DEFORMATION AND ULTIMATE LOAD OF REINFORCED SOIL STRUCTURES,
Theory and Experiment

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A dissertation submitted in partial fulfillment of the requirements for the Degree of Doctor of Engineering

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MARCH 1995

ABSTRACT

The mechanism and behavior of reinforced soils are studied under both the initial loading and the limit equilibrium state of the soil mass. A new concept of computation of the initial load-settlement relation, bearing capacity/safety factor, distribution of axial and shear (or bending) forces in the reinforcement, velocity vectors and stress distribution in reinforced soil structures is presented.

Brief literature review of the existing philosophies on the reinforced soil systems, the concept and the applications is carried out. Need for a new simplified and realistic tool for the analysis and design of reinforced soil structures has been derived based on the deficiency observed in the existing analysis and design tools and the over-conservatism in their performances.

A new formulation of the mechanism of reinforcing a soil mass is presented. The reinforced effect is coupled in the conventional rigid plastic finite element method (RPFEM) by introducing a set of linear constraint conditions of "*no length change*" and "*no-bending*" upon plastic flow of the soil element nodes corresponding to the reinforcement at limit equilibrium state of soil mass. These constraint conditions are shown to be equally applicable in formulating the reinforced effect at the initial loading state of soil mass by coupling it with the conventional linear elastic finite element method (LEFEM).

These two new linear constraint conditions are subsequently incorporated in two energy functions: stored energy function for the linear elastic problems and the plastic energy dissipation function for the limit state problems. The corresponding Lagrange multipliers are shown to be representing the axial force and the shear force (/bending moment) in the reinforcing material per unit length, respectively.

Behaviors of reinforced soil structures under both the initial loading state and at the limit state of reinforced soil mass are investigated employing the proposed concept. The proposed methodology is tested numerically in a bearing capacity problem with strip footing loading, and in slope stability and excavation problems under gravity loading. Later, applicability of the proposed numerical method is examined through analyzing the results of a series of medium scale 1g model tests of the reinforced soil slopes. Using these observations on the real model tests, advantages and limitations of the proposed method are assessed.

Effect of the soil reinforcement is shown through the improvements in the load-deformation relations, bearing capacity values, the reinforcement axial force, stress distribution and displacement/ or velocity fields in the soil mass. The effect of facing rigidity on the soil is explained through the bending moments developed in the facing.

The computed factor of safety shows that the reinforcement is more effective in frictional (c-ϕ) material than in purely cohesive clay. The reinforcement in the frictional (c-ϕ) material acts like an anchor while in the purely cohesive clay the bar does not show such kind of effects. The axial force in the reinforcement is treated as an internal stress that develops because of the soil-reinforcement interaction and cannot be controlled from outside the soil system.

Substantial improvement in the response of the soil structure due to the soil reinforcement is demonstrated through the model test results and then, supported by the numerical simulation results obtained by employing the proposed numerical method.

Through numerical investigations of the excavation problems, a new concept on the positioning of vertical reinforcements has been recommended depending on the reinforcement types, axial or bending member.

Overall, conclusion is that the proposed methodology offers promising features and wide applicability for the analysis and design of complex reinforced soil structures. The results presented through this study provide enough confidence to the practicing engineers to adopt the methodology in the practice.

ACKNOWLEDGMENTS

At the outset, the author expresses his deepest gratitude to *Professor Minoru Matsuo* who as a Dean of School of Engineering admitted in his laboratory as a Doctoral Student. Prof. Matsuo's valuable suggestions and gesture of helps in various affairs concerning research as well as private matters are also gratefully acknowledged. It was a matter of great pleasure to have him as a committee member.

The author takes this great opportunity to express his profound gratitude to his academic advisor *Professor Akira Asaoka* for his superlative flow of ideas and guidance as well as moving inspirations all throughout the period of this research. It was a matter of great pleasure to sail through several turbulent phases of this work with him. He is a great sailor, indeed.

The author owes a lot to *Dr. T. Kyoya*, Associate Professor for his kind gesture in serving as a committee member and for his very detailed comments for amendment and improvements of the first draft of this thesis.

Author is really grateful to *Dr. Satoru Ohtsuka*, Assoc. Professor for his nice gesture of helps especially in the first few months of stay in Japan and continuing encouragement.

Dr. Takeshi Kodaka, a senior doctoral student during first year of this study and later as research associate in the same laboratory, is a very special person to be acknowledged here. He is the one who in-spite-of his busy periods helped to understand various secrets of the research techniques in this laboratory. His kind help during the experimental model tests is greatly appreciated.

The author fondly acknowledges the inspiring efforts of *Dr. Y. Suzuki*, *Dr. M. Sugai*, *Dr. M. Nakano* and *Dr. T. Noda* for their wonderful ideas and personal helps those proved helpful in completing this work. Additionally *Mr. T. Miyagawa* and *Mr. Moritomo*, masters students who helped in conducting the experimental model tests and in the numerical computations without their help the research report wouldn't look as it is now. Author is also grateful to Masters students: *Mr. S. Baba*, *Mr. Onishi* and *Mr. Y. Kato* for their assistance in preparing some of the figures.

Mr. T. Ochiai and *Mr. T. Katoh*, Yahagi Corporation who provided model testing facility and the instruments as well as sponsored financially to make the experiment successful, are sincerely appreciated and very many thanks to *Mr. Kodama* for his help throughout model testing period.

A sincere thanks is also due for the Monbusho Scholarship Program, Ministry of Education and Culture, Japanese Government for providing the scholarship that made it possible for this author to spend a most gratifying period of study in Nagoya university.

A special thanks extends to *Mr. M. Nozu* and *Mr. G.S.K. Fernando*, fellow doctoral students for their wonderful ideas and thought-provoking remarks those proved to be instrumental in wrapping up the thesis and other private communications in the laboratory. The author appreciates *Mr. H Hazarika*, a fellow doctoral student for his sincere help in proof reading the manuscript. Nonetheless, very many masters and bachelor students in this laboratory who helped directly or indirectly are gratefully acknowledged.

A special note of sincere appreciation also extends to *Dr. Yusuke Honjo*, *Professor Yudhbir* and *Professor A.S. Balasubramaniam* for their continuing inspirations. Sincere appreciation goes to all those who helped in numerous ways in succeeding this piece of research work.

A very special debt of deep gratitude is offered to author's parents and parents-in-law for their unceasing sacrifices, endeavors and encouragement.

Finally, thanks are due to wife *Ila*, son *Asit* and daughter *Anu* for their forbearance and affection althroughout the research period. This piece of work is dedicated to them.

