

where:

Ts = sum of required tensile force per unit width of reinforcement in all reinforcement layers intersecting the failure surface.

DM = driving moment about the center of the failure circle

D = moment arm of Ts about the center of failure circle

= radius of circle R for extensible reinforcement (i.e. assumed to act tangentially to the circle)

= vertical distance, Y, to the centroid of Ts for inextensible reinforcement (i.e. assumed to act in a horizontal plane intersecting the failure surface at H/3 above the slope base), Fig.5.3

F.S.r = target minimum slope safety factor

F.S.u = unreinforced slope safety factor

The largest Ts calculated establishes the required design tension, Tmax.

5.4.3 Determine the distribution of reinforcement:

For low slopes ($H \leq 6m$) assume a uniform distribution of reinforcement and use Tmax to determine spacing .

For high slopes ($H > 6m$) divide the slope into two (top and bottom) or three (top, middle, and bottom) reinforcement zones of equal height and use a factored Tmax in each zone for spacing. The total required tension in each zone are found from ;

For two zones:

$$T_{bottom} = 3/4\ T_{max} \qquad (5.4)$$

$$T_{top} = 1/4\ T_{max}$$

For three zones:

$$T_{top} = 1/6\ T_{max} \qquad (5.5)$$

$$T_{middle} = 1/3\ T_{max}$$

$$T_{bottom} = 1/2\ T_{max}$$

Determine the number of primary reinforcement for each zone based on:

$$N = \frac{Tzone}{Tall} \tag{5.6}$$

and

$$Tall = \frac{Tu \quad CRF}{FD \; FC \; FS} \tag{5.7}$$

where:

Tu = ultimate or yield tensile strength of the geosynthetic

FD = Durability factor of safety. (It is dependent on the susceptibility of the geosynthetic to attack by microorganisms and chemicals, thermal oxidation, and environmental stress cracking and can range from 1.1 to 2.0. In the absence of product specific durability information, use 2.0)

FC = Construction damage factor of safety. It can range from 1.1 to 3.0. In the absence of product specific construction damage use 3.0)

FS = Overall factor of safety to account for uncertainties in the geometry of the structure, fill properties, reinforcement properties and externally applied loads. A minimum value should not be less than 1.5.

CRF = Creep reduction factor. If the CRF value for the specific reinforcement is not available, the following values are recommendated in Table 5.1.

Use short (1.2 to 1.8 m) lengths of intermediate reinforcement layers to maintain a maximum vertical spacing of (60 cm) or less for face stability and compaction quality, Fig.5.5.

Intermediate reinforcement should be placed in continuous layers and need not be as strong as the primary reinforcement.

5.4.4 Determine the reinforcement length

The embedment length Le, Fig.5.3, of each reinforcement layer beyond the most critical sliding surface (i.e., circle found for Tmax) must be sufficient to provide adequate pullout resistance.

Table 5.1 Creep Reduction Values Recommendated for Some Polymers (FHWA,1990)

Polymer Type	CRF
Polyester	0.4
Polypropylene	0.2
Polyamide	0.3
Polyethylene	0.2

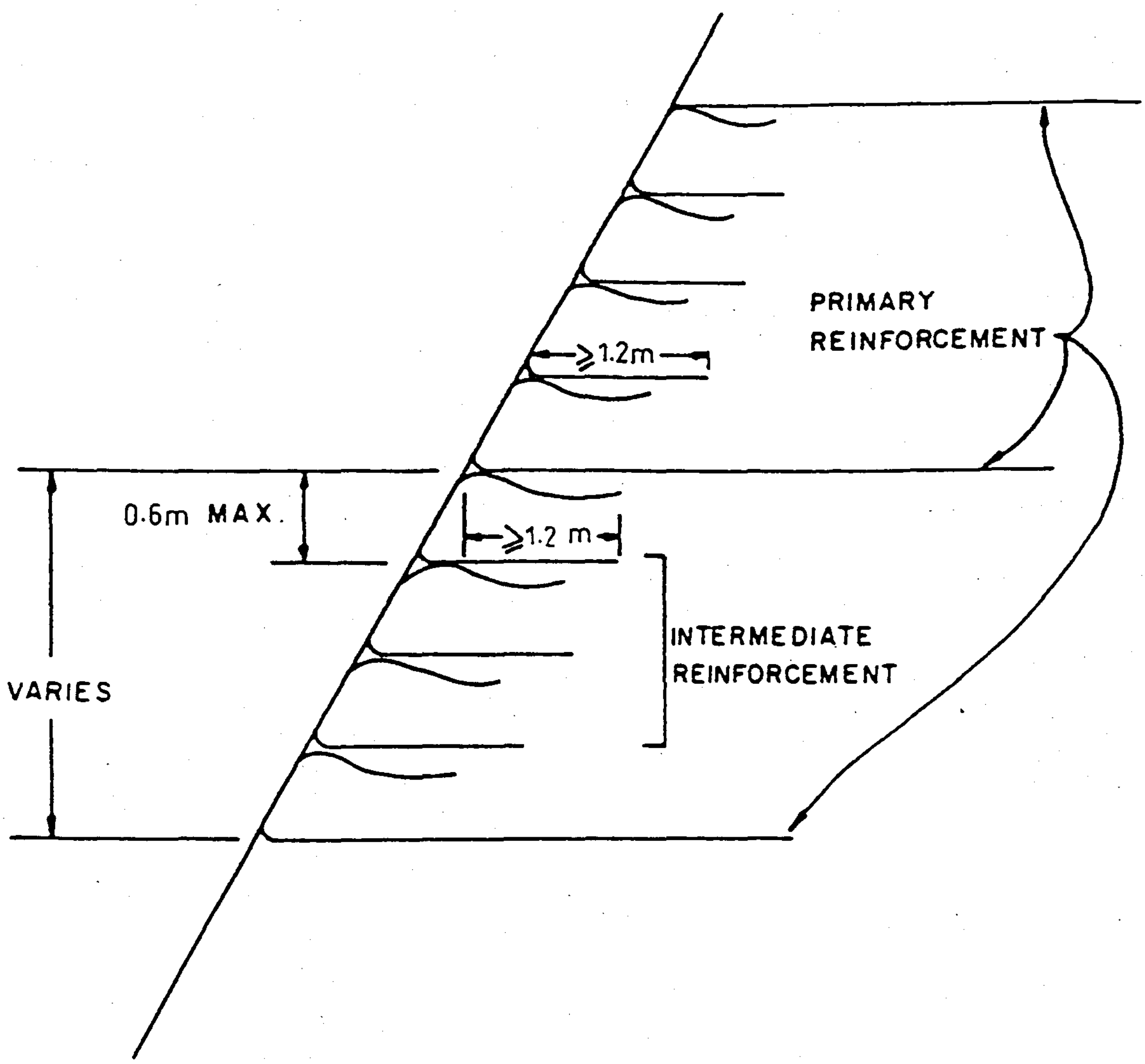


Fig.5.5 Spacing and Embedment Requirements for Slope Reinforcement with Intermediate Layers

$$Le = \frac{Tall \quad F.S}{Fp \quad \alpha \quad \sigma v \quad C} \geq 0.9 \text{ m} \qquad (5.8)$$

where:

Le = The embedment or adherence length in the resisting zone behind the failure surface

C = The reinforcement effective unit perimeter; e.g., C=2 for strips, grids, and sheets

Fp = The pull out resistance factor ≈ 0.5

α = A scale effect correction factor

σv = The effective vertical stress at the soil reinforcement interfaces

FS = The factor of safety against pull out

Plot the reinforcement lengths obtained from the pullout evaluation on the a slope cross section containing the rough limits of the critical zone. The length of the layers must extend to or beyond the limits of the critical zone. Upper levels of reinforcement may not be required to extend to the limits of the critical zone provided sufficient reinforcement exists in the lower levels to provide the target factor of safety for all circles within the critical zone. It must also be verified that the sum of the reinforcement passing through each failure surface is greater than Ts, required for that surface.

Only reinforcement that extend long enough beyond the surface to account for pullout resistance. If the available reinforcement is not sufficient, the length of reinforcement not passing through the surface must be increased or the lower level reinforcement must be strengthened. It is also possible to simplify the layout by lengthening some reinforcement layers to create two or three sections of equal reinforcement length or even making all of them having same length, rather than having different lengths which may cause some practical problems.

5.5 Tensar Chart Procedure

In this method, under some limiting assumptions the maximum tensile force Tmax, is obtained using some charts presented in Fig.5.6 and Fig.5.7, in the following way:

1) Determine force coefficient K from Fig.5.6 where

   $\phi f = \arctan(\tan \phi r / F.S)$
2) Determine $Tmax = 0.5 K \gamma H'^2$

   where $H' = H + q/\gamma$
3) Determine length of reinforcement required from Fig.5.7

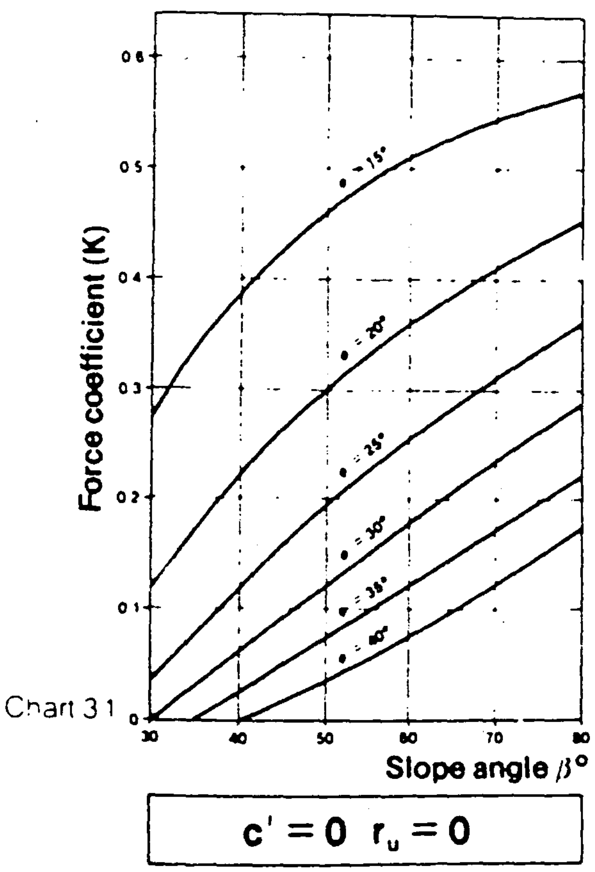


Fig.5.6 TENSAR Chart Gives Values of the Forces Coefficient K for Combinations of Slope Angle β, Soil Friction Angle ø with No Pore Water Pressure (Netlon,1990)

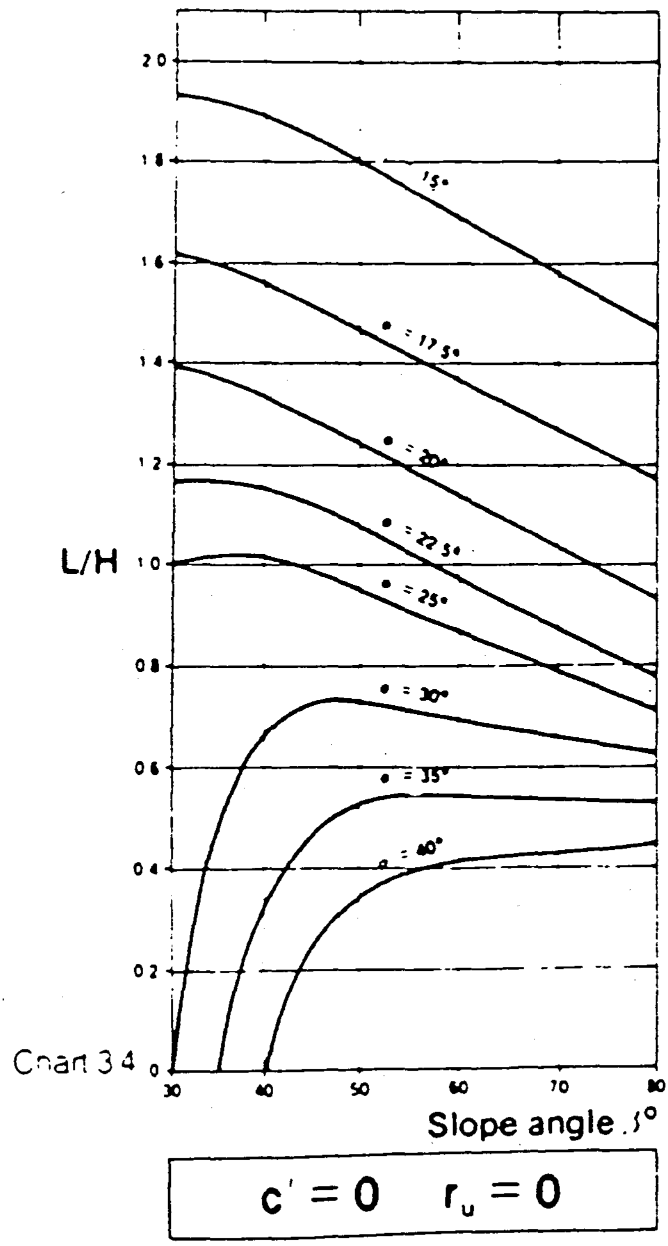


Fig.5.7 TENSAR Chart Give Values of Reinforcement Length Le for Combinations of Slope Angle β, Soil Friction Angle ø with No Pore Water Pressure (Netlon,1990)

The limiting assumptions are:

a. Inextensible reinforcement

b. Slopes constructed with uniform, cohesionless soil

c. No pore water pressure within the slope

d. Competent, level foundation soil

e. No seismic forces

f. Uniform surcharge no greater than 0.2 H

g. High soil/reinforcement interface friction angle

And the results of this method will be compared with the method given by FHWA.

5.6 EXTERNAL STABILITY

The external stability of a reinforced soil mass depends on the ability of the mass to act as a stable block and withstand all external loads without failure. Failure possibilities include sliding and deep seated overall instability as well as compound failures initiating internally and external through the reinforced zone.

5.6.1 Sliding stability

The reinforced mass must be sufficiently wide at any level to resist sliding along the reinforcement. To evaluate external sliding stability, a wedge type failure surface defined by the limits of the reinforcement can be analyzed and checked using an equivalent rigid structure.