Gyaneswor Pokharel

March 27, 1995 Nagoya University, Japan

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CHAPTER I INTRODUCTION

1.1 GENERAL

The past three decades have shown great achievements in the advancement of reinforced soil system using stiff metal to flexible/extensible geosynthetic materials as reinforcing elements. Many reinforced soil structures have been performing well and are considered safe and convenient in construction. Parallel to the advancement in the construction technology, in these years a lot of efforts has been devoted to find a suitable method/procedure for the analysis and design (e.g. Vidal, 1966; Schlosser and Long, 1972; Haussman, 1976; Chapius, 1978; Yang, 1972; ASCE, 1978; Jarret et al., 1987), Tatsuoka, 1992; Yamanouchi et al., 1978; Ochiai, 1992). Many assumptions have been postulated and many solution procedures have been proposed about the mechanism of different components comprising these systems (e.g. reinforcement force, soil-reinforcement-facing interaction) and the mechanism is still not well understood. The commonly accepted analysis and design method is still lagging.

In the analysis of most soil engineering problems, specially reinforced soil structure, stability and deformation are considered both critical and independent but they are always dealt separately. In this dissertation, these two aspects of the behavior of reinforced soil structures are studied introducing some mechanisms to model the facing, reinforcement and soil interactions. The mechanism of axial force development in the reinforcement is also newly proposed. The length along reinforcing element is assumed to be constant by imposing a constrained condition of no-length change. Similarly, the flexural (bending i.e. shear force) rigidity is modeled by imposing additional constrained condition of "*no-angle change*". Further, the difference between soil anchors and soil reinforcement is distinguished through the axial/shear forces developed along the soil reinforcement and soil anchors. In the former, the axial force can be controlled externally (out side the soil/anchor system) while in the latter (i.e. soil reinforcement) case, the axial force is not externally controllable, rather develops internally due to soil-reinforcement interaction depending on the confining pressure. In this context, the conventional methods of the reinforced soil structures that require the tensile force distribution along reinforcements be prescribed, as an initial condition cannot be accepted, at least, from the theoretical point of view.

Thus, the deformation behavior of reinforced soil structure under a initial loading stage is studied by introducing these newly proposed mechanisms in the linear elastic finite element method (LEFEM). LEFEM is used as a numerical tool in all deformation analyses. The proposed numerical method is demonstrated through some typical soil engineering deformation problems and the results reveal that the reinforcement is much effective in reducing the lateral deformation in addition to vertical settlements of reinforced soil mass.

Similarly, a detailed investigation of the behaviors of reinforced soil structures at limiting equilibrium state is attempted to examine how plastic velocities and axial/shear force develop in the reinforcement. Such an investigation is also extended to excavation problems where axial/shear forces are obtained. Rigid Plastic Finite Element Method (RPFEM) is used throughout this research as a numerical tool in the study of stability problems. Thus, these illustrations will offer the practicability of the proposed mechanism in the design and analysis of the reinforced soil structure considering both serviceability and stability aspects.

A series of medium sized 1g model tests were carried out to verify the methodology in addition to the ideal foundation, excavation, slope stability problems. Steep and mild slope surfaces were unreinforced, reinforced and reinforcement connected with flexible and rigid facing panels were tested. The steep slope was tested under long reinforcements in addition to the reinforcement lengths equal to footing width. The tests clearly shows the effectiveness of reinforcements and use of facing panels shows more effectiveness in the distribution of reinforcement force, prevention of local failures near slope faces and reduction in vertical and horizontal deformations. It is shown by numerical simulations that the proposed mechanism and numerical procedure work well in such real data in addition to the aforesaid typical ideal soil engineering problems.

Through applications of the proposed methodology to some typical ideal example problems and model test simulations, the general tendency of solutions provides information/confidence enough for practicing engineers in order to make up their engineering judgment whether the method is applicable to daily design works or not.

1.2 SCOPES AND OBJECTIVES OF STUDY

An attempt is made to formulate a set of mechanism of reinforced soil mass from initial loading to the limiting equilibrium state. The RPFEM and LEFEM are used as general framework in this study because these methods appeal to only very few assumption/idealizations instead of depending on large number of unrealistic idealizations. Comprehensive medium sized 1 g model test were carried out on unreinforced, reinforced and reinforced with panel faced soil slopes.

In this study, a set of mechanisms to describe the behavior of reinforced soils is developed based on some assumptions and hypotheses in conjunction with well known constitutive models in the theory of elasticity and plasticity. A rigid plastic stress-strain model to describe the Mises material e.g. purely cohesive clay is extended to the non-dilatant frictional (c-ϕ) material. An attempt is made to describe the non-dilatant plastic material as an assembly of inhomogeneous Mises material whose strength depends on the confining stress. The prediction of F_S, s , $\boldsymbol{u}$, n , x .... from proposed model will then be compared with other predictions as well as the model test results.

This research reviews the development of design criteria for reinforced soil structures especially for foundations, embankment, retaining walls, slope and excavations, with a special attention to the use of linear elastic and stability analysis of these reinforced soil structures. The history and development of soil reinforcement is briefly discussed and the limit analysis based on the rigid plastic finite element model originally pioneered by Tamura et al. (1984) in the field of Geotechnical Engineering, is discussed in detail. Tamura's model is extended to the Stability analysis of reinforced soil structures. The applicability of the proposed scheme is examined/illustrated/demonstrated through some typical soil engineering problems. In this perspective, the current research of the author complement the previous works by Asaoka et al.(1990, 1992) to the reinforced soil structure as a new area of application.

1.3 ORGANIZATION OF THE DISSERTATION

Following the introductory chapter which describes the aim and scope of the work in relation to the current status on the understanding of behavior and mechanism of reinforced soil structure, Chapter II is devoted to a review of the literature associated with the author's work. It deals with history and developments of reinforced soil structures to the philosophy behind the analysis and design of reinforced soil structure and its different components e.g. fill material, reinforcement, facing, to elasto-plastic theories used in the analysis. RPFEM and LEFEM are reviewed in detail in the context of the author's present work.

Chapter III describes the mathematical modeling/formulation of the proposed mechanism of the reinforced soil structure and their incorporation into the LEFEM and RPFEM. The mathematical derivation of the non-dilatant Frictional (c-ϕ) material as assemble of inhomogeneous Mises material is explained and incorporated into the RPFEM. In Chapter IV, some numerical investigations of the proposed model is presented through some typical soil engineering problems where soil is reinforced. In this chapter it is also shown that the axial/shear force along reinforcement develops due to internal action and also shown that the axial/shear force along reinforcement can not be controlled from outside the reinforced soil system in contrast to anchoring of a soil mass to bed rock.

First part of Chapter V is devoted on describing the model-testing program, the testing procedures, test results and discussions. Three series of medium sized 1 g model tests were conducted on silty sand slopes. First series was on mild face slope (1V:0.5H), others were on steep slopes(1V:0.2H) where first two series had reinforcement lengths same as footing length while the third series was on steep slope but the length of reinforcement was longer then the footing length. In the first two series, there were four models in each case while on the last series only two models were tested. The four models series cases had 1. Unreinforced plain slope 2. Reinforced without facing 3. Reinforced with thin panel facing (thickness 3mm) and 4. Reinforced with thick panel facing (5mm thick). In the case of last series where only 2 models were tested, had 1. Reinforced with steel bars without facings and 2. Reinforced with thick facing panels. All models were loaded till failure.

Latter part of the Chapter V presents numerical simulations of the model test results employing the proposed numerical formulation on the mechanism of reinforced soils. Out of the first two series of aforementioned model tests, total six models (3 from each series) are simulated employing the proposed numerical method. As stated before, novel feature of the results presented in Chapter V is that good agreement between the model test results and numerical analysis results were obtained.

Chapter VI presents a typical excavation of soft clay ground. The horizontal reinforcement, e.g. soil nailing, and vertical reinforcements, e.g. 'I' shaped sections or sheet pile are analyzed through the proposed method. A new concept on the vertical reinforcement positioning is proposed based on the reinforcement type. Thus, two types of reinforcements are distinguished, a. reinforcements capable to carry axial forces while the other type is the reinforcements offering very high flexural resistance.

Concluding remarks are made at the end of each chapter and an overall conclusion is also made in Chapter VII.

CHAPTER II REVIEW ON DEVELOPMENTS IN REINFORCED SOIL SYSTEMS

2.1 GENERAL

Strength of the natural /fill soil in earth structures is improved by various techniques, e.g., mechanical processes, chemical process, inserting a strong material into the soil mass (sand compaction piles, bamboo strip, straw, etc.) and the interesting one is natural plant roots. Besides these natural and traditional techniques, the important development of Reinforced Earth®, and the concept of reinforced soil as construction material, introduced by its inventor French architect H. Vidal, in the sixties, have introduced the modern form of soil reinforcement technique (Schlosser and Delage, 1987). This technique has been used in various structures, e.g. slopes and embankment, retaining walls, foundations, dams and others. Mitchell (1981) noted that no other soil improvement techniques have been so intensively studied and having advanced application in the past several years, as has soil reinforcement.

The concept of soil reinforcement is based on the existence of strong soil-reinforcement interaction like roots, due to their tensile strength and frictional or adhesion properties reinforce the soil. Many hypotheses have been postulated, in the past 25 years, about the load transfer between the soil and reinforcement and their interaction. A lot of research has been carried out to find suitable method for the analysis and design of reinforced soil structures.

There are three basic categories of literature available relevant to this research work. The first category is on the type of reinforced soil structures e.g. foundations, embankments, retaining wall, slopes and excavations. The second, the most important category is on the development of the components of the reinforced soils. The third category is devoted on analysis and design of the reinforced soil structures. The selection of the material contained in this chapter is perhaps somewhat deliberate in the sense that it covers those aforesaid three aspects of reinforced soil structures.

2.2 HISTORY AND DEVELOPMENTS ON REINFORCING SYSTEMS

Development of Reinforced Earth®:

Henri Vidal in 1963 invented the Reinforced Earth® and much of the current development can be attributed to his pioneering work. Vidal introduced the basic mechanism underlying reinforced soil behaviors in his first paper published in 1966. Reinforced Earth® is a composite construction material (Fig. 2.1a) in which the strength of fill is enhanced by the addition of strong inextensible as well as extensible reinforcing materials. The basic mechanism of Reinforced Earth involves the generation of frictional interaction between soil and reinforcements (Schlosser and Delage, 1987).

York Method:

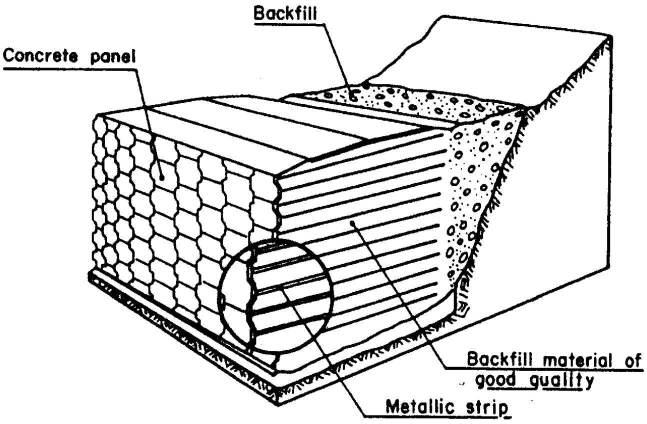
Jones (1973) developed the York method (Fig. 2.1b), which is similar to the Reinforced Earth technique except two minor differences, regarding facing units and sliding mechanism of reinforcements. The York method is the first reinforced soil wall totally built with plastic material (Schlosser and Delage, 1987). According to Jones (1978), differential settlements can easily be accommodated in the sliding mechanism.

GRS-RW System:

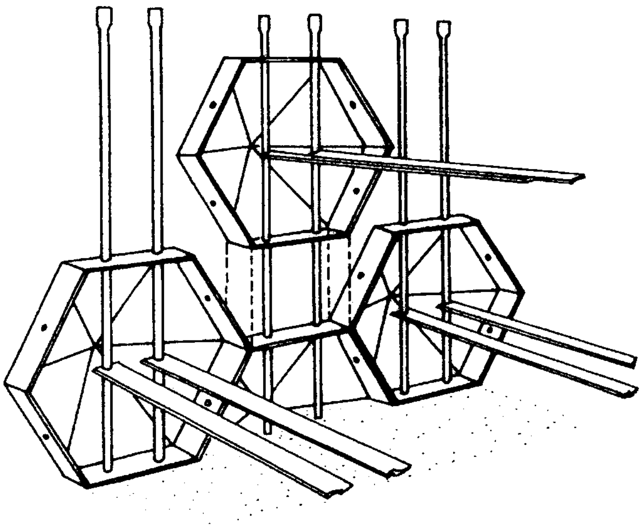
Geosynthetic-reinforced soil retaining wall (GRS-RW) system, developed in Japan, is a hybrid wall system of mechanically reinforced earth wall with a cast-in-place full-height rigid facing and a schematic diagram is shown in (Fig. 2.1c). Some advantages of GRS-RW system are small lateral deformation due to full height continuous rigid facing, and excavation may not be required because of short reinforcements. This system can be used in sites e.g. bridge abutment or laterally loaded walls.

Miscellaneous:

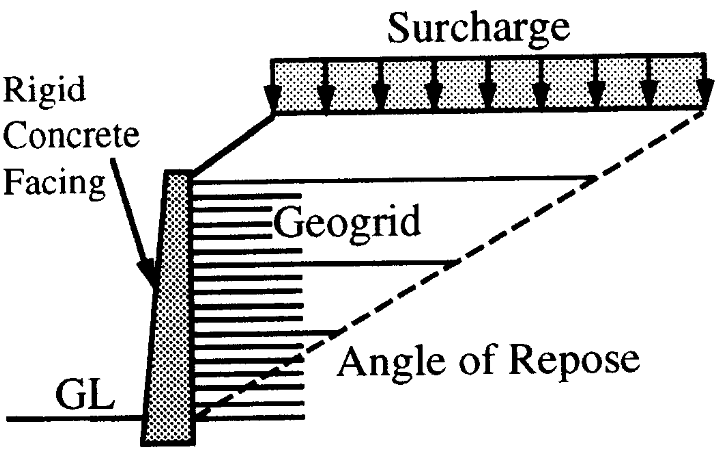
There are several other reinforcing systems developed by many manufacturers used for particular purpose and suitable for typical site conditions. Tervoile, Websol system, Cellular Confining system, Genesis Highway Wall System consisting of Tensar structural geogrids, Con-wall system, etc. are interesting systems to be noted here.