A rigid equivalent structure is defined as shown in Fig.5.8

The safety factor against sliding is given by the following relationship :

$$F.S.s = \frac{\text{Resisting Force } P_r}{\text{Sliding Force } P_{sl}} \tag{5.9}$$

and the calculations steps are

a) Determine active coefficient Ka using Coulomb's equation

$$Ka = \{ [\sin(\theta-\phi)/\sin\theta]/[\sqrt{\sin(\theta+\delta)} + \sqrt{\sin(\phi+\delta)}] \}^2$$

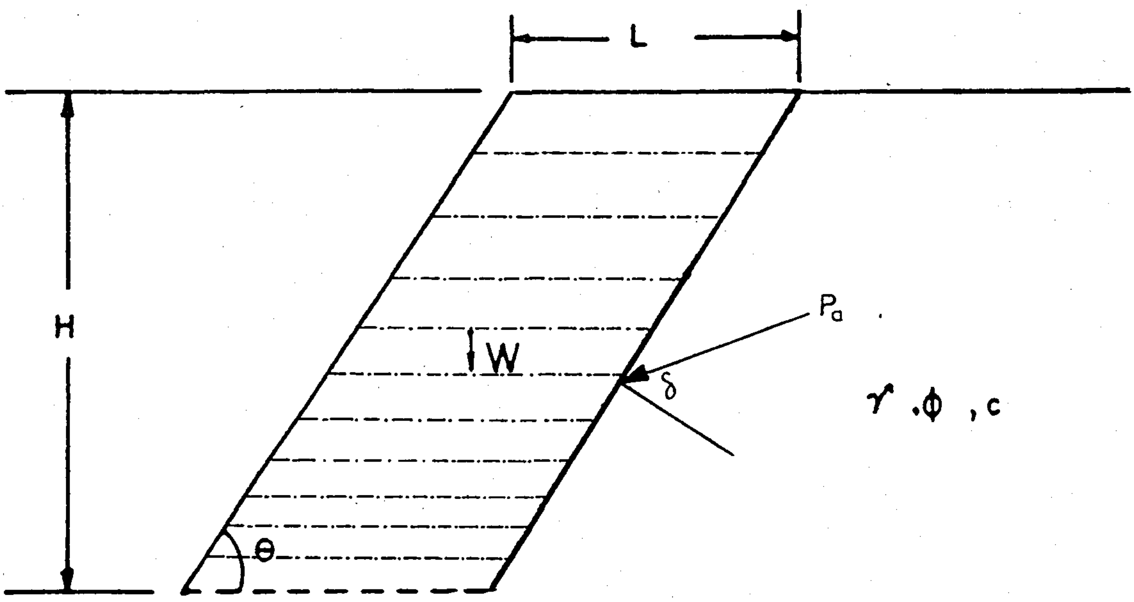


Fig.5.8 Equivalent Rigid Structure to be Analyzed for Sliding Safety Factor

b) Calculate the horizontal thrust (sliding force)

$$Psl = [\ 0.5 \ \ H^2 \ Ka\ ] \cos(\ \delta\ )$$

c) Calculate the resisting force :

$$Pr = W \tan \phi$$

d) check that the safety factor is greater than 1.5

$$F.S.s = \frac{Pr}{Psl} \geq 1.5 \qquad (5.10)$$

If not, increase the reinforcement length at the base of the slope.

5.7 DESIGN EXAMPLE

An embankment will be constructed on a sandy clay foundation with a maximum height of 30 m and the desired slope of the elevated embankment is 1.0H to 1.5V. It is desired to utilize a geogrid for reinforcing the slope of the embankment. The geogrid to be used in the project is a bidirectional geogrid with an ultimate tensile strength of 50 kN/m. A uniform surcharge of 12 kN/m is to be used for the traffic loading condition.

Available information indicates that the natural soil foundation has a drained friction angle of 10°, cohesion of 25 kN/m^2 and unit weight of 18 kN/m. The backfill to be used in the reinforced section will have a minimum friction angle of 30° and unit weight of 17 kN/m.

The reinforced slope design must have a minimum factor of safety of 1.5 for slope stability. The foundation is stable and water may not be expected.

Determine the number of layers, vertical spacing and total length required for the reinforced section.

Solution:

Step 1. Establish the Geometric and Loading Requirements for Design

a. Slope height, $H = 30$ m

b. Slope angle, $\theta = \arctan(1.5/1) = 56.3°$

c. External loading, $q = 12$ kN/m

Step 2. Determine the Engineering Properties of the Natural Foundation Soil in the Slope

For this project, the foundation soil has the following properties

$\phi = 10°$, $c = 25$ kN/m², $\gamma = 18$ kN/m

Water may not be expected

Step 3. Determine Properties of Available Fill

The backfill material to be used in the reinforced section was reported to have the following properties.

$\phi = 30°$, $c = 0$, $\gamma = 17$ kN/m

Step 4. Establish Performance Requirement

$$T_{all} = \frac{T_u \;\; CRF}{FD \;\; FC \;\; FS} \qquad \text{where} \quad T_u = 50 \text{ kN/m}$$

For the proposed geogrid to be used in the design of the project, the following factors are used:

CRF = 0.5

FD = 1.25

FC = 1.2

FS = 1.5

Therefore :

$$T_{all} = \frac{(50)\;(0.5)}{(1.25)\;(1.2)\;(1.5)} = 11 \text{ kN/m}$$

Pullout resistance has a FS = 1.5 with a 0.9 m minimum length in resisting zone.

Step 5. Check Internal Stability

a. Check Unreinforced Stability

The proposed new slope is analyzed without reinforcement using the computer program developed by the author in order to find the unreinforced factor of safety. The computer program calculates factors of safety F.S.u using Bishop Method for circular failure surface. Failure is considered through the toe of the slope, and the minimum factor of safety is less than 1.0.

b. The total reinforcement tension, Ts, required to obtain a F.S.r = 1.5 is then evaluated for each failure surface.

The results obtained from the computer output are:

F.S.u = 0.843

DM = 4133.85 kN.m/m

D = 25.11 m (D =Y ,moment arm)

$$Tmax = (F.S.r - F.S.u) \frac{DM}{D}$$

$$= (1.5 - 0.843) \frac{4133.85}{25.11} = 108 \text{ kN/m}$$

c. Determine the distribution of reinforcement since H = 30 m > 6 m divide the slope into three reinforcement zones of equal height:

T top = 1/6 Tmax = 1/6 (108) = 18 kN/m

T middle = 1/3 Tmax = 1/3 (108) = 36 kN/m

T bottom = 1/2 Tmax = 1/2 (108) = 54 kN/m

d. Determine reinforcement vertical spacing Sv:

Minimum number of layers

$$N = \frac{Tmax}{Tall} = \frac{108}{11} = 9.8$$

Distribute the reinforcement at :

Top zone $N_t = \dfrac{18}{11} = 1.6$ use 2

Middle zone $N_m = \dfrac{36}{11} = 3.2$ use 4

Bottom zone $N_b = \dfrac{54}{11} = 4.9$ use 5

Total number of layers: 11 > 9.8 OK

Vertical spacing :

Total height of slope = 30 m

Height of each zone = 30/3 =10 m

Required spacing at:

Top zone Sv top = 10/2 = 5.0 m

Middle zone Sv middle = 10/4 = 2.5 m

Bottom zone Sv bottom = 10/5 = 2.0 m

1.2 m length of intermediate reinforcement layers will be provide every 50 cm.

e. Determine the reinforcement length required beyond the critical surface used to determine Tmax

$$Le = \frac{Tall\ FS}{F\ \alpha\ \sigma v\ C}$$

$$= \frac{(11)\ (1.5)}{(0.54)(0.67)(17*0.03*30)(2)} = 1.5\ m > 0.9\ m \quad OK$$

From the computer output the length of the critical zone corresponding to the Tmax = 108 kN/m, was found to be 16.0 m.

So total length of the reinforcement is

16 + 1.5 = 17.5 m.

The distribution of the reinforcement is shown in Table 5.2 and the final layout of the primary reinforcements is shown in Fig.5.9.

Table 5.2 (a)

Distribution of Reinforcements in the Top Zone

Z (m)	L (m)	TYPE
0.5	1.2	I
1.0	1.2	I
1.5	1.2	I
2.0	1.2	I
2.5	1.2	I
3.0	1.2	I
3.5	1.2	I
4.0	1.2	I
4.5	1.2	I
5.0	17.5	P
5.5	1.2	I
6.0	1.2	I
6.5	1.2	I
7.0	1.2	I
7.5	1.2	I
8.0	1.2	I
8.5	1.2	I
9.0	1.2	I
9.5	1.2	I
10.0	17.5	P

2 Primary Reinforcements
18 Intermidiate Reinforcement

Table 5.2 (b)

Distribution of Reinforcements in the Middle Zone

Z (m)	L (m)	TYPE
10.5	1.2	I
11.0	1.2	I
11.5	1.2	I
12.0	1.2	I
12.5	17.5	P
13.0	1.2	I
13.5	1.2	I
14.0	1.2	I
14.5	1.2	I
15.0	17.5	P
15.5	1.2	I
16.0	1.2	I
16.5	1.2	I
17.0	1.2	I
17.5	17.5	P
18.0	1.2	I
18.5	1.2	I
19.0	1.2	I
19.5	1.2	I
20.0	17.5	P

4 Primary Reinforcements
16 Intermidatiate Reinforcements

Table 5.2 (c)

Distribution of Reinforcements in the Bottom Zone

Z (m)	L (m)	TYPE
20.5	1.2	I
21.0	1.2	I
21.5	1.2	I
22.0	17.5	P
22.5	1.2	I
23.0	1.2	I
23.5	1.2	I
24.0	17.5	P
24.5	1.2	I
25.0	1.2	I
25.5	1.2	I
26.0	17.5	P
26.5	1.2	I
27.0	1.2	I
27.5	1.2	I
28.0	17.5	P
28.5	1.2	I
29.0	1.2	I
29.5	1.2	I
30.0	17.5	P

5 Primary Reinforcements
12 Intermidiate Reinforcements

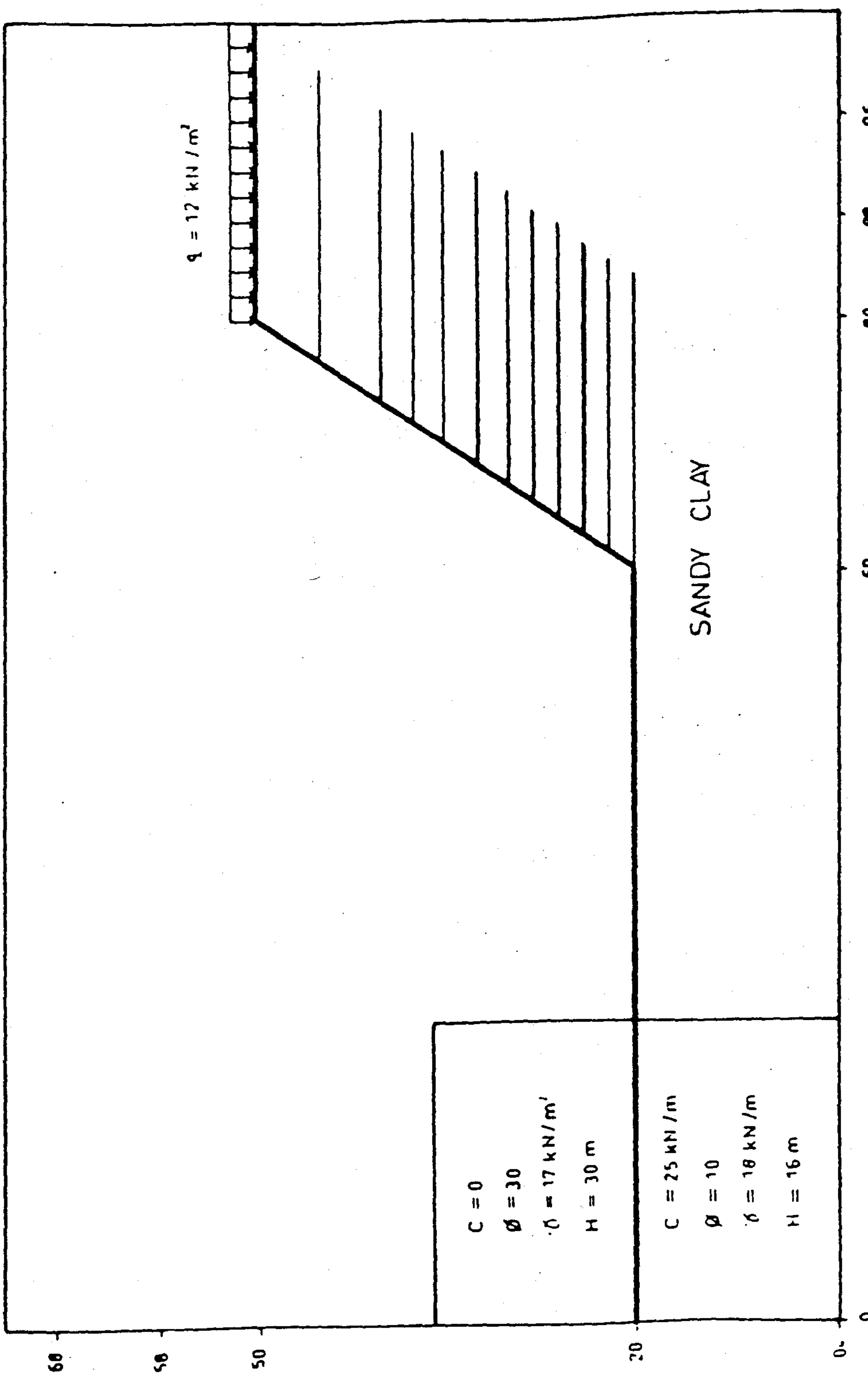


Fig.5.9 The Layout of Primary Reinforcements
of the Design Example

f. Chart Design Procedure

for β = 56.3 and

ϕ = arctan (tan ϕ / F.S.r)

= arctan (tan 30°/ 1.5) = 21°

Force coefficient, K = 0.35 (from Fig.5.6.)

H = H + q/ =30 + 12/17 = 30.7 m

Tmax = 0.5 K H^2 = 0.5 (0.35)(17)$(30.7)^2$=2804 kN/m

L/H = 1.17 (from Fig.5.7)

L = 1.17 * (30.7) = 36 m

N=Tmax/Tall = 2804 / 11 = 255

CHAPTER VI

COMPUTER PROGRAMMING

6.1 PURPOSE AND SCOPE

The purpose of the computer program ISMEIK, is to perform a comprehensive study for the external and internal stability of a geosynthetic reinforced slope. The program is developed using Bishop's method for slope stability analysis and the design method recommended by FHWA (1990).