(a) Typical *Reinforced Earth*® system (*Schlosser and Delage*, 1987)



(b) York Method (Sliding method of construction) (*Jones*, 1992)



(c) Geosynthetic reinforced soil-rigid wall (GRS-RW) system (*Tatsuoka*, 1994)

Figure 2.1 Schematic diagram of typical reinforced soil systems.

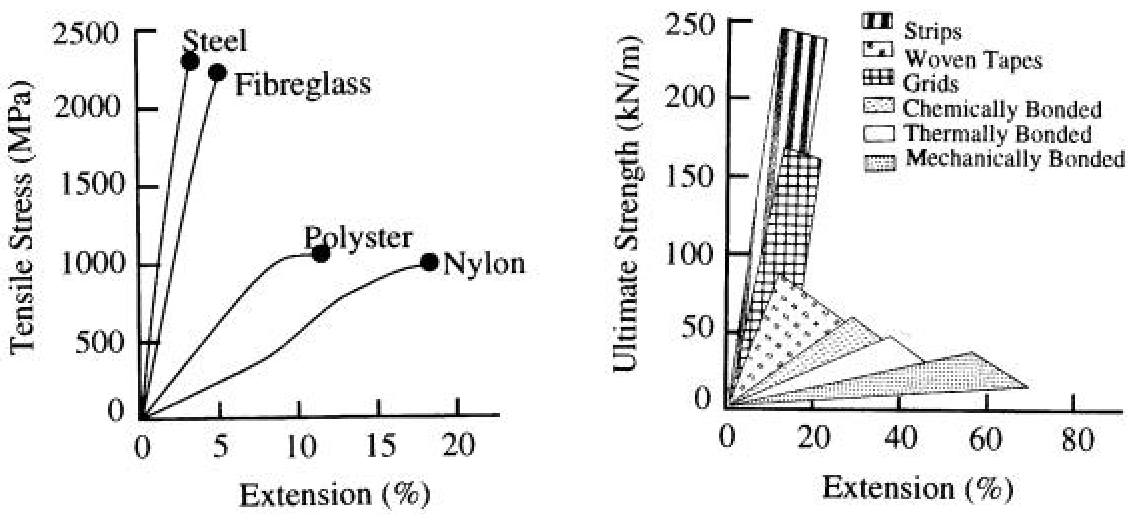
2.3 TYPES OF REINFORCING MATERIALS

In the literature, there mainly two groups of reinforcements, extensible and inextensible, are discussed with respect to the stress-strain response of soil mass. Stress-strain characteristics of typical inextensible and extensible reinforcing materials are illustrated in Fig. 2.2. McGown et al. (1978) originally defined inextensible and extensible reinforcements and Bonaparte et al. (1987) extended as follows:

a. Inextensible reinforcement is reinforcement used in such a way that the tensile strain in the reinforcement is significantly less than the horizontal extension required to develop an active plastic state in the soil. An "absolutely" inextensible reinforcement is so stiff that equilibrium is achieved at virtually zero horizontal extension (K_o conditions prevail)

b. Extensible reinforcement is reinforcement used in such a way that the tensile strain in the reinforcement is equal to or larger than the horizontal extension required developing an active plastic state in the soil. An "absolutely" extensible reinforcement has such a low modulus that virtually no tensile forces are introduced to the soil mass at the strain required to develop an active plastic state (K_a conditions theoretically prevail)

Bonaparte et al. (1987) considered steel reinforcement as an inextensible reinforcement and geosynthetic reinforcing materials as extensible reinforcements, for almost all practical applications. Thus, an inextensible metallic reinforcement makes the structure brittle and the extensible geosynthetic increases the ductility of the reinforced soil structure (Fig. 2.3).



(a) Different material fibers (*Schlosser and Delage*, 1987)

(b) Geosynthetic products (*John*, 1987)

Figure 2.2 Stress-strain characteristics of typical reinforcing materials

2.3.1 Inextensible reinforcements

Steel Bars/fiber glass reinforcements:

The choices on the reinforcing material vary from inextensible reinforcements like steel, fiberglass to extensible polyester resins. Galvanized steel has been used in wide variety of environments over very long periods, thus, its corrosion mechanism and the rate of corrosion have been known for long time. Similarly, polyester coated fiberglass, stainless steel and aluminum are also used. The corrosion rate of these metals is faster than galvanized steel. Despite these drawbacks, the steel and fiberglass reinforcing materials have also gained popularity specially when the construction requires less post construction deformation such as in the case of bridge abutments, railway embankments, etc. The advantage of steel and fiberglass is due to their unique combination of elasticity, ductility/stiffness and favorable economics. Bonaparte et al.(1987) states that the tensile stiffness of steel reinforcements is stiff enough to keep the state of soil stress close to the at-rest (K_o) condition.

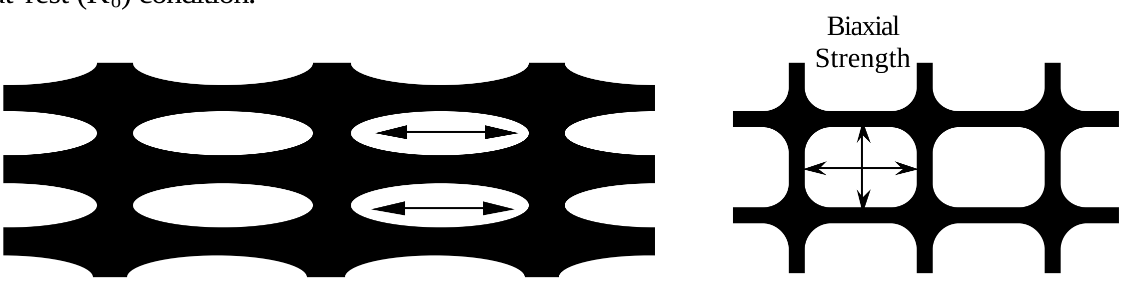
(a) Series failure (inextensible reinforcements) (b) ...ements

Figure 2.3 Analogy of reinforced soil fail mechanisms (*Jones*, 1992).

2.3.2 Extensible Reinforcements

Geosynthetic and related products:

Major geosynthetic materials currently used as reinforcements in soil structures are geogrid sheet (*see* Fig.2.4), woven and non-woven geotextile sheet, coated fiber strips, rigid plastic strips, composites and three-dimensional honeycomb type products. Geosynthetic materials have large ranges of deformation modulus and tensile strengths compared to metals (see Fig.2.2). Geosynthetic materials also exhibit creep behavior. Bonaparte et al.(1987) has grouped geosynthetic reinforcements as extensible reinforcements, thus, the state of soil stress is far from at-rest (K_o) condition.



(a) Uniaxial geogrid (b) Biaxial geogrid

Figure 2.4 Typical geogrids used as soil reinforcements (*John*, 1987).

2.3.3 Miscellaneous

There are several other types of reinforcing materials used for particular purposes. Small inclusions (fibers, small plates) or continuous filaments (e.g. Texsol) are some typical reinforcing materials. Sometime natural materials (e.g. bamboo, jute) are also used as reinforcing material. In UK and USA, redundant car tires have been used as reinforcement.

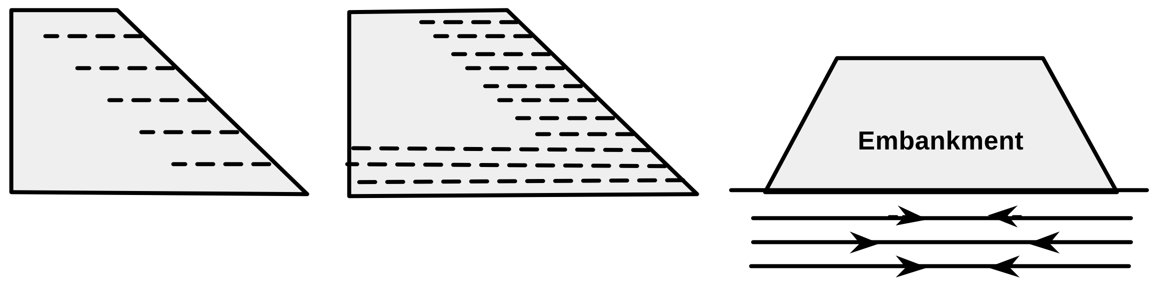
2.4 APPLICATIONS OF REINFORCED SOILS

More common applications of reinforced soil are in the form of retaining walls. Reinforced soil structures can be grouped into three classes (Ingold, 1982), (a) Embankment and retaining walls, (b) Foundations / sub-soil reinforcements and (c) In-situ reinforcement (*soil nailing*)- existing slopes and excavations.

2.4.1 Embankments/ Retaining Walls

Several reinforcing systems with varieties of reinforcing materials and facings have been successfully used to construct many reinforced embankment and retaining walls (e.g. Yamanouchi, 1988; McGown et al., 1991; Ochiai et al., 1992). Some of them are very tall and long e.g. 2000m of 2~3m height (Tatsuoka et al., 1994).

A primary role of reinforcement in an embankment or a retaining wall is to support the outward earth pressure (lateral thrust) in the fill while maintaining the full bearing capacity in the foundation (e.g. Ingold, 1982; Gourc, 1993). The reinforcement provided at the embankment base prevents lateral displacements of the embankment and foundations soils, subsequently the bearing capacity of the soft soil and stability of embankments are increased significantly (Madhav, 1993). Purpose of these reinforcements is to perform as (i) superficial slope reinforcement and edge stiffening; (ii) main body reinforcement; (iii) reinforcement at the base of the retaining walls. Reinforcement in the main body is essentially the major application of reinforcement in reinforced embankment or retaining wall structures.

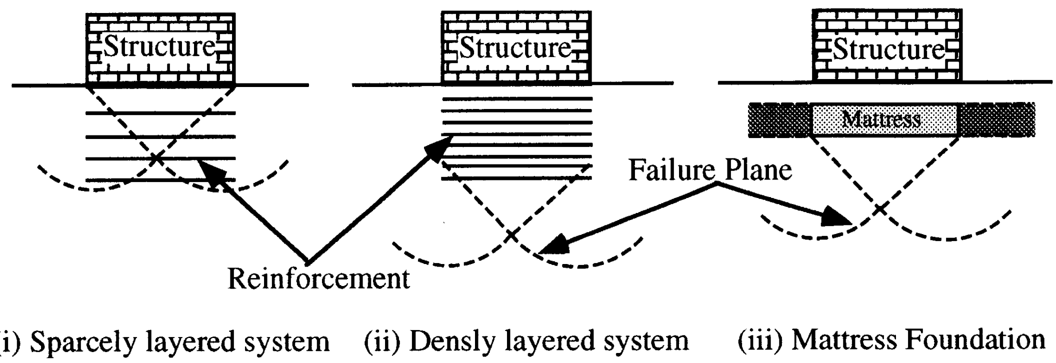


(a) Superficial reinforcement (b) Body reinforcement (c) Foundation reinforcement

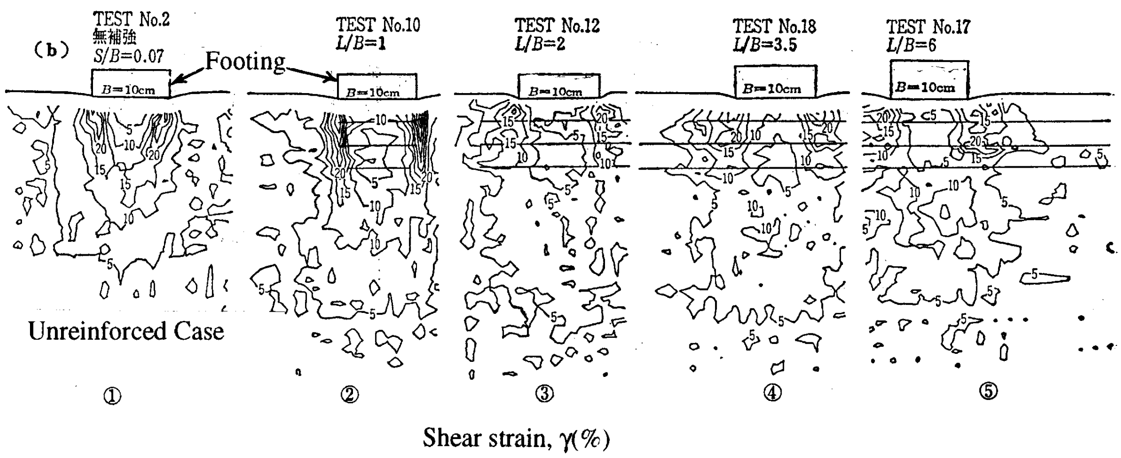
Figure 2.5 Embankment reinforcing modes (*Ingold*, 1984).

2.4.2 Subsoil Reinforcement Beneath Foundations

In the soil beneath the reinforced soil foundation two distinct zones are formed (e.g., Binquet - Lee, 1975), and John, 1987) as shown in Fig. 2.6. In the first zone, the wedge of soil directly beneath the structure is forced vertically downwards (punching failure) whilst outside the footing, there are symmetrical zones which have both lateral and upward movements, the function of an effective reinforcement being to hold these two zones together. Binquet-Lee (1975), Oka et al. (1992), Takemura et al.(1992) and other researchers reported that the maximum bearing capacity ratio occurs at a depth ratio 0.8 to 1.0.