The complete list of the program is given in Appendix A. Instruction for data supply, definitions of variables is given in section 6.4, as well as listing of data of the design example and the results are given in Appendix B, and Appendix C, respectively.

6.2 BASIC FEATURES OF THE PROGRAM

The computer program ISMEIK developed for the design of reinforced slope, first search for all possible failure slips, in each iteration it calculates the factor of safety and the corresponding required tensile force which will produce the target factor of safety. All data are stored in arrays, and then it prints the geometry of the slip surface corresponding to the maximum tensile force, gives the distribution of reinforcement of that critical circle as well as the length of these reinforcements.

The program is capable of considering the following features:

A) Type of Reinforcement

Two types of reinforcement are considered, polymer strips (geotextiles), and Polymer grids (geogrids), provided that their ultimate strengths are supplied as part of data as well as type identification.

B) Type of Loading

Only static loads are considered including a uniform traffic surcharge.

C) Length of Reinforcement

The embedment length is computed as well as the total length of the reinforcement where adequate factor of safety is against pullout is supplied as data.

D) External Stability

For the external stability, the program checks the sliding stability of an equivalent rigid block against the active earth pressure force.

6.3 OPERATION OF THE PROGRAM

The program will solve the slope stability problem of an embankment having soil parameters different than the foundation soil, it also allows for describing the pore water pressure if any, therefore it computes both the total and effective slice weights.

It is necessary in using this program to:

1. Number all joints in increasing X coordinates from left to right
2. Number the upper external (closest to arc center) soil lines first in order from left to right.
3. Interior soil lines may be numbered in any order
4. The different soils in the mass may be numbered in any order

The program uses only SI units i.e., force unit is kN, and length unit is m.

6.4 NUMERICAL DATA INSTRUCTIONS

Card 1	Any title not exceeding 75 alphanumeric characters	
Card 2	NTYPE	= type of the reinforcement 1 extensible 2 inextensible
	Q	= surcharge value (kN/m^2)
Card 3	NOL	= total number of soil lines
	NLIT	= total number of joints(the end of any line whether or not intersected by another is a joint)
	NOS	= number of soils in mass(same soil submerged is counted twice)
	NOLE	= number of top external lines
	ITX, ITY	= number of circles in X, Y directions to be analyzed for a single point
	DIMEN	= control number of slices as 75,80,90
	CROL	= to send the results to a file 0 for no output 1 for out put
	LIST	= to obtain detailed calculations 0 for no output 1 for out put

Card 4	CX, CY	= initial trial circle center coordinates
	ENTX, ENTY	= trial circle entrance coordinates
	DELX,DELY	= center X, Y coordinate increments for each trial
	SWIDTH	= initial slice width
	NLOOP	= number of iterations to analyzed in entrance points
	DELTA	= unit distance to be moved in X direction
Card 5	NLI	= number of line intersections of each line in turn one entry
Card 6	C(I,J)	= line data including line number, number of joints for the lines, the X, Y coordinates of the end points left to right
	NOLIT(I,N)	= all joints numbers on the i'th line including the end vales
Card 7	INTAR(I,J)	= line intersections X, Y in increasing number
Card 8	NSLIN(I)	= number of soil lines defining the boundary of the soil, include lines

terminating at a joint. If a line intersects a soil line boundary between the ends, count the soil boundary line twice

	G(I)	= unit weight (kN/m^3)
	PHI(I)	= angle of internal friction
	COHES(I)	= cohesion (kn/m^2)
	SAT	= saturation 0 dry 1 saturated
Card 9	LINSOL	= soil line number
	INTL, INTR	= intersection number on left and right end of a line, if a soil line terminates at a joint on a soil boundary , that line is included
Card 10	TULT	= ultimate strength of the reinforcement (kN/m)
	CRF	= creep reduction factor
	FD	= durability factor
	FC	= construction damage factor of safety
	FSPR	= over all factor of safety
	FS	= target factor of safety
Card 11	FSTAR	= the pullout resistance factor
	SCAL	= scale effect correction factor

6.5 VALIDITY TEST

The design example shown in section 5.7 will be solved here twice using the computer program first, and then the results will varified by hand calculations. The data file preparations corresponding to the problem are shown in Appendix B.

CHAPTER VII

DISCUSSIONS

1. In order to rely upon the results received from the computer ,especially, about the computed slope safety factor, hand calculations of the same problem are carried out where the geometry of the failure surface is also the same.

The critical section shown in Fig.7.1 is divided into 8 slices. The radius is 35 m, and the soil parameters are are the same used in the design example.

The results of hand calculations are shown in Table 7.1. It is seen that the results are of fair agreement with the output received from th computer. For example, total area is 414 m^2 and 404 m^2 computed from the computer, driving moment is 4353 kN/m and 4133 kN/m computed from the computer and factor of safety of the unreinforced slope is 0.807 and 0.843 computed from the computer. These slight differences resulted from mainly, errors in measuring the lengths and circulating the areas from the drown slip surface and due to

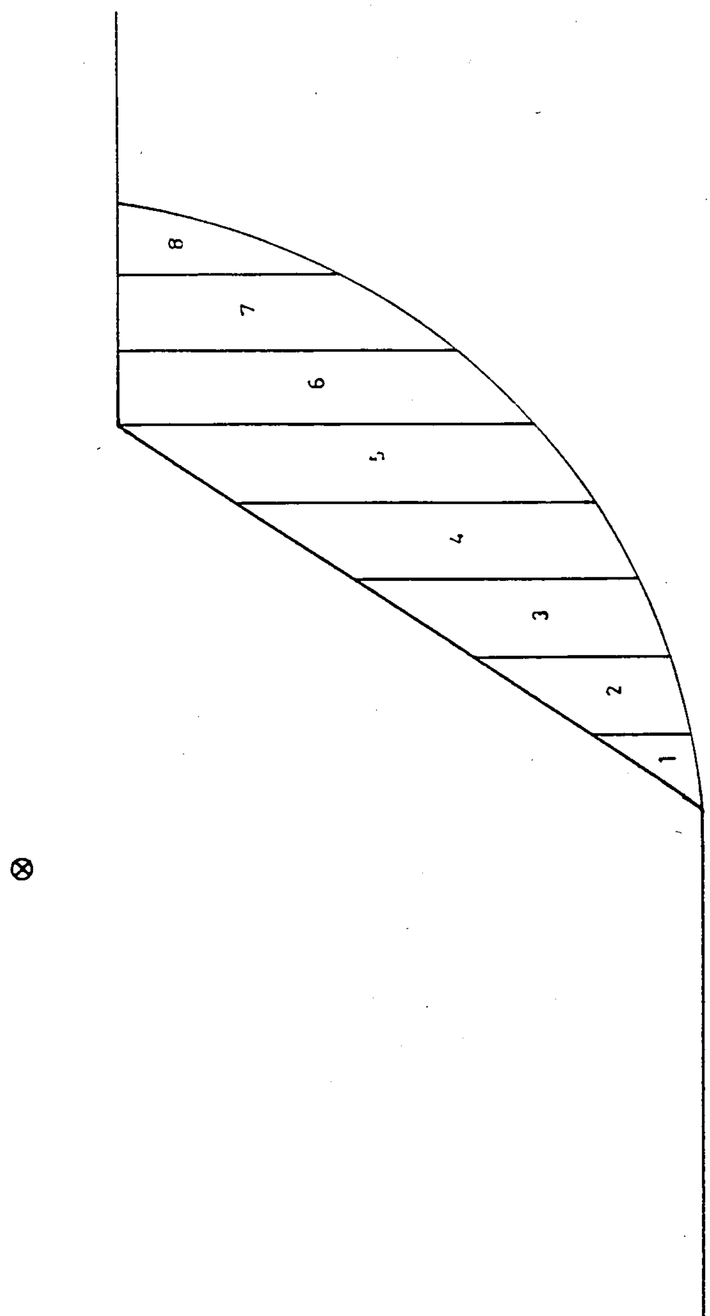


Fig.7.1 The Failure Slip Surface of Design Example

Table 7.1 Hand Calculation of the Design Example

slice #	h (m)	α'	sec α	A m²	tan α tan φ	W (kN)	Wsinα	Wtanφ sec α
1	2.8	9	1.012	11.2	0.091	190.4	29.7	111.2
2	7.6	16	1.040	30.4	0.165	516.8	142.4	310.3
3	12.8	22	1.078	51.2	0.233	870.4	326.0	541.9
4	16.8	30	1.154	67.2	0.333	1142.4	571.2	761.6
5	20.4	37	1.252	81.6	0.435	1387.2	834.8	1002.8
6	20.0	45	1.414	80.0	0.577	1360.0	961.6	1110.4
7	15.2	56	1.788	60.8	0.855	1177.6	976.2	1215.8
8	8.0	70	2.923	32.0	1.586	544.0	511.1	918.3
			Σ	414		7188	4353	

round-off numbers while the calculations are carried out by the computer. Furthermore, the results obtained about the reinforcement distribution and their lengths are in close agreement with those shown in section 5.7.

At this stage, it is now confidently possible to rely on the computer program for all design process, provided that all necessary data are correctly, supplied.

2. It is very important to distinguish between the method recommended by FHWA and Tensar chart method. In the former method, the maximum tensile force Tmax obtained to be 108 kN/m, where in the later method, Tmax found to be 2804 kN/m. This value is substantially large, about 69 times more. This will give the number of primary reinforcement layers as Tmax/Tall = 2804/11 = 255, while FHWA method gives only 11 layers. This great difference is due to the reduction of the angle of internal friction by a safety factor, and another reason is the that Tensar method assumes that all the tensile force would be resisted by the reinforcements only, and no contribution will be provided by the soil resistance. In other words, it assumes that the soil has no cohesion and no frictional resistance. It is clear that, this method is too conservative, and it will yield to a heavily reinforced over designed slope.

The method recommended by FHWA, accounts for the soil resistance, but not in a very conservative way. This is achieved by rsisting the horizontal thrust (sliding force) by the weight of an equivalent rigid structure define by the limits of reinforcement, Fig.5.8, rather than the reinforcements themselves only, as proposed by the Tansar method.

3. The critical section was defined as the one which requires the maximum tensile force, Tmax, and since every other section requires a tensile force which is less than Tmax, so Tmax governs the design criteria. However, the resistance provided by the reinforcement may not be fully utilized in other possible failure slips.

Let us change the location of the center of rotation in order to obtain another failure surface, for example, Fig.7.2 (last row in Table 7.2), where it is clear that

F.S.u=0.996 > 0.843

Tmax = 69 < 108.

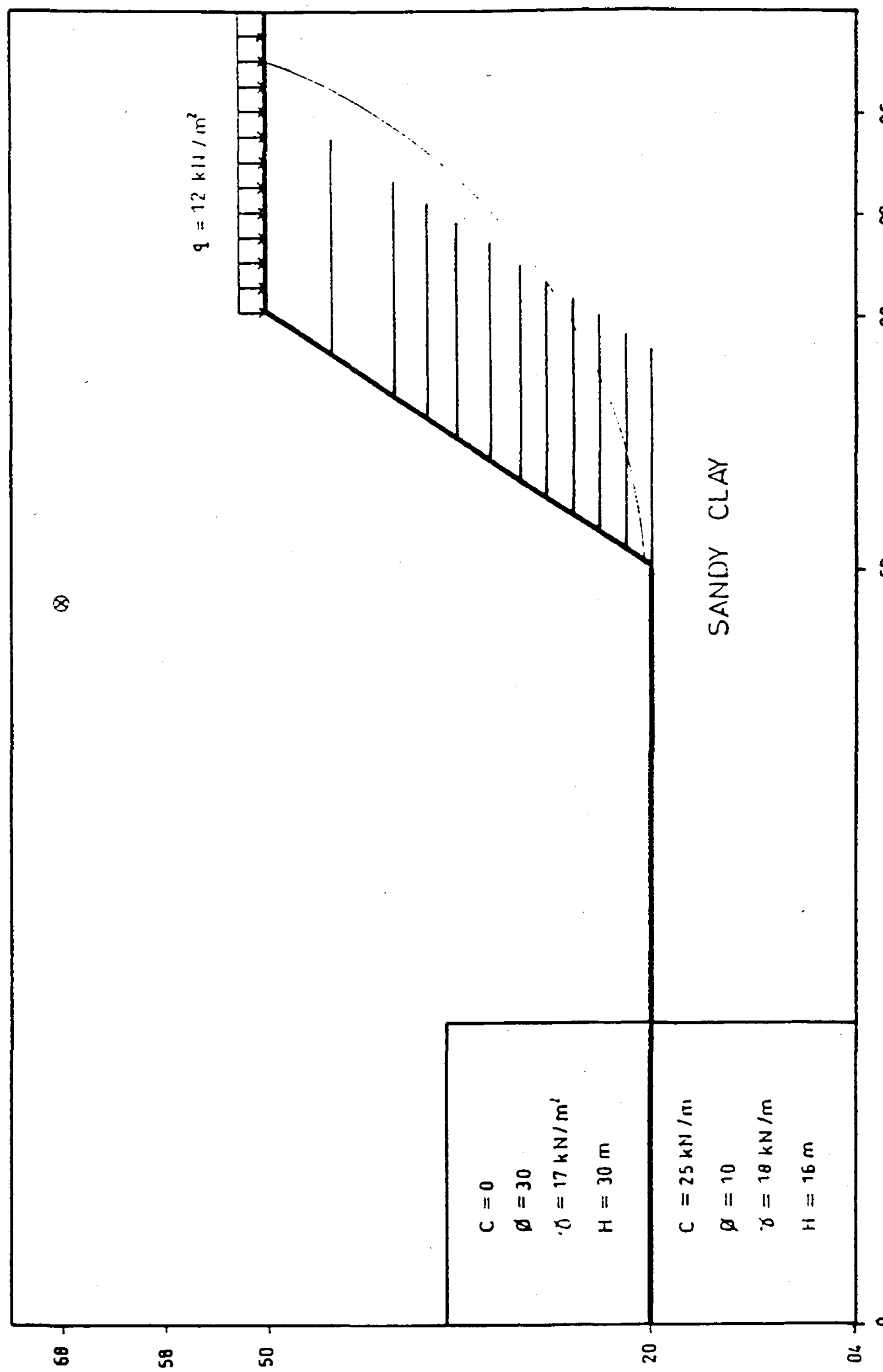


Fig.7.2 Another Slip Surface

Table 7.2 Different Analysis for the Design Example

FS	Tmax	L	X	Y	R	DM
0.843	108	17.5	57.2	55.1	35	4133
0.905	90	20.0	57.2	60.1	40	4601
0.939	80	21.3	57.2	63.1	43	4745
0.996	69	23.7	57.2	67.1	47	5080

At the first glance, this slip failure may look safe, since the required Tmax is smaller than the designed Tmax value, but the reinforcements are not being used at their full capacity. This is shown clearly in Fig.7.2, where only three layers are acting in the resisting zone, and the others are no longer resisting, since their lengths are not long enough beyond the slip failure.