(a) Critical zones beneath reinforced foundations (*Fukuda et al.*, 1987)



(b) Experimental observation (*Tatsuoka*, 1992)

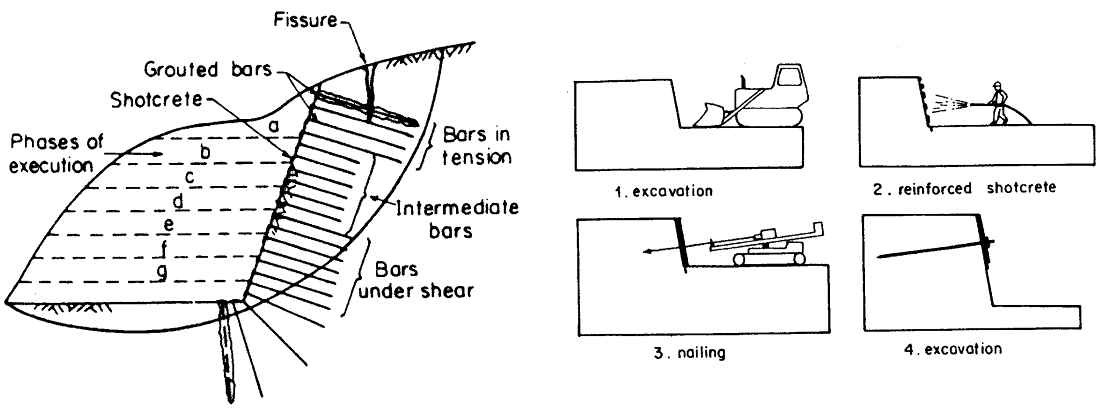
Figure 2.6 Effect of sub-soil reinforcements.

2.4.3 In-situ Reinforcement (*soil nailing*): *slope stability/excavation.*

Soil nailing is an in-situ soil reinforcement technique, which has been used during the last two decades. Soil nailing is being used at present to stabilize natural slopes, cuts or excavation, walls in stiff clays, granular soils (with some suction) and also soft rocks. The purpose of this technique is essentially to limit the decompression and the opening of pre-existing discontinuities by restraining the deformations. They are usually steel rods 20-30 mm in diameter that are inserted into the soil either by simple driving or by grouting in predrilled borehole (Fig.2.7). Soil nailed slopes behave like a reinforced soil wall although there are some major differences between these two techniques (John, 1987), e.g.,

i. Construction method: Soil nailed slopes have top-downwards construction method whereas reinforced soil walls are constructed from the bottom upwards
ii. Shear and bending stresses may develop in soil nails depending on the stiffness of the nails relative to soil, while this is not generally observed in soil reinforcements.
iii. Soil nailing is applied to existing soil slopes and may therefore involve more cohesive soils than the selected fills used for reinforced soil walls.
iv. Soil reinforcement sheets or strips are usually laid horizontally, whereas soil nails are usually driven at an inclined angle.

Schlosser (1982) observed that the active failure zone for nailed slopes was similar to, but larger than, that of a reinforced soil wall. In both cases, the active failure zone is smaller than the standard Coulomb active wedge assumed with the other retaining structures. He suggested that this difference in behavior is attributable to the inclination of the soils nails.



(a) Typical soil nailed structure.
(*Schlosser and Juran*, 1980)

(b) Construction steps
(*Schlosser and Delage*, 1987)

Figure 2.7 Typical in-situ soil-reinforcing techniques.

2.5 CONCEPTS AND MECHANISM OF REINFORCED SOIL

Several experimental and theoretical investigations have been performed since the invention of Reinforced Earth wall (Vidal, 1963) to understand the concepts and mechanism of reinforced soil structure and interaction among its basic components, generally, reinforcing elements, backfill soil and facing. H. Vidal, the pioneer of Reinforced Earth system seems to be the first person to propose a general and realistic concept of reinforcing a soil.

Anisotropic Cohesion Concept

Schlosser and Long (1972) indicated that the reinforced soil has higher shear strength than unreinforced plain samples (Fig.2.8a). Hausemann (1976) independently postulated a more unified anisotropic cohesion theory. They have shown that two failure modes can develop in such reinforced sand samples: (a) failure by slippage of the reinforcement at low confining pressure leading to a curved yield line passing through the origin and (b) failure by reinforcement breakage at higher confining pressure leading to a straight failure line which proves that the reinforced sand behaves as a cohesive material having the same frictional angle as the original sand and an anisotropic pseudo-cohesion due to reinforcements as shown in Fig. 2.8b. This pseudo-cohesion is very rapidly mobilized at low axial deformations.

Enhanced Cohesion Concept

Chapius (1972) and Yang (1972) independently presented *enhanced confining pressure concept* on the mechanism of reinforcing a soil mass. This concept is based on the assumption that the horizontal and vertical planes are no longer principal stress planes due to the shear stresses induced between the soil and reinforcements. Mohr's circle of stress is shifted due to reinforcing of the soil mass (Fig. 2.8b) while failure envelope remained same for both reinforced and unreinforced samples. Such effect is called enhanced confining pressure effect.

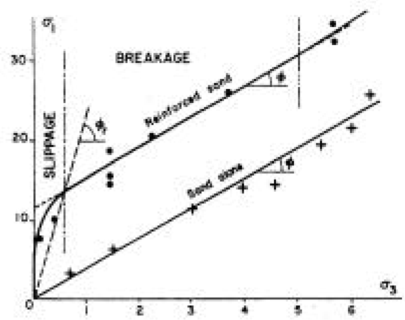


Figure 2.8a Reinforced and unreinforced samples in triaxial tests (*Schlosser et al., 1972*)

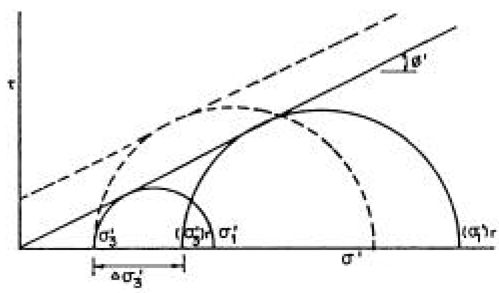


Figure 2.8b Anisotropic Cohesion and Enhanced Cohesion Concepts (*Ingold*, 1984)

Basset and Last (1978)

Basset and Last (1978) considered that the mechanism of tensile reinforcement involves anisotropic restraint of the soil deformations in the directions of the reinforcements. Using Roscoe's failure criteria for sands based on zero extension concepts, they demonstrated that the presence of the reinforcement leads to rotation of the principal directions of the deformation tensors. Reinforcements should be aligned with the zero extension lines, thus, exhibiting a vertical failure surface. Thus, the stress and the strain patterns are greatly modified due to the soil-reinforcement interaction (Fig.2.9).

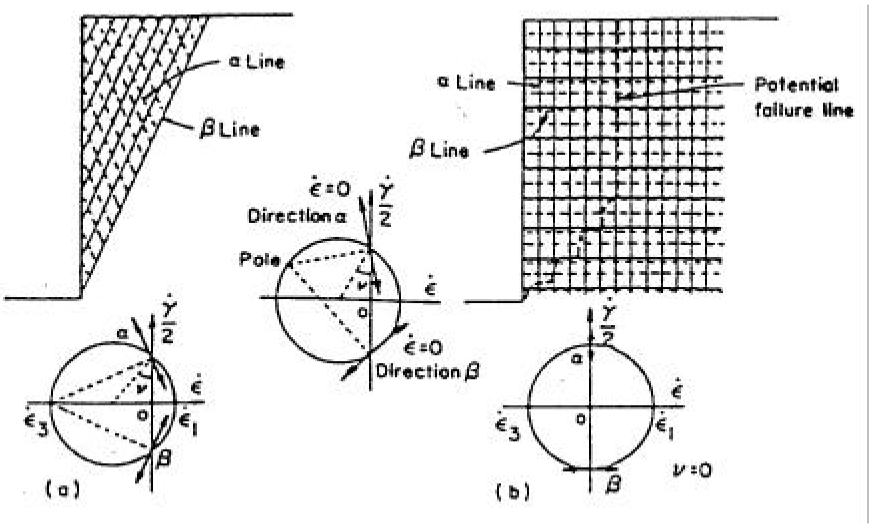


Figure 2.9 Influence of reinforcements on potential failure lines (*Basset and Last*, 1978)

2.6 BEHAVIOR OF REINFORCED SOIL STRUCTURES

In the analysis and design of reinforced soil structure, stability and deformation are considered both critical and independent concerns for a soil structure and they are always dealt separately. Past research reveals that major work was concentrated on stability analysis compared to the deformation problems. In deformation analysis, serviceability with respect to excessive differential settlement and horizontal deformation of the slope face are considered important. The stability analysis of reinforced soil structures is divided into internal and external stability analyses (Gourc, 1992; Rowe and Ho, 1992) as will be illustrated in later sub-sections.

Rowe and Ho (1993) suggested that the overall behavior of a reinforced soil structure may be considered known if one understands:

a. State of stress within the reinforced soil mass.
b. State of strain in both the soil and the reinforcement.
c. Axial force distribution in the reinforcement.
d. Horizontal soil pressure acting at the back of the reinforced soil mass and the vertical soil

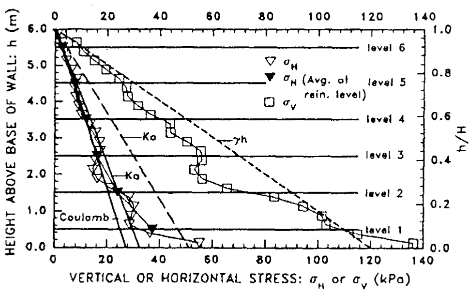
pressure at the base.

e. Vertical soil stress on each reinforcement layer.
f. Horizontal soil pressure acting at the face.
g. Horizontal and vertical forces transferred to the wall face.
h. Horizontal deformation of the reinforced soil mass
i. Effect of varying the design parameters (i.e. reinforcement stiffness, soil properties, facing stiffness, foundation stiffness, surcharge condition, construction procedures, etc.) on the response of the system.

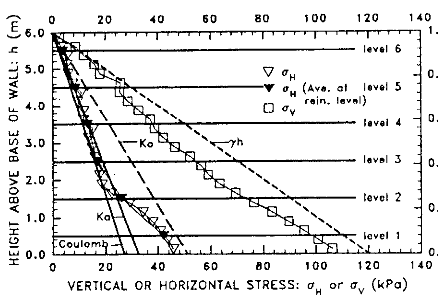
2.6.1 Vertical and Horizontal Soil Stress Distribution:

Several types of vertical stress distribution patterns are assumed in the analysis and design of reinforced soil mass. Uniform, trapezoidal, Meyerhof distributions and 2:1 stress dispersion method are typical examples. Maximum stress is attained within the reinforced zone. Close to the far end of reinforced zone the vertical soil stress reaches a minimum. Further away into the unreinforced retained fill, the vertical soil stress attains the minimal value. The vertical soil stress close to the facing depends on the facing rigidity (Tatsuoka, 1993). Rigid facing decreases the vertical soil stress close to the facing due to load transfer from the soil to the facing. Such effect of the facing leads to higher reinforcement force and requires higher bearing capacity in the design of foundations.

Horizontal soil stress primarily depends on the number of reinforcement layer, the stiffness and the creep of the reinforcement and the degree of yielding of the wall face as shown in Fig.2.10. Relative deformation of the wall face and soil with the reinforcement results increased transfer of horizontal stress to reinforcement rather than to facing. The horizontal soil stress increases as the number of reinforcement layers is increased. Rowe and Ho (1993) noted that there are no literatures giving any real observed information on the horizontal soil stress distribution further back into the reinforced soil.



(a) at wall face



(b) at back of reinforced soil block

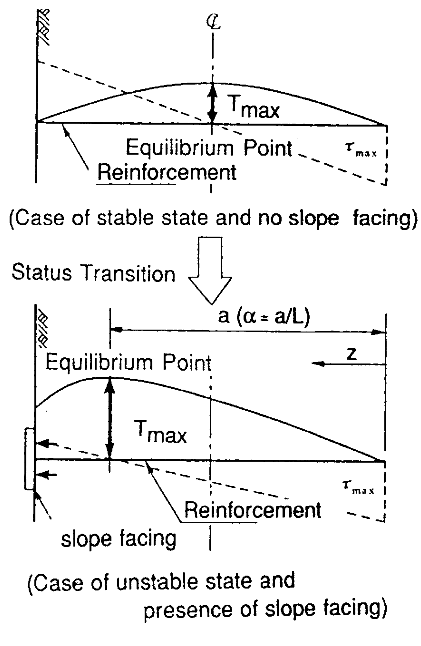
Figure 2.10 Vertical and Horizontal soil stress distributions from numerical analysis (*Ho and Rowe*, 1992)

2.6.2 Force in Reinforcement

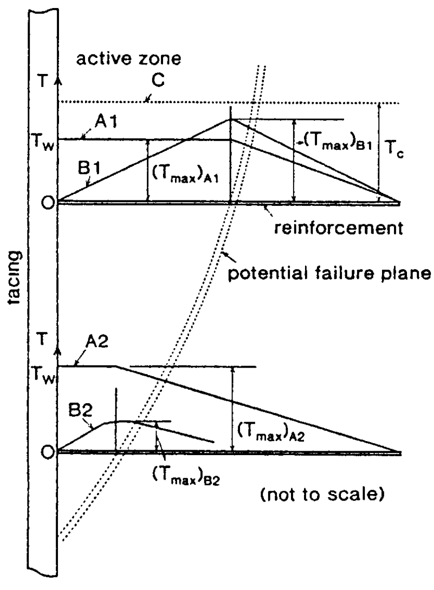
The magnitude of reinforcement force primarily depends on the shear strength mobilized in the backfill, the horizontal soil strain, the stiffness of the reinforced system, and the creep of reinforcements. Maximum tensile force close to toe is usually observed less than predicted by the Rankine active condition (Lesniewska, 1992; Bathurst et al.,1988). Fannin (1991), Jewel (1987) and Ho-Rowe (1992) indicated that the maximum force in reinforcement becomes more uniform with decreasing reinforcement stiffness and lower near the bottom due to the influence of foundation.