This is to show, though the slope was reinforced to the case where Tmax would be the largest(first row in Table 7.2) this Tmax will not be fully utilized in other possible slip failures, because the corresponding lengths will be always larger than designed one. In other words, length requirement governs the design criteria rather than the largest Tmax. The solution to this problem is simply, to extend the reinforcement length (Le = 23.7) as shown in Fig.7.3, where certainly the F.S.r will be achieved because the available number reinforcements are greater than the designed one (Tmax=69 < 108).

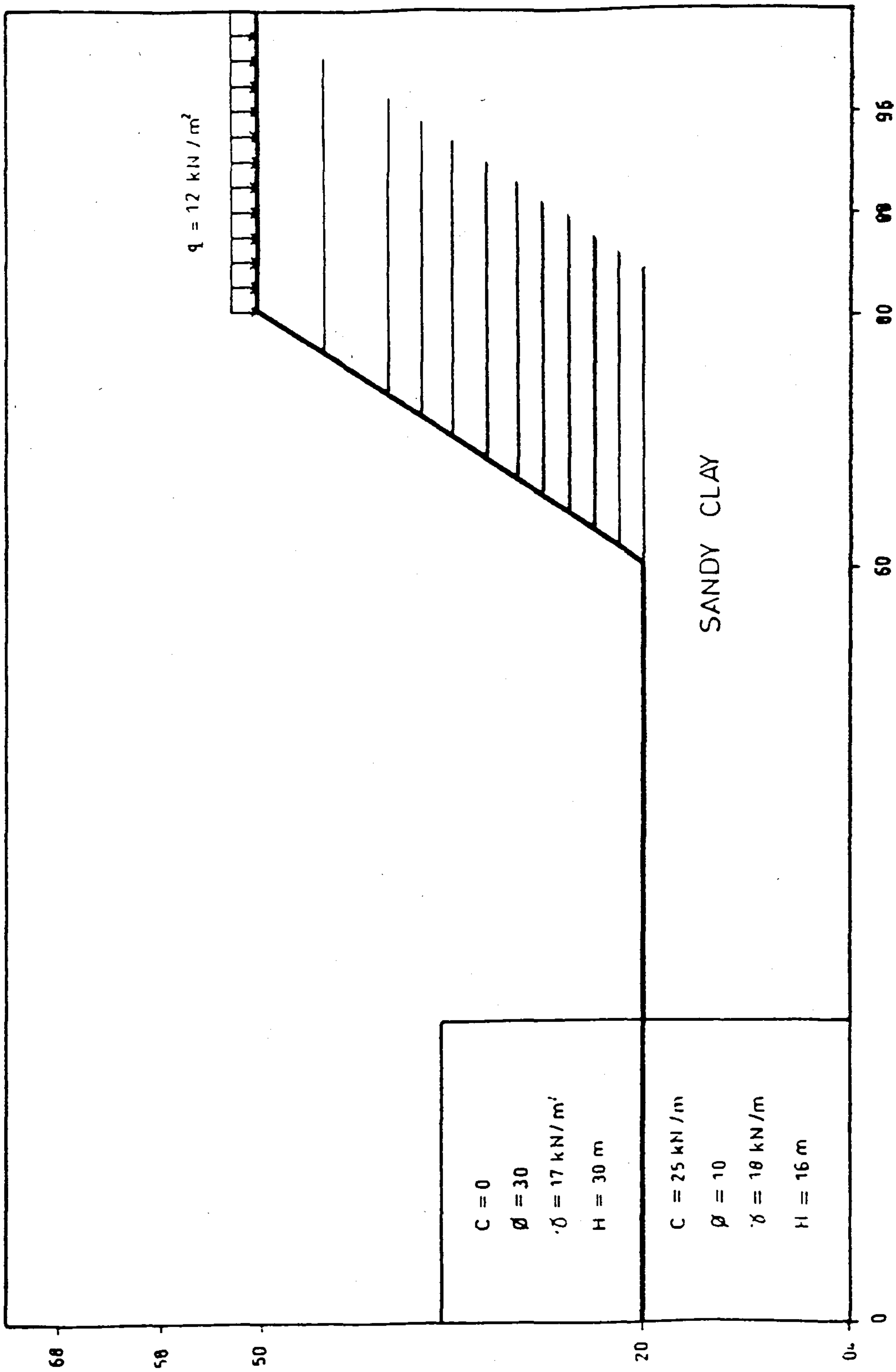


Fig.7.3 Extending the Reinforcement Length in order to Achieve the Target Factor of Safety for a Slip Surface Which Is Not Critical

4. Now let us recalculate the factor of safety of the reinforced slope of design example,Fig.7.4. In the worse case the tensile force in each layer would be Tall=11 kN/m. From Table 7.3 the resisting moment contribution from reinforcements is (Σ T r = 2944) , substituting in

$$F.S = F.S.u + \frac{\Sigma T r}{DM}$$

$$= 0.843 + \frac{2944}{4133} = 1.555 > 1.5 \text{ OK}$$

While in the case where the slip surface cuts only three reinforcements Fig.7.2, the resisting moment will be only (Σ T r = 1099) Table 7.4 and resultant factor of safety is

$$F.S = 0.996 + \frac{1099}{5080} = 1.212 < 1.5$$

and it is seen that the target factor of safety is not achieved.

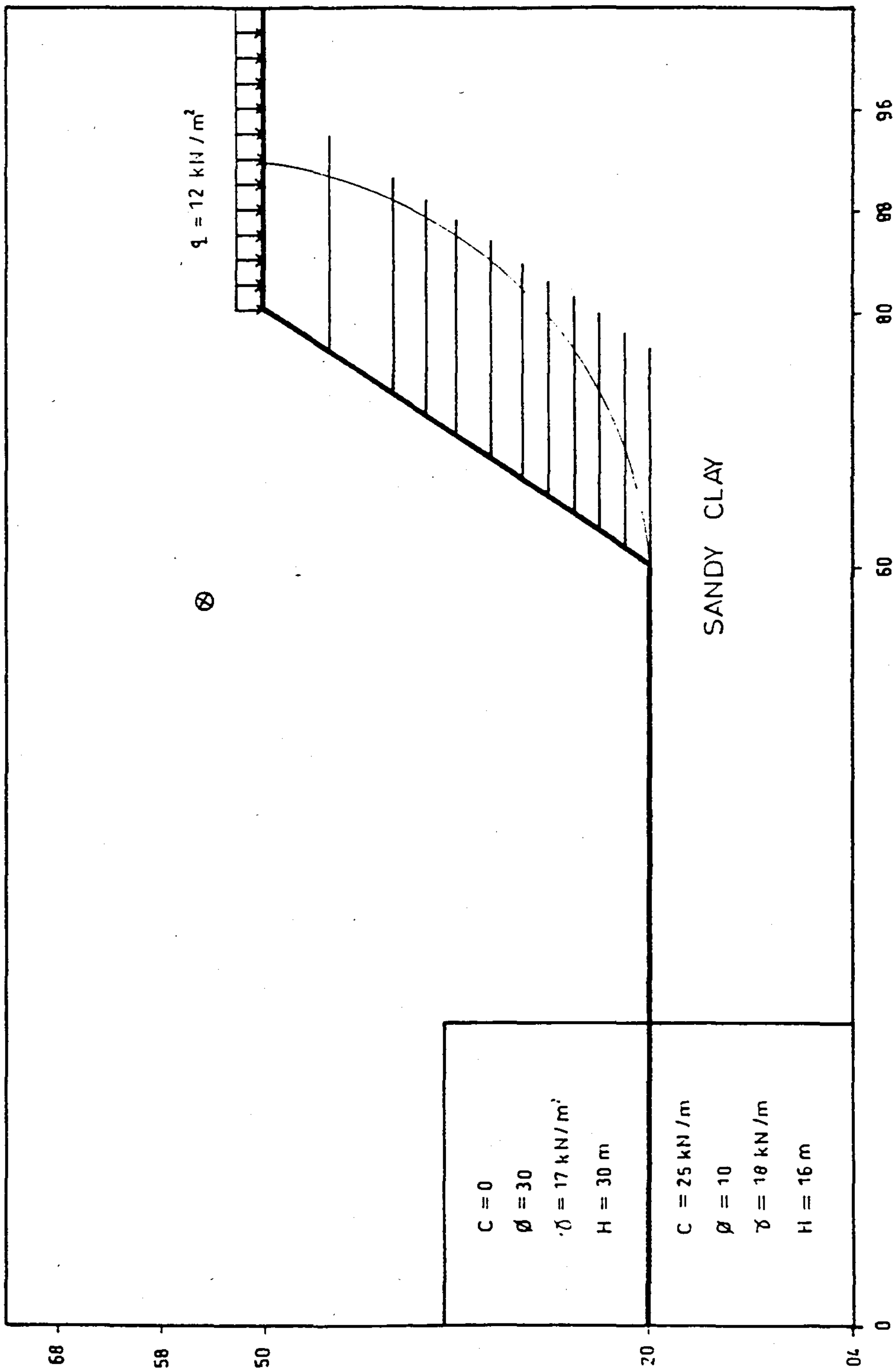


Fig.7.4 The Reinforcement Distribution Of the Design Example

Table 7.3 Forces in the Reinforcement Corresponding to Fig.7.4

	Tali	r
Top Zone	11	10.0
	11	15.0
Middle Zone	11	17.0
	11	20.0
	11	22.5
	11	25.0
Bottom Zone	11	27.0
	11	29.0
	11	31.0
	11	33.0
	11	35.0

Table 7.4 Forces in the Reinforcements Corresponding to Fig.7.2

	Tail	r
Top Zone	0	10.0
	0	15.0
Middle Zone	0	17.0
	0	20.0
	0	22.5
	0	25.0
Bottom Zone	0	27.0
	0	29.0
	11	31.0
	11	33.0
	11	35.0

But after increasing the length of reinforcements to 23.7 m the resisting moment would be, Σ T r = 2944 and

$$F.S = 0.996 + \frac{2944}{5080} = 1.575 > 1.5$$

so the target factor of safety is achieved as it was expected.

5. An economic analysis is performed in order to compare the amount of saving in steeping an embankment by utilizing reinforcement with an unreinforced embankment designed with classical methods.

An unreinforced embankment having a typical slope of 2:1 is compared with another reinforced embankment having a steep slope of 0.6:1, Fig.7.5.

The following data are adopted:

Excavation Cost = 1 $/cubic m

Transportation Cost = 2 $/cubic m

Placement and Compaction Cost = 1 $/cubic m

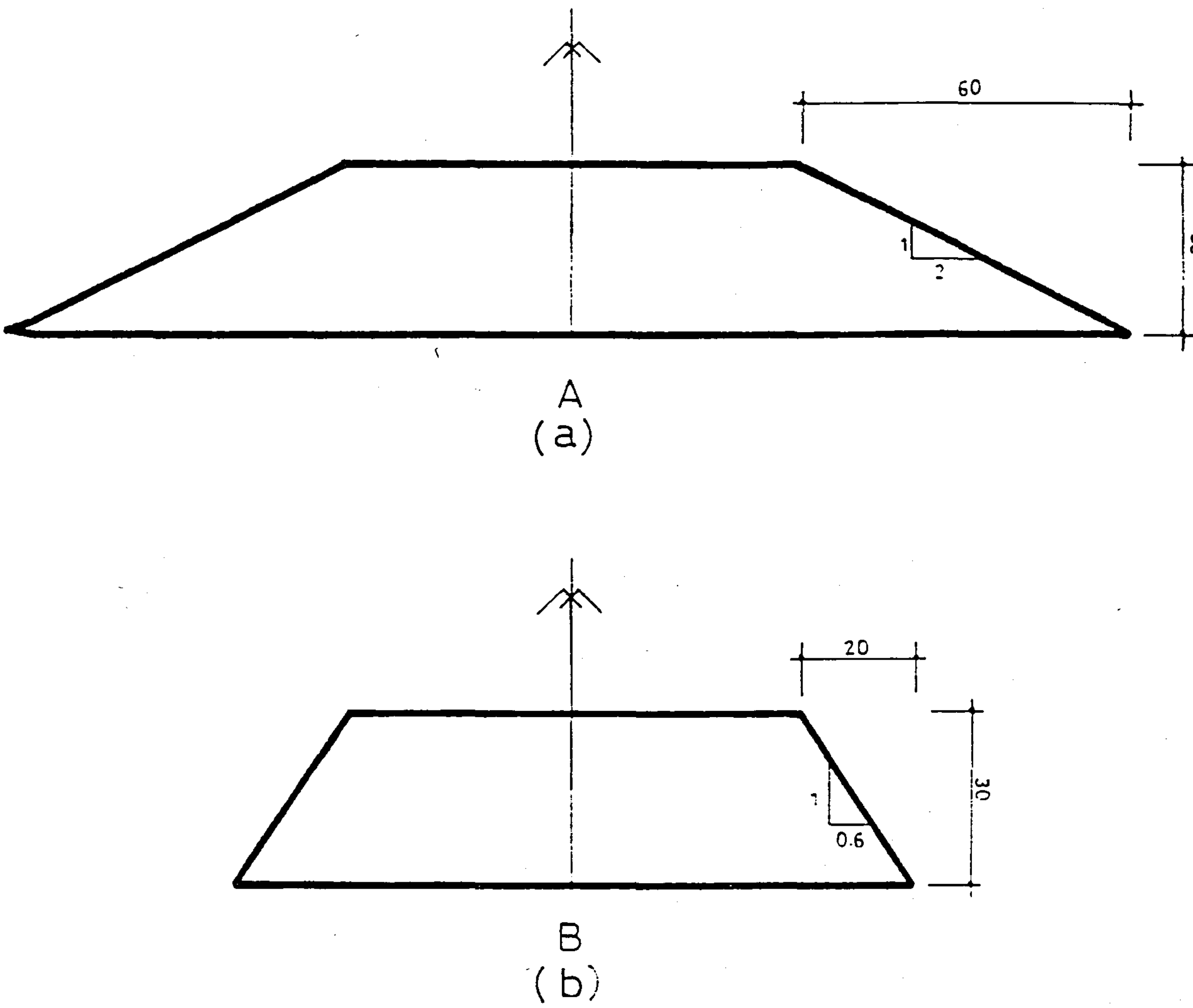


Fig.7.5 Comparison between Two Embankments

(a) Unreinforced Embankment

(b) Reinforced Embankment

Table 7.5 Sensitivity Analysis and Comparison betwwen Reinforced Emankment and Unreinforced one Corresponding to Fig.7.5

	Initial Cost	Excavat	Transpo	Compact	R. way	Geogrid	Labor
N.cost	9000	10800	10800	10800	9120	9000	9000
R.cost	3278	3878	3878	3878	3298	3470	3470
Saving	63	64	64	64	64	61	61

Right of Way Cost = 15 \$/ m^2

Reinforcement Cost = 2 \$/ m^2

Labor Cost = 1 \$/m^2

A sensitivity Analysis is performed Table 7.5 (variation of the prices by unity and comparing the obtained results with old prices), and it is seen that the costs of excavation, transportation, and compaction change largely (more sensitive) rather than right of way, cost of reinforcement and labor. Furthermore, the percent saving is more or less constant 63.

6. Finally, let us check if the assumed location of the resultant tensile force, in of case using inextensible reinforcement (geogrid), is about H/3 from the bottom or not, Fig.5.3.

From simple statics

$$Y\ T = \Sigma\ Ti\ r$$

and from Fig.7.6,

$$Y\ T = (T/2)(H/6) + (T/3)(H/2) + (T/6)(5H/6) = 7/18\ T\ H$$

therefore

$Y = 7H/18 \approx 0.38\ H$ (14 percent error)

and from Fig7.7,

$Y\ T = (3T/4)(H/4) + (T/4)(3H/\$) + 3/8\ T\ H$

therefore

$Y = 3/8\ H \approx 0.37\ h$ (11 percent error)

This shows that the location of the resultant force is within an acceptable error, and by assuming that its location of it is H/3 from the bottom may not result in a great error.

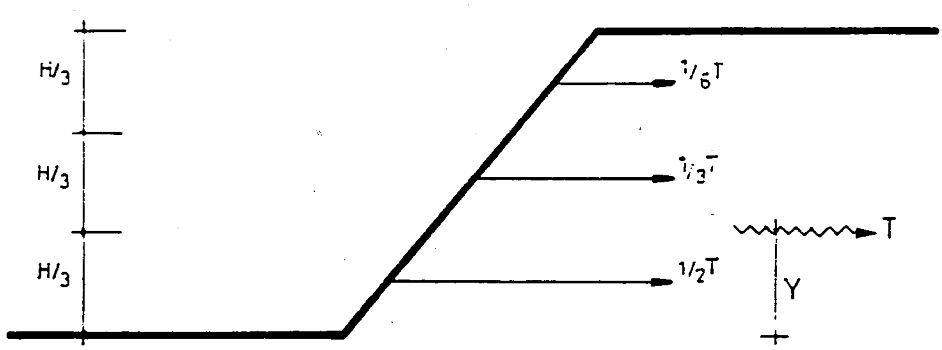


Fig.7.6 Determination of the Resultant Factor of Safety (H > 6 m)

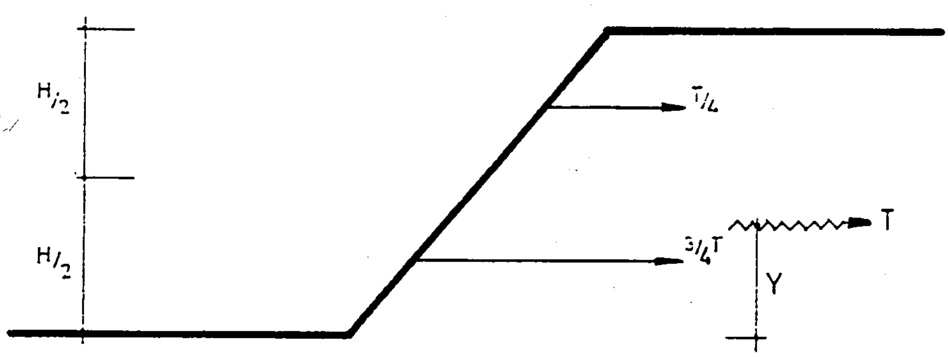


Fig.7.7 Determination of the Resultant Factor of Safety (H < 6 m)

CHAPTER VIII

CONCLUSIONS

1. The reinforcement of earth, which may be defined as the inclusion of resisting elements in a soil mass to improve its mechanical properties is technically attractive and cost effective technique. This is especially true with steep slopes where a reduction of the required width of right of way is saved and more suitable for widening of existing traffic lanes in constrained right of way, and best utilized with poor foundation soils that would otherwise require prohibitively expensive soil improvement measures.

2. The computer program ISMEIK was developed for all internal design calculations of a reinforced soil slope and its output was verified by hand calculations.

3. The design method proposed by Tensar group is too conservative, therefore its results should not be compared with FHWA method.

4. The FHWA method may be used in design, provided that all possible slip failure are checked, since length requirement criteria may govern the design besides than the maximum tensile force, Tmax.

5. The distribution of the reinforcements in the critical zone is adequate since the recalculated resultant factor of safety is slightly larger than the target factor of safety.

6. In Turkey, the cost of constructing an embankment is very sensitive to excavation, transportation, and compaction costs rather than right of way cost. This is because the right of way cost is not too expensive. However, in all cases, an average saving of the cost is achieved (63 per cent) if reinforcements are used.

7. It is justified that the resultant Tmax (in case of inextensible reinforcement) will act at a location of H/3 from the bottom of the embankment.

8. It is important to recognize, however, that there is no generally accepted universal design methodology.

REFERENCES

Bailey A. and Christian J.T., " Slope Stability Analysis-User's Manual " ICES LEASE. 1 Soil Mechanics Publications No.235, Massachusetts Institute of Technology, Cambridge, 1969.

Bishop A.W., " The Use of the Slip Circle in the Stability Analysis of Slopes " Geotechnique, 5 (1), 1955.

Fellenius W., " Calculation of the Stability of Earth Dams" Transacitions 2nd Congress on Large Dams, 4, Washington, D.C., 1936.

FHWA, Federal Highway Administration, " Reinforced Soil Structures, Design and Construction Guidelines ", Volume I and II, Virginia, 1990

Giroud J.P., "Geotechnical Modeling and Applications " edited by Sayed M.S., Gulf Publishing Company, Houston, 1986.

Hultin S., " Grufyllander for Kejbyggnader" Teknist Tidsskeift, V.U., 31, Stockholm, 1916.

Janbu N., " Slope Stability Computations", Embankment-dam Engineering, Casagrand Volume, edited by R.C. Hirsschfield and S.J. Poulos, John Wiley and Sons Inc., 1973.

Johnson S.J., " Analysis and Design Relating to Embankments" Proceeding of Conference on Analysis and Design in Geotechnical Engineering, II, ASCE, Austin, Texas, 1975.

Morgenstern N.R. and Price V.E., " The Analysis of the Stability of General Slip Surfaces", Geotechnique, 15, 1965.

Netlon, " Guidelines for the Design and Construction of Embankments over Stable Foundations Using Tensar Geogrids" London, U.K., 1990.

Netlon, " Tensar Geogrids in Civil Engineering" , London , U.K., 1986.

Pettersson K.E., " The Early History of Circular Sliding Surfaces", Geotechnique, 5, 1955.

Terzaghi K., " Stability of Slopes of Natural Clay", Proceedings, 1st International Conference on Soil Mechanics, Cambridge, Mass, 1936.

REFERENCES
(NOT CITED)

Andrawes K.Z., Yeo K.C. and McGown A., " Performance of Reinforced Soil Structures " Proceeding of the International Reinforced Soil Conference organized by the British Geotechnical Society and held in Glasgow on 10-12 September 1990 , Thomas Telford, London, 1990 .

Bowles J.E., " Physical and Geotechnical Properties of Soils " McGraw-Hill, New York, 1979 .

Bowles J.E., " Foundation Analysis and Design ", McGraw-Hill , New York, 1988 .

Bowles J.E., " Analytical and Computer Methods in Foundation Engineering ", McGraw-Hill, New York, 1974 .

Duncan J.M. and Buchignani A.L. , " An Engineering Manual For Slope Stability Studies ", Department of Civil Engineering Institute of Transportation and Traffic ", University of California, Berkeley, March 1975 .

Dunn I.S., Anderson L.R., and Kiefer F.W.," Fundamentals of Geotechnical Analysis ", John Wiley and Sons Inc., New York,1980.

Durukan Z.S., " A Study on Reinforced Soil Retaining Walls " Master Thesis, Department of Civil Engineering Boğaziçi University , Istanbul , 1986 .

Ingold T.S., and Miller K.S., " Geotextiles Handbook ", Thomas Telford , London , 1988 .

Ingold T.S., " Reinforced Earth " , Thomas Telford , London, 1982 .

Kovacs W.D and Holtz R.D. (1984), " An Introduction to Geotechnical Engineering ", Prentice-Hall Inc., New Jersey, 1984 .

Peck R.B. (1968) ," Foundation Engineering " John Wiley and Sons Inc., 1968 .

Tschebotarioff G.P.," Foundation Retaining and Earth Structures ", McGraw-Hill Book, New York , 1986 .

Ward T. and Bromhead E. (1989), " Fortran and the Art of Pc Programming ", John Wiley and Sons Inc. New York 1989 .

APPENDICES

Appendix A

List of the Computer Program

```
      DIMENSION C(30,6),NOLIT(30,10),SLOPE(30),INTAR(30,2),EFFWT(100),
     *NSLIN(30),PHI(0:10),COHES(0:10),SLICX(99),SOIL(8,9,4),SAT(0:10),
     *ARCINT(20,3),LNU(15),CD(100),ALPHA(100),DL(100),
     *P(100),B(100),AREA(100),WEIGH(100),ALLINT(0:30,3),IBUF(4000),
     *SLIC(0:99,0:10,2),G(0:10),FACTOR(4000),CXX(4000),CYY(4000),
     *RR(4000),DM(4000),  DLL(4000),
     *ETX(4000),ETY(4000),XTX(4000),XTY(4000),TMAX(4000),
     *RDM(200),RFAC(200),RCXX(200),RCYY(200),RRR(200),
     *RENTRX(200),RENTRY(200),REXTX(200),REXTY(200)
      INTEGER DIMEN,CROL
      REAL INTAR,H,LET,LEM,LEB,KA,LT,LB,MAXT,INNERL,LAMDA
      CHARACTER*3 TITLE(25)
      OPEN(1,FILE='ISMEIK.DAT',STATUS='UNKNOWN')
      OPEN(3,FILE='ISMEIK.OU1',STATUS='UNKNOWN')
      OPEN(4,FILE='ISMEIK.OU2',STATUS='UNKNOWN')
      FU4=9.81
      DO 111 MMM=0,10
      DO 111 NNN=0,99
111   SLIC(NNN,MMM,1)=0
      DO 222 MMM=1,99
222   SLICX(MMM)=0
      ALLINT(0,1)=0
      BIGNO=9999999.
      SMLNO=0.01
      PCOUN=0
      READ(1,2201)  TITLE
2201  FORMAT(25A3)
      READ(1,*) NTYPE,Q
      READ(1,*)NOL,NLIT,NOS,NOLE,ITX,ITY,DIMEN,CROL,LIST
      READ(1,*)CX,CY,ENTX,ENTY,DELX,DELY,SWIDTH,NLOOP,DELTA
      IF(CROL.EQ.0)GO TO 221
      WRITE(3,2000)TITLE
2000  FORMAT(/2X,25A3/)
221   WHOLD=SWIDTH
      NOSP1=NOS+1
      IF(CROL.EQ.0)GO TO  800
      WRITE(3,2001) NOL,NLIT,NOS,NOLE,ITX,ITY,SWIDTH
2001  FORMAT(T5,'NO OF LINES =',I3,5X,'NO OF LINE INTERSECT =',I3,//,T5,
     *'NO OF SOILS =',I3,5X,'NO OF EXTERNAL SOIL LINES =',I3,//,T5,
     *'NO OF X-INCREMENTS =',I3,5X,'NO OF Y-INCREMENTS =',I3,//,T10, 'IN
     *ITIAL SLICE WIDTH =',F5.1,1X,A2//)
      WRITE(3,2013) Q
2013  FORMAT(//,'THE SURCHARGE LOAD = ',F7.2)
      WRITE(3,2003)
2003  FORMAT(//,T5,'THE LINE END COORD MATRIX',/,'LINE #',3X,'# INT',
     *2X,'X1',2X,'Y1',4X,'X2',4X,'Y2',4X,'SLOPE',4X,'LINE INTER NO')
800   DO 333 I=1,NOL
      READ(1,*)  NLI
      READ(1,*)   (C(I,J),J=1,6),(NOLIT(I,N),N=1,NLI)
      SLOPE(I) = BIGNO
```

```
      IF(ABS(C(I,5)-C(I,3)).LE.0.001)GO TO 334
      SLOPE(I)=(C(I,6)-C(I,4))/(C(I,5)-C(I,3))
334   IF(CROL.EQ.0) GO TO 333
      WRITE(3,2004)(C(I,J),J=1,6),SLOPE(I),(NOLIT(I,KK),KK=1,NLI)
333   CONTINUE
2004  FORMAT(2X,F3.0,4X,F3.0,4(F6.2),1X,G9.4,6I5)
      IF(CROL.EQ.0) GO TO 801
      WRITE(3,2005)
2005  FORMAT(//,T5,'LINE INTERSECT ARRAY',/,T4,'INT NO',T16,'X',T28,'Y')
801   DO 2 J=1,NLIT
      READ(1,*)   (INTAR(J,K),K=1,2)
      IF(CROL.EQ.0) GO TO 2
      WRITE(3,2006)J,(INTAR(J,K),K=1,2)
2     CONTINUE
2006  FORMAT(T6,  I3,T12,F10.2,2X,F10.2)
      IF(CROL.EQ.0) GO TO 802
      WRITE(3,2008)
2008  FORMAT(//,T5,'SOIL DATA ARRAY',/,T4,'SOIL NO',T13,'LINE #',T21,
     *'LEFT INT ',3X,'RT.INT',3X,'SAT',3X,'UNIT WT ',3X,'PHI',3X,'COHESI
     *ON')
802   H=INTAR(3,2)-INTAR(2,2)
      DO 5 I=1,NOS
      READ(1,*)   NSLIN(I),G(I),PHI(I),COHES(I),SAT(I)
      NS=NSLIN(I)
      DO 5 K=1,NS
      READ(1,*)LINSOL,INTL,INTR
      SOIL(I,K,1)=LINSOL
      SOIL(I,K,2)=INTL
      SOIL(I,K,3)=INTR
      SOIL(I,K,4)=SAT(I)
      IF(CROL.EQ.0) GO TO 5
      WRITE(3,2009)I,(SOIL(I,K,MM),MM=1,4),G(I),PHI(I),COHES(I)
5     CONTINUE
2009  FORMAT(T5,I3,6X,F3.0,7X,F3.0,6X,F3.0,6X,F2.0,5X,F6.1,3X,F4.1,3X,F7
     *.1)
      READ(1,*)TULT,CRF,FD,FC,FSPR,FSR
      READ(1,*)FSTAR,SCAL
      G(0)=G(1)
      PHI(0)=PHI(1)
      COHES(0)=COHES(1)
      SAT(0)=SAT(1)
      KP=ITX*ITY*NLOOP
      IF(KP.GE.4000) GO TO 513
      IF (NLOOP.GE.200) GO TO 513
      DO 370  MUH=1,NLOOP
100   DO 360 IY=1,ITY
      IF(IY.GT.1)CY=CY+DELY
      DO 360 IX=1,ITX
      PCOUN=PCOUN+1.
      NCOUN=PCOUN
```

```
      SWIDTH=WHOLD
      IF(IX.GT.1)CX=CX+DELX
      R=SQRT((ENTX-CX)**2+(CY-ENTY)**2)
      CXX(NCOUN)=CX
      CYY(NCOUN)=CY
      RR(NCOUN)=R
      IF(CROL.EQ.0) GO TO 803
      WRITE(3,2121)NCOUN,CX,CY,ENTX,ENTY,R
 2121 FORMAT(//,T5,'TRIAL CIRCLE NO =',I3,/,T5,'CIRCLE CTR COORDS:',2X,'
     *X =',F10.2,2X,'Y =',F10.2,/,T5,'ENTRANCE PT. COORDS:',2X,'X =',F10
     *.2,2X,'Y =',F10.2,/,T10,'TRIAL ARC RADIUS =',F10.3,//)
 803  K1=0
      DO 8 I=1,NOL
      LNU(I)=0
      IF(ABS(SLOPE(I)).LE.0.0001)GO TO 9
      CON=C(I,3)-C(I,4)/SLOPE(I)
      AA=1.0/SLOPE(I)**2+1.0
      BB=2.0*CON/SLOPE(I)-2.0*CX/SLOPE(I)-2.0*CY
      CC = CON**2 - 2.*CX*CON + CX**2 + CY**2 - R**2
      DIFF=BB**2-4.0*AA*CC
      IF(DIFF.LT.0.0)GO TO 20
      YPR=(-BB+SQRT(DIFF))/(2.0*AA)
      YNR=(-BB-SQRT(DIFF))/(2.0*AA)
      XPR=YPR/SLOPE(I)+CON
      XNR=YNR/SLOPE(I)+CON
      GO TO 10
 9    DIFF = R**2 - (CY-C(I,4))**2
      IF(DIFF.LT.0.) GO TO 20
      XPR = CX + SQRT(DIFF)
      XNR = CX - SQRT(DIFF)
      YPR=C(I,4)
      YNR=C(I,4)
 10   J1=0
      J2=0
      IF(ABS(SLOPE(I)).GE.BIGNO) GO TO 11
      IF(XPR.GE.C(I,3).AND.XPR.LE.C(I,5))J1=1
      IF(XNR.GE.C(I,3).AND.XNR.LE.C(I,5))J2=1
      IF(J1.EQ.1.AND.J2.EQ.1) GO TO 20
      GO TO 12
 11   IF(SLOPE(I))66,66,666
 66   IF(YPR.GE.C(I,6).AND.YPR.LE.C(I,4))J1=1
      IF(YNR.GE.C(I,6).AND.YNR.LE.C(I,4))J2=1
      GO TO 12
 666  IF(YPR.GE.C(I,4).AND.YPR.LE.C(I,6))J1=1
      IF(YNR.GE.C(I,4).AND.YNR.LE.C(I,6))J2=1
 12   IF(J2.EQ.0)GO TO 13
      K1=K1+1
      ARCINT(K1,1)=I
      ARCINT(K1,2)=XNR
```

```
      ARCINT(K1,3)=YNR
13    IF(J1.EQ.0) GO TO 7
      K1=K1+1
      ARCINT(K1,1)=I
      ARCINT(K1,2)=XPR
      ARCINT(K1,3)=YPR
      GO TO 8
7     IF(J1.NE.0.OR.J2.NE.0) GO TO 8
20    LNU(I)=I
      IF(CROL.EQ.0) GO TO 8
      WRITE(3,2101) I
2101  FORMAT(//,T5,'XXX LINE',I3,'  NOT INTERSECTED BY TRIAL CIRCLE')
8     CONTINUE
      DO 400 I=1,NOL
      IF(LNU(I).EQ.0) GO TO 400
      R1=SQRT((CX-C(I,3))**2+(CY-C(I,4))**2)
      R2=SQRT((CX-C(I,5))**2+(CY-C(I,6))**2)
      IF(R.LT.R1.AND.R.LT.R2) GO TO 400
      LNU(I) =0
      IF(SLOPE(I).EQ.BIGNO)LNU(I)=I
      IF(SLOPE(I).EQ.BIGNO)   THEN
      IF(CROL.EQ.0) GO TO 400
      WRITE(3,403) LNU(I)
403   FORMAT(//,'****LINE',I3,' IS IN ARC BUT VERT. AND NOT USED')
      WRITE(3,401)LNU(I)
401   FORMAT(//,T5,'***LINE',I3,'IS NOT INTERSECTED BUT IS IN ARC')
      ELSE
      CONTINUE
      END IF
400   CONTINUE
      K1M=K1-1
24    DO 26 KY=1,K1M
      IF(ARCINT(KY,2).LE.ARCINT(KY+1,2)) GO TO 26
      DO 25 KX=1,3
      SAVE=ARCINT(KY,KX)
      ARCINT(KY,KX)=ARCINT(KY+1,KX)
      ARCINT(KY+1,KX)=SAVE
25    CONTINUE
      GO TO 24
26    CONTINUE
      IF(CROL.EQ.0)GO TO 804
      WRITE(3,2112)
2112  FORMAT(//,T5,'ARC INTERSECT WITH LINE ARRAY',/,T4,'LINE NO',T19,
     *'X',T32,'Y')
      WRITE(3,2114)((ARCINT(KZ,JJ),JJ=1,3),KZ=1,K1)
2114  FORMAT(T5,F3.0,T13,F10.3,2X,F10.2)
804   LINE1=ARCINT(1,1)
      S1=ARCINT(1,2)
      S2=ARCINT(1,3)
      IF(CROL.EQ.0)GO TO 855
```

```
      WRITE(3,8053)
8053  FORMAT(//,T5,'THE ARRAY WITH ALL INTERSECTIONS FOLLOWS:')
855   ICOUN=0
      K=1
      KK=0
      LL=NLIT+K1
      DO 70 I=1,LL
      KK=KK+1
      DO 75 J=1,2
75    ALLINT(I,J)=INTAR(KK,J)
      IF(I.NE.1.AND.ALLINT(I-1,1).EQ.INTAR(KK,1))GO TO 70
      IF(ARCINT(K,2).GE.INTAR(KK,1))GO TO 70
      IF(ICOUN.GT.0)GO TO 70
72    DO 73 L=1,2
73    ALLINT(I,L)=ARCINT(K,L+1)
      IF(K.EQ.K1) ICOUN=1
      K=K+1
      IF(K.GT.K1)K=K1
      KK=KK-1
70    IF(CROL.EQ.1)  WRITE(3,8051)I,(ALLINT(I,J),J=1,2),K,KK
      CONTINUE
8051  FORMAT(T5,'I =',I3,2X,2F12.3,2X,' K =',I3,2X,'KK =',I3)
      IF(CROL.EQ.0)GO TO 805
      WRITE(3,8052)
8052  FORMAT(//,T5,'THE APPLICABLE ARRAY ARCINT FOLLOWS:')
805   LAL=0
      DO 77 I=1,LL
      R2=SQRT((CX-ALLINT(I,1))**2+(CY-ALLINT(I,2))**2)
      IF(R2.GT.(R+SMLNO))GO TO 77
      LAL=LAL+1
      DO 78 K=1,2
78    ARCINT(LAL,K)=ALLINT(I,K)
      IF(CROL.EQ.0)GO TO 806
      WRITE(3,8051) LAL,(ARCINT(LAL,J),J=1,2),I,LAL
806   EXTX=ARCINT(1,1)
      EXTY=ARCINT(1,2)
77    CONTINUE
33    SLICX(1)=S1
      SLIC(1,1,1)=S2
      SLIC(1,1,2)=LINE1
      IF(CROL.EQ.0)GO TO 98
      WRITE(3,8057)
8057  FORMAT(//,T5,'FIND SLICE WIDTH AND NO OF SLICES')
98    N=1
      NOSLIC=1
      KM = 1
      K=LAL-1
      DO 45 L=1,K
      MM=1
      IF((ARCINT(L+1,1)-ARCINT(L,1)).LE.SWIDTH) GO TO 46
```

```
      DO 47 MM=1,100
      AM=MM
      WIDTH=(ARCINT(L+1,1)-ARCINT(L,1))/AM
      IF(WIDTH.LE.SWIDTH) GO TO 49
47    CONTINUE
46    WIDTH=ARCINT(L+1,1)-ARCINT(L,1)
49    NOSLIC=NOSLIC+MM
      IF(NOSLIC.LT.DIMEN) GO TO 99
      SWIDTH=SWIDTH+0.5
      IF (CROL.EQ.0)GO TO 807
      WRITE(3,9999) SWIDTH
9999 FORMAT('0',T5,'***** MAXIMUM SLICE WIDTH HAS BEEN INCREMETED TO',
    *F5.2,1X,A2)
807   GO TO 98
99    NSM1 = NOSLIC-1
      DO 51  I=N,NOLE
      IF(LNU(I).EQ.I) GO TO 51
101   DO 52 JJ=KM,NSM1
      SLICX(JJ+1)=SLICX(JJ)+WIDTH
      SLIC(JJ+1,1,1) = SLIC(JJ,1,1)+WIDTH*SLOPE(I)
52    SLIC(JJ+1,1,2)=I
      DIFF=SLICX(JJ+1)-C(I,5)
      IF(ABS(DIFF)-.010)50,50,48
50    N=I+1
48    KM=NOSLIC
      GO TO 45
51    CONTINUE
45    CONTINUE
      NOLP1=NOL+1
      NOLEP1 = NOLE+1
      DO 60 I=1,NOSLIC
      N=2
      ARCY=CY-SQRT(R**2-(CX-SLICX(I))**2)
      DO 59  J= NOLEP1,NOL
      IF (LNU(J).EQ.J) GO TO 59
      SLIC(I,N,2)=J
      SLIC(I,N,1) = C(J,4) + (SLICX(I)   -C(J,3))*SLOPE(J)
      IF(SLICX(I).LT.(C(J,3)-SMLNO).OR.SLICX(I).GT.(C(J,5)+SMLNO))
    *SLIC(I,N,1) = -10.
      IF(SLIC(I,N,1).GT.(SLIC(I,1,1)+SMLNO).OR.SLIC(I,N,1).LT.(ARCY-
    *SMLNO))SLIC(I,N,1)=-10.0
57    N = N+1
59    CONTINUE
      SLIC(I,N,1)=ARCY
60    SLIC(I,N,2) = NOLP1
      IF(LIST.NE.0)WRITE(4,2116)
2116 FORMAT('SLICE #',1X,'X-COORD',3X,'LINE NO',3X,'SURFACE NO',3X,
    *'UPPER Y-COORD',3X,'LOWER Y- COORD')
      MCOUN=N
      N=MCOUN-1
```

```
      LLL=0
      XYZ=0.5
      DO 81 KZ=1,NOSLIC
84    NUM = 1
      DO 85 KY = 1,N
      IF(SLIC(KZ,KY,1).LE.-9.50) GO TO 82
      IF((SLIC(KZ,KY,1)+SMLNO).GE.SLIC(KZ,KY+1,1))GO TO 85
      SAVE=SLIC(KZ,KY,1)
      SLIC(KZ,KY,1)=SLIC(KZ,KY+1,1)
      SLIC(KZ,KY+1,1)=SAVE
      SAVE=SLIC(KZ,KY,2)
      SLIC(KZ,KY,2)=SLIC(KZ,KY+1,2)
      SLIC(KZ,KY+1,2)=SAVE
      GO TO 85
82    SLIC(KZ,KY,1)=SLIC(KZ,KY-1,1)
      SLIC(KZ,KY,2)=SLIC(KZ,KY-1,2)
85    IF(KY.NE.1.AND.SLIC(KZ,KY,1)-SMLNO.LE.SLIC(KZ,KY-1,1))NUM=NUM+1
      IF(NUM.NE.N)GO TO 84
      IF(SLIC(KZ,1,1).GE.INTAR(3,2))SLIC(KZ,1,1)=INTAR(3,2)
      IF(SLICX(KZ).GE.INTAR(3,1))THEN
      LLL=LLL+1
      ELSE
      CONTINUE
      END IF
      IF(SLIC(KZ,1,2).GE.INTAR(3,2)) SLIC(KZ,2,1)=INTAR(3,2)
      XO=SLICX(KZ)
      YO=SLIC(KZ,2,1)
      BB=INTAR(2,2)-SLOPE(2)*INTAR(2,1)
      X2= (YO-BB )/SLOPE(2)
      DL(KZ)=XO-X2
81    IF(LIST.NE.0)WRITE(4,3)KZ,SLICX(KZ),
     *(SLIC(KZ,KY,2),KY=1,MCOUN),(SLIC(KZ,KY,1),KY=1,MCOUN)
      DO 87  KZ=1,NOSLIC
      IF(DL(KZ).GE.XYZ) XYZ=DL(KZ)
87    CONTINUE
      DLL(NCOUN)=XYZ
      IP=NOSLIC-LLL
      ML=(IP+NOSLIC)/2 +1
      IF(ML.GE.NOSLIC) ML=NOSLIC-1
3     FORMAT(I5,3X,F7.2,3X,F7.2,3X,F7.2,6X,F7.2,9X,F7.2,
     *T15,8F7.2,/,T15,8F7.2,/,T15,8F7.2)
      ALFA=0
      TW=0
      TEW=0
      ANET=0
      V=Q*(ENTX-INTAR(3,1))
      DO 306 I=1,NSM1
      SAREA=0.0
      WEIGHT=0.0
      EFWT=0.
```

```
      ISOIL=0
      NN=MCOUN-1
      IF(LIST.NE.0)WRITE(4,350) I
350   FORMAT(/,T5,'SLICE LINE NUMBER',I4)
      DO 303 J=1,NN
      DA=(SLIC(I,J,1)+SLIC(I+1,J,1)-SLIC(I,J+1,1)-SLIC(I+1,J+1,1))*
     *(SLICX(I+1)-SLICX(I))/2.0
      IF(DA.LE.SMLNO) GO TO 303
      DO 305 II=1,NOSP1
      IF(II.EQ.NOSP1)   THEN
      SAREA=SAREA+DA
      ANET=ANET+SAREA
      GSUB=G(ISOIL)
      IF(SAT(ISOIL).GT.0.1)GSUB=G(ISOIL)-FU4
      EFWT=EFWT+DA*GSUB
      WEIGHT=WEIGHT+DA*G(ISOIL)
      IF(LIST.EQ.0) GO TO 8888
      WRITE(4,351) J,I,DA
      WRITE(4,352) ISOIL,J,SAREA,WEIGHT,EFWT
8888  GO TO 303
      ELSE
      CONTINUE
      END IF
      IF(ISOIL.EQ.II)GO TO 305
      N=NSLIN(II)
      ICOUNT=0
      JCOUNT=0
311   DO 304 JJ=1,N
      IF(JCOUNT.EQ.2)GO TO 305
      INTL=SOIL(II,JJ,2)
      INTR=SOIL(II,JJ,3)
      IF(ICOUNT.EQ.1)GO TO 310
      IF(SLIC(I,J,2).NE.SOIL(II,JJ,1))GO TO 304
      ICOUNT=1
      JSOIL=II
      IF((SLICX(I)+SMLNO).GE.INTAR(INTL,1).AND.(SLICX(I)-SMLNO).LE.
     *INTAR(INTR,1))GO TO 310
      ICOUNT=0
      GO TO 304
310   IF(SLIC(I+1,J,2).NE.SOIL(II,JJ,1))GO TO 304
      IF((SLICX(I+1)+SMLNO).LT.INTAR(INTL,1).OR.(SLICX(I+1)-SMLNO).GT.
     *INTAR(INTR,1))GO TO 304
      ICOUNT=2
      IF(JSOIL.NE.II)GO TO 305
302   ISOIL=II
      SAREA=SAREA+DA
      ANET=ANET+SAREA
      GSUB=G(ISOIL)
      IF(SAT(ISOIL).GT.0.1)GSUB=G(ISOIL)-FU4
      EFWT=EFWT+DA*GSUB
```

```
      WEIGHT=WEIGHT+DA*G(ISOIL)
      IF(LIST.EQ.0) GO TO 9092
      WRITE(4,351)J,I,DA
351   FORMAT(T1,'DSLICE NO',I2,'OF SLICE -',I3,'WITH DA OF',F7.3)
      WRITE(4,352)ISOIL,J,SAREA,WEIGHT,EFWT
352   FORMAT(T10,'SOIL -',I3,'LIES IN DSLICE -',I3,/,T10,'TOTAL AREA ='
     *,F10.3,3X,'TOTAL WEIGHT =',G8.3,2X,'EFFECT.WT =',G8.3)
9092  GO TO 303
304   CONTINUE
      IF(ICOUNT.EQ.1)JCOUNT=JCOUNT+1
      IF(ICOUNT.EQ.1)GO TO 311
305   CONTINUE
303   CONTINUE
      ALPHA(I)=ASIN(ABS(CX-((SLICX(I+1)-SLICX(I))/2.0+SLICX(I)))/R)
      AREA(I)=SAREA
      IF(I.EQ.ML)THEN
      EFFWT(I)=EFWT+V
      ELSE
      EFFWT(I)=EFWT
      END IF
      WEIGH(I)=WEIGHT
      ALFA=ALFA+ALPHA(I)
      TW=TW+WEIGH(I)
      TEW=TEW+EFFWT(I)
      CO(I)=COHES(ISOIL)
306   P(I)=PHI(ISOIL)
      IF(LIST.EQ.0)GO TO 777
      WRITE(4,354)
354   FORMAT(T5,'SLICE #',3X,'AREA',3X,'WEIGHT',4X,'COHESION',3X,'PHI',
     *3X,'ALPHA')
      DO 307 I=1,NSM1
      IF(AREA(I).LE.SMLNO)GO TO 362
      WRITE(4,353)I,AREA(I),WEIGH(I),CO(I),P(I),ALPHA(I)
      GO TO 307
362   WRITE(4,353)I,AREA(I),WEIGH(I)
353   FORMAT(T7,I2,2X,3F10.3,F6.2,F9.4)
307   CONTINUE
777   ALFA=ALFA/NSM1
      IF(LIST.NE.0)  WRITE(4,356) ALFA,TW,TEW,ANET
356   FORMAT(//'   AVERAGE   ALPHA = ',F9.2,/
     *          '   SUM OF T.WEIGHT = ',F9.2,/
     *          '   SUM OF E.WEIGHT = ',F9.2,/
     *          '   SUM OF     AREA = ',F9.2)
365   DO 367 I=1,NSM1
      IF(AREA(I).LE.SMLNO)P(I) = 0.00
      IF(AREA(I).LE.SMLNO)CO(I) = 0.00
367   P(I) = P(I)/57.2958
      FI=1.0
383   ZUM=0.0
      TF=0.0
```

```
      ANGLE=SIN(ALPHA(ML))
      DO 382 K=1,NSM1
      CENTR=(SLICX(K+1)-SLICX(K))/2.0+SLICX(K)
      IF((CENTR-CX).LT.0.0) T=-WEIGH(K)*SIN(ALPHA(K))
      IF((CENTR-CX).EQ.0.0) T=0.0
      IF((CENTR-CX).GT.0.0) T=WEIGH(K)*SIN(ALPHA(K))
394   TF=TF+T+0.0001
      B(K) = (SLICX(K+1)-SLICX(K))
      A1=(CO(K)*B(K)+EFFWT(K)*TAN(P(K)))/(COS(ALPHA(K)))
      A2=(((1+(TAN(ALPHA(K))*TAN(P(K))/(FI+.00001)))))
      Z=A1/A2
701   FORMAT(5F9.2)
382   ZUM=ZUM+Z
      TF=TF+V*ANGLE
      FO=ZUM/TF
      WRITE(3,116) FI,FO
116   FORMAT(20X,'FI= ',F10.5,3X,'FO= ',F10.5)
      IF(ABS(FO-FI).GE.0.001)THEN
      FI=FO
      GO TO 383
      ELSE
      WRITE(3,108) NCOUN,FO
      END IF
108   FORMAT('THE SAFETY  FACTOR FOR POINT',I4,' IS  ',F7.3)
      DM(NCOUN)=TF
      Y=(.667*H)+(CY-ENTY)
      D=RR(NCOUN)
      IF( NTYPE.EQ.2) THEN
      TMAXW=(FSR-FO)*TF/Y
      ELSE
      TMAXW=(FSR-FO)*TF/D
      END IF
405   CONTINUE
      FACTOR(NCOUN)=FO
      ETX(NCOUN)=ENTX
      ETY(NCOUN)=ENTY
      XTX(NCOUN)=EXTX
      XTY(NCOUN)=EXTY
      TMAX(NCOUN)=TMAXW
360   IF(IX.EQ.ITX)CX=CX-(IX-1)*DELX
      SMALL=20
      IPNT=1
      DO 407 I=1,NCOUN
      IF(FACTOR(I).LT.0.2)FACTOR(I)=10
      IF(FACTOR(I).LE.SMALL) THEN
      SMALL=FACTOR(I)
      IPNT=I
      ELSE
      CONTINUE
      END IF
```

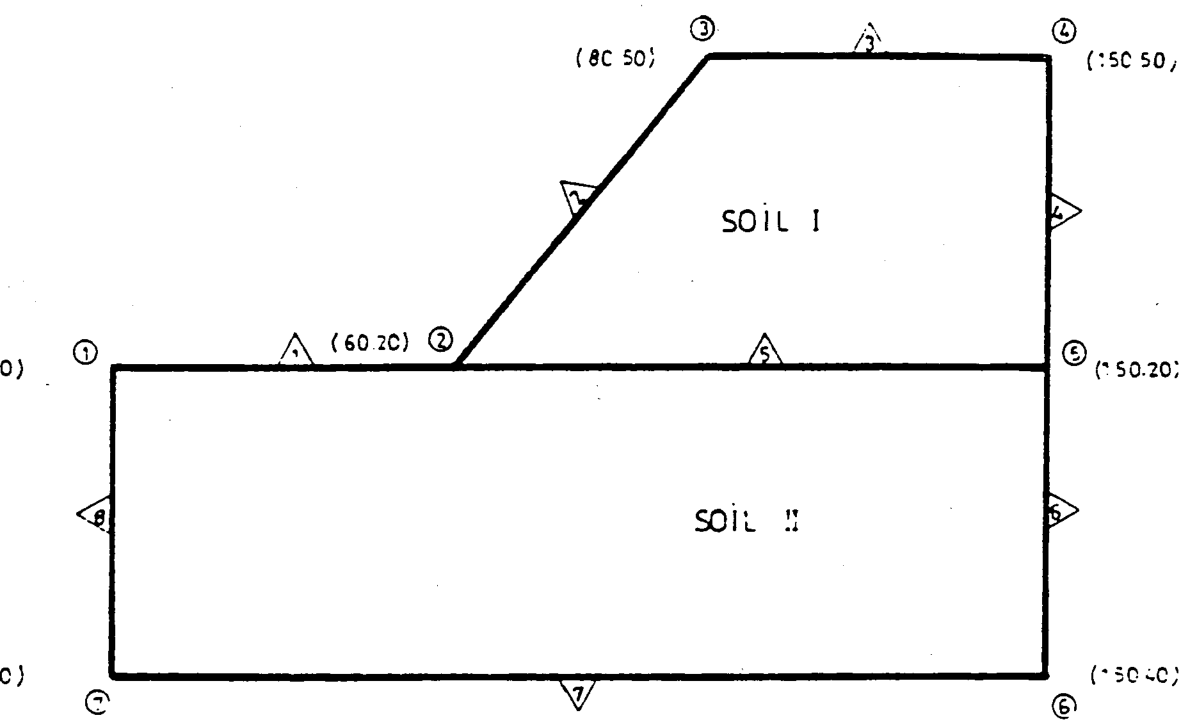
```
 407  CONTINUE
      RDM(MUH)   =DM(IPNT)
      RFAC(MUH)  =SMALL
      RCXX(MUH)  =CXX(IPNT)
      RCYY(MUH)  =CYY(IPNT)
      RRR(MUH)   =RR(IPNT)
      RENTRX(MUH)=ETX(IPNT)
      RENTRY(MUH)=ETY(IPNT)
      REXTX(MUH)=XTX(IPNT)
      REXTY(MUH)=XTY(IPNT)
      ENTX=ENTX+DELTA
 370  CONTINUE
      SSML=20.
      DO 371 I=1,NLOOP
      IF(RFAC(I).LE.0.2)RFAC(I)=2000
      IF(RFAC(I).LE.SSML)THEN
      SSML=RFAC(I)
      L=I
      ELSE
      CONTINUE
      END IF
 371  CONTINUE
      WRITE(3,605)
 605  FORMAT(// '   AFTER  TOO  MANY ITERATIONS ')
      WRITE(3,606) SSML
 606  FORMAT('THE LOWEST FACTOR OF SAFETY IS  ',F5.3)
      WRITE(3,607) RCXX(L),RCYY(L),RRR(L)
 607  FORMAT('CENTER AT','   X=',F7.2,'   Y=',F7.2,'   R=',F7.2)
      WRITE(3,608)RENTRX(L),RENTRY(L),
     *REXTX(L),REXTY(L)
 608 FORMAT('ENTR  X-COORD =',F7.2,/,
     *        'ENTR  Y-COORD =',F7.2,/,
     *        'EXIT  X-COORD =',F7.2,/,
     *        'EXIT  Y-COORD =',F7.2)
      WRITE(3,609) RDM(L)
 609  FORMAT(/'THE DRIVING MOMENT IS =',F10.2)
      READ*,
      MAXT=0.0001
      DO 610 I=1,NCOUN
      IF(TMAX(I).GE.MAXT)THEN
      MAXT=TMAX(I)
      J=I
      ELSE
      CONTINUE
      END IF
 610  CONTINUE
      WRITE(3,611) FACTOR(J)
 611  FORMAT('FACTOR OF SAFETY OF THE UNREINFORCED SLOPE ',F5.3)
      WRITE(3,612)CXX(J),CYY(J),RR(J)
 612  FORMAT('CENTER AT ',' X=',F7.2,'   Y=',F7.2,'   R=',F7.2)
```

```
      WRITE(3,613)ETX(J),ETY(J),XTX(J),XTY(J)
 613  FORMAT('ENTR X-COORD =',F7.2,/,
     *       'ENTR Y-COORD =',F7.2,/,
     *       'EXIT X-COORD =',F7.2,/,
     *       'EXIT Y-COORD =',F7.2)
     WRITE(3,614)DM(J)
614  FORMAT('THE DRIVING  MOMENT IS ',F10.2)
     TALL=(TULT*CRF)/(FD*FC*FSPR)
     WRITE(3,501)TALL
501  FORMAT(/'THE  ALLOWABLE  TENSILE  FORCE =',2X,F7.2)
     WRITE(3,502)MAXT
502  FORMAT(/'THE MAXIMUM TENSILE FORCE USED =',2X,F7.2)
     CONN=TALL*FSR/(FSTAR*SCAL*G(1)*2)
     WRITE(3,507)  H
507  FORMAT(/'THE HEIGHT',F7.2,' m IS DIVIDED INTO THREE EQUAL ZONES')
     IF(H.GT.6) THEN
     WRITE(3,503)
503  FORMAT(/,'NOTE THAT THE HEIGHT IS GREATER THAN 6 m')
     TT=TMAX(J)/6
     TM=TMAX(J)/3
     TB=TMAX(J)/2
     WRITE(3,504)
504  FORMAT(/,20X,'TOP ZONE',3X,'MIDDLE ZONE',3X,'BOTTOM ZONE')
     NT=TT/TALL+1
     NM=TM/TALL+1
     NB=TB/TALL+1
     SVT=H/(NT*3.0)
     SVM=H/(NM*3.0)
     SVB=H/(NB*3.0)
     WRITE(3,505) NT,NM,NB
505  FORMAT('NUMBER OF LAYERS', I7 ,3X,I7  ,7X,I7  ,7X)
     WRITE(3,506) SVT,SVM,SVB
506  FORMAT('VERTICAL SPACING',3X,F7.2,3X,F7.2,7X,F7.2,7X,'m')
     ELSE
     WRITE(3,508)
508  FORMAT(//'NOTE THAT THE HEIGHT IS LESS THAN 6 m')
     WRITE(3,504)
     NG=TMAX(J)/TALL + 1
     SVG=H/NG
     WRITE(3,505) NG,NG,NG
     WRITE(3,506) SVG,SVG,SVG
     END IF
     LET=CONN/(0.03*H)
     IF(LET.LT.0.91) LET=0.91
     WRITE(3,509)LET,LET,LET
509  FORMAT('EMBEDMENT LENGTH',3X,F7.2,3X,F7.2,7X,F7.2,7X,'m')
     LET=LET+DLL(J)
     WRITE(3,570)LET,LET,LET
570  FORMAT('REINF.   LENGTHT',3X,F7.2,3X,F7.2,7X,F7.2,7X,'m')
     S=SQRT(((INTAR(3,1)-INTAR(2,1))**2)+((INTAR(3,2)-INTAR(2,2))**2))
```

```
      LT=LET
      LB=LET
      THETA=ASIN(H/S)
      W=1.5707-ATAN((LT+S*COS(THETA)-LB)/H)
      WT=G(1)*H*0.5*((2*LB)-(S*COS(THETA))+(H*TAN(1.5707-W)))
      LAMDA=1.5707-W
     PHII=PHI(1)/57.2958
      IF(LAMDA.GE.PHII) LAMDA=PHII
      B1=SQRT(SIN(PHII+LAMDA))
      B2=SQRT(SIN(W+LAMDA))
      B3=SIN(W-PHII)/SIN(THETA)
      KA=(B3/(B1+B2))**2
      PSL=((.5*G(1)*H*H*KA)-(2*  0 *COHES(1)*H*(SQRT(KA))))*
     *COS(LAMDA+W-1.5707)
      PR=WT*TAN(PHII)
      FSLID=PR/PSL
      WRITE(3,510) FSLID
510   FORMAT(/'THE SLIDING SAFETY FACTOR IS ',F7.2)
      IF(FSLID.LT.1.5) WRITE(3,511)
511   FORMAT('NOTE THAT IT IS NOT SAFE')
      GO TO 512
513   WRITE(*,*)' THE NUMBER OF ITERATIONS IS TOO LARGE'
512   STOP
      END
```

Appendix B

Data File Praparation to the Design Example



```
Analysis of an Embankment  on Sandy Clay , slope 1.5
2,12
8,7,2,3,1,1,90,1,0
57.2,55.1,92.00,50,0.1,1,4,1,1
2
1,2,0,20,60,20,1,2
2
2,2,60,20,80,50,2,3
2
3,2,80,50,150,50,3,4
2
4,2,150,50,150,20,4,5
2
5,2,60,20,150,20,2,5
2
6,2,150,20,150,4,5,6
2
7,2,150,4,0,4,6,7
2
8,2,0,20,0,4,1,7
0,20
60,20
80,50
150,50
150,20
150,4
0,4
6,17,30,0,0
1,2,2
2,2,3
3,3,4
4,4,5
5,2,5
6,5,5
7,18,10,25,0
1,1,2
2,2,2
4,5,5
5,2,5
6,5,6
7,6,7
8,1,7
50,0.5,1.25,1.2,1.5,1.5
0.54,0.67
```

Appendix C

The Output of the Design Example

```
Analysis of an Embankment on Sandy Clay , slope 1.5

  NO OF LINES =  8     NO OF LINE INTERSECT =  7

  NO OF SOILS =  2     NO OF EXTERNAL SOIL LINES =  3

  NO OF X-INCREMENTS =  1     NO OF Y-INCREMENTS =  1

       INITIAL SLICE WIDTH =  4.0

  THE SURCHARGE LOAD =   12.00

  THE LINE END COORD MATRIX
LINE #   # INT  X1  Y1     X2     Y2     SLOPE    LINE INTER NO
   1.     2.  0.00 20.00 60.00 20.00 .0000E+00    1    2
   2.     2. 60.00 20.00 80.00 50.00 1.500        2    3
   3.     2. 80.00 50.00150.00 50.00 .0000E+00    3    4
   4.     2.150.00 50.00150.00 20.00 .1000E+08    4    5
   5.     2. 60.00 20.00150.00 20.00 .0000E+00    2    5
   6.     2.150.00 20.00150.00  4.00 .1000E+08    5    6
   7.     2.150.00  4.00  0.00  4.00 .0000E+00    6    7
   8.     2.  0.00 20.00  0.00  4.00 .1000E+08    1    7

  LINE INTERSECT ARRAY
 INT NO      X           Y
    1         0.00       20.00
    2        60.00       20.00
    3        80.00       50.00
    4       150.00       50.00
    5       150.00       20.00
    6       150.00        4.00
    7         0.00        4.00

  SOIL DATA ARRAY
 SOIL NO  LINE #  LEFT INT    RT.INT    SAT   UNIT WT    PHI   COHESION
    1       1.        2.        2.       0.       17.0   30.0       0.0
    1       2.        2.        3.       0.       17.0   30.0       0.0
    1       3.        3.        4.       0.       17.0   30.0       0.0
    1       4.        4.        5.       0.       17.0   30.0       0.0
    1       5.        2.        5.       0.       17.0   30.0       0.0
    1       6.        5.        5.       0.       17.0   30.0       0.0
    2       1.        1.        2.       0.       18.0   10.0      25.0
    2       2.        2.        2.       0.       18.0   10.0      25.0
    2       4.        5.        5.       0.       18.0   10.0      25.0
    2       5.        2.        5.       0.       18.0   10.0      25.0
    2       6.        5.        6.       0.       18.0   10.0      25.0
    2       7.        6.        7.       0.       18.0   10.0      25.0
    2       8.        1.        7.       0.       18.0   10.0      25.0
```

TRIAL CIRCLE NO = 1
CIRCLE CTR COORDS: X = 57.20 Y = 55.10
ENTRANCE PT. COORDS: X = 92.00 Y = 50.00
TRIAL ARC RADIUS = 35.172

XXX LINE 1 NOT INTERSECTED BY TRIAL CIRCLE

XXX LINE 4 NOT INTERSECTED BY TRIAL CIRCLE

XXX LINE 5 NOT INTERSECTED BY TRIAL CIRCLE

XXX LINE 6 NOT INTERSECTED BY TRIAL CIRCLE

XXX LINE 7 NOT INTERSECTED BY TRIAL CIRCLE

XXX LINE 8 NOT INTERSECTED BY TRIAL CIRCLE

ARC INTERSECT WITH LINE ARRAY

LINE NO	X	Y
2.	60.028	20.04
3.	92.000	50.00

THE ARRAY WITH ALL INTERSECTIONS FOLLOWS:

I = 1	0.000	20.000	K = 1	KK = 1
I = 2	60.000	20.000	K = 1	KK = 2
I = 3	60.028	20.042	K = 2	KK = 2
I = 4	80.000	50.000	K = 2	KK = 3
I = 5	92.000	50.000	K = 2	KK = 3
I = 6	150.000	50.000	K = 2	KK = 4
I = 7	150.000	20.000	K = 2	KK = 5
I = 8	150.000	4.000	K = 2	KK = 6
I = 9	0.000	4.000	K = 2	KK = 7

THE APPLICABLE ARRAY ARCINT FOLLOWS:

I = 1	60.028	20.042	K = 3	KK = 1
I = 2	80.000	50.000	K = 4	KK = 2
I = 3	92.000	50.000	K = 5	KK = 3

```
                  FI=    1.00000   FO=    0.89315
                  FI=    0.89315   FO=    0.86013
                  FI=    0.86013   FO=    0.84896
                  FI=    0.84896   FO=    0.84506
                  FI=    0.84506   FO=    0.84368
                  FI=    0.84368   FO=    0.84319
THE SAFETY  FACTOR FOR POINT   1 IS    0.843


   AFTER  TOO  MANY ITERATIONS
THE LOWEST FACTOR OF SAFETY IS  0.843
CENTER AT   X=  57.20   Y=  55.10   R=  35.17
ENTR  X-COORD =  92.00
ENTR  Y-COORD =  50.00
EXIT  X-COORD =  60.03
EXIT  Y-COORD =  20.04

THE DRIVING MOMENT IS =   4133.85
FACTOR OF SAFETY OF THE UNREINFORCED SLOPE 0.843
CENTER AT   X=  57.20   Y=  55.10   R=  35.17
ENTR X-COORD =  92.00
ENTR Y-COORD =  50.00
EXIT X-COORD =  60.03
EXIT Y-COORD =  20.04
THE DRIVING  MOMENT IS    4133.85

THE  ALLOWABLE  TENSILE  FORCE =    11.11

THE MAXIMUM TENSILE FORCE USED =   108.13

THE HEIGHT  30.00 m IS DIVIDED INTO THREE EQUAL ZONES

NOTE THAT THE HEIGHT IS GREATER THAN 6 m

                    TOP ZONE   MIDDLE ZONE   BOTTOM ZONE
NUMBER OF LAYERS      2          4             5
VERTICAL SPACING      5.00       2.50          2.00       m
EMBEDMENT LENGTH      1.51       1.51          1.51       m
REINF.    LENGHT     17.56      17.56         17.56       m

THE SLIDING SAFETY FACTOR IS    8.89
```

SLICE #	X-COORD	LINE NO	SURFACE NO	UPPER Y-COORD	LOWER Y- COORD
1	60.03	2.00	9.00	20.04	20.04
2	64.02	2.00	9.00	26.03	20.60
3	68.02	2.00	9.00	32.03	21.63
4	72.01	2.00	9.00	38.02	23.20
5	76.01	2.00	9.00	44.01	25.38
6	80.00	2.00	9.00	50.00	28.32
7	83.00	2.00	9.00	50.00	31.20
8	86.00	2.00	9.00	50.00	34.91
9	89.00	2.00	9.00	50.00	40.07
10	92.00	2.00	9.00	50.00	50.00

```
   SLICE LINE NUMBER   1
DSLICE NO 1OF SLICE -  1WITH DA OF 10.860
       SOIL -  1LIES IN DSLICE -  1
       TOTAL AREA =    10.860   TOTAL WEIGHT =185.      EFFECT.WT =185.

   SLICE LINE NUMBER   2
DSLICE NO 1OF SLICE -  2WITH DA OF 31.615
       SOIL -  1LIES IN DSLICE -  1
       TOTAL AREA =    31.615   TOTAL WEIGHT =537.      EFFECT.WT =537.

   SLICE LINE NUMBER   3
DSLICE NO 1OF SLICE -  3WITH DA OF 50.350
       SOIL -  1LIES IN DSLICE -  1
       TOTAL AREA =    50.350   TOTAL WEIGHT =856.      EFFECT.WT =856.

   SLICE LINE NUMBER   4
DSLICE NO 1OF SLICE -  4WITH DA OF 66.803
       SOIL -  1LIES IN DSLICE -  1
       TOTAL AREA =    66.803   TOTAL WEIGHT =.114E+04  EFFECT.WT
       =.114E+04

   SLICE LINE NUMBER   5
DSLICE NO 1OF SLICE -  5WITH DA OF 80.509
       SOIL -  1LIES IN DSLICE -  1
       TOTAL AREA =    80.509   TOTAL WEIGHT =.137E+04  EFFECT.WT
       =.137E+04

   SLICE LINE NUMBER   6
DSLICE NO 1OF SLICE -  6WITH DA OF 60.727
       SOIL -  0LIES IN DSLICE -  1
       TOTAL AREA =    60.727   TOTAL WEIGHT =.103E+04  EFFECT.WT
       =.103E+04

   SLICE LINE NUMBER   7
DSLICE NO 1OF SLICE -  7WITH DA OF 50.840
       SOIL -  0LIES IN DSLICE -  1
       TOTAL AREA =    50.840   TOTAL WEIGHT =864.      EFFECT.WT =864.
```

SLICE LINE NUMBER 8
DSLICE NO 1OF SLICE - 8WITH DA OF 37.525
SOIL - 0LIES IN DSLICE - 1
TOTAL AREA = 37.525 TOTAL WEIGHT =638. EFFECT.WT =638.

SLICE LINE NUMBER 9
DSLICE NO 1OF SLICE - 9WITH DA OF 14.891
SOIL - 0LIES IN DSLICE - 1
TOTAL AREA = 14.891 TOTAL WEIGHT =253. EFFECT.WT =253.

SLICE #	AREA	WEIGHT	COHESION	PHI	ALPHA
1	10.860	184.612	0.000	30.00	0.1376
2	31.615	537.456	0.000	30.00	0.2535
3	50.350	855.945	0.000	30.00	0.3729
4	66.803	1135.646	0.000	30.00	0.4983
5	80.509	1368.656	0.000	30.00	0.6329
6	60.727	1032.367	0.000	30.00	0.7627
7	50.840	864.286	0.000	30.00	0.8886
8	37.525	637.917	0.000	30.00	1.0382
9	14.891	253.139	0.000	30.00	1.2431

AVERAGE ALPHA = 0.65
SUM OF T.WEIGHT = 6870.02
SUM OF E.WEIGHT = 7014.02
SUM OF AREA = 404.12