Variation in soil properties and construction methods results shifting of the position of maximum tensile forces away from the failure plane. It also depends on the length and stiffness of reinforcements. Jewell (1987) stated that the locus of maximum tensile force will always be inclined to 45 + $\phi/2$ to the horizontal if the soil-reinforcement interface is sufficiently bonded, otherwise, the locus will move towards the facing. The maximum tensile force shifts towards the facing in the case of short reinforcements.

Force distribution in a reinforcement layer: The force distribution in a reinforcement layer is most influenced by the construction method, the existence of facing, the lateral restraint of facing during construction and the facing reinforcement connections. There are two general type axial force distributions (e.g. Muramatsu et al., 1992 and Tatsuoka, 1992) as shown in Fig.2.11(a).



(a) Muramatsu et al. (1992)



(b) Tatsuoka (1992)

Figure 2.11 General tensile force distribution patterns along a reinforcement.

Type A: This pattern is observed when lateral deformation of the wall face is restrained till the end of construction, e.g., ideal pull-out test. In this situation the maximum tensile force is induced at the back of the facing and remains more or less constant up to the potential failure plane and decreases to zero close to inner end of the reinforcement (e.g., Jowell, 1987 and Tatsuoka, 1993) When perfect lateral restraining of facing during construction is not possible, the tensile force in the reinforcement at the back of facing may be much smaller than its maximum value attained near the potential failure surface.

Type B: The parabolic tensile force distribution is observed when facing provides little or no lateral restraint against deformation e.g. wrapped back facing, slope face without any facing. The maximum force in the reinforcement is assumed to occur at the potential failure plane as shown in Fig. 2.11(b).

2.6.3 Horizontal Displacement

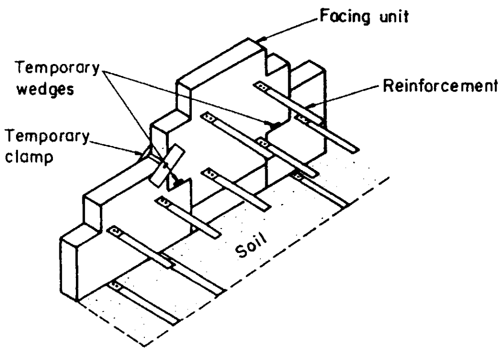
Magnitude of horizontal movement depends on the interaction between various components of reinforced soil structure and construction methods. Higher reinforcement density and stiffness reduce the strain in the soil, and larger shear strength of fill results in less force in the reinforcement, being required to maintain equilibrium and hence less deformation. The soil movement behind the reinforced zone depends on the strain level of the unreinforced zone above the stable slope.

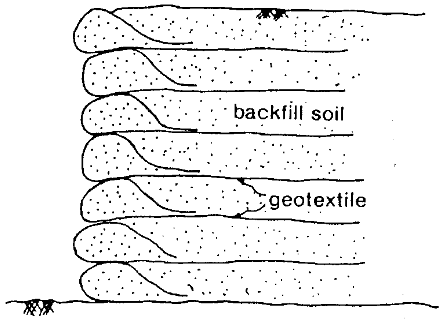
2.6.4 Role of Facing rigidity:

Currently, facing material ranges from rigid full-faced concrete facing to flexible wrapped around geosynthetic facing as shown in Fig. 2.12(a~h). Most of the soil reinforced stabilization techniques assume that facing does not play a significant structural role; they are rather used for aesthetic reason (e.g. Vidal, 1978; Bruce and Jewell, 1986). However, Tatsuoka (1993) has demonstrated the roles of the facing in improving the stability of reinforced soil structures based on extensive literature review. Horizontal movement of the wall face and subsequent earth pressure development within the reinforced zone as well as the reinforcement force are significantly affected by the facing rigidity.

Tatsuoka (1993) has classified various types of facing according to the degree of facing rigidity. The facing rigidity increases the stability of wall in the following three ways:

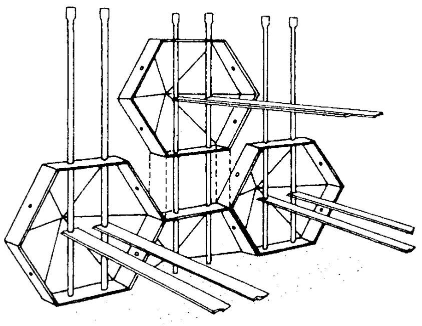
1. Rigid facings (Types D and E) support the combination of earth pressure and tensile force in reinforcement.
2. Weight of backfill is partly transmitted to the facing through the frictional force on the back face.
3. Due to high confining pressure behind rigid facing, the location of the overall reaction force becomes closer to the facing.

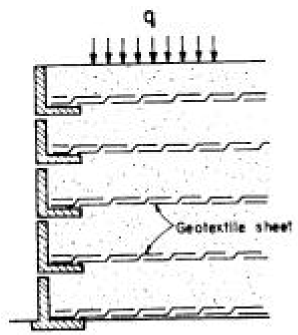




(a) Concrete Panel facing (*Reinforced Earth® system*)

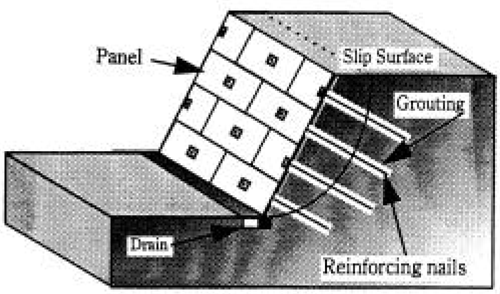
(b) Wrapped around facing

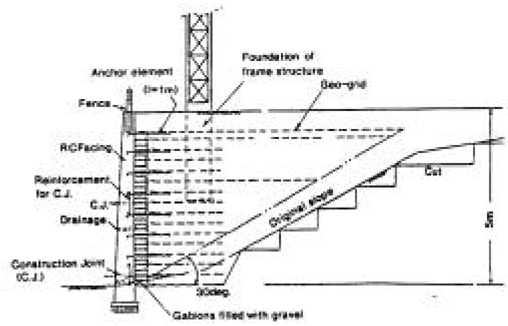




(c) York wall facing (*Jones*, 1992)

(d) L-shaped concrete facing (*Broms*, 1988)





(e) Reinforced Concrete Panel (Japanese system)

(f) Full Height Rigid Reinforced Concrete Facing (GRS-RW System)

Figure 2.12 Currently used typical facings in reinforced soil structures.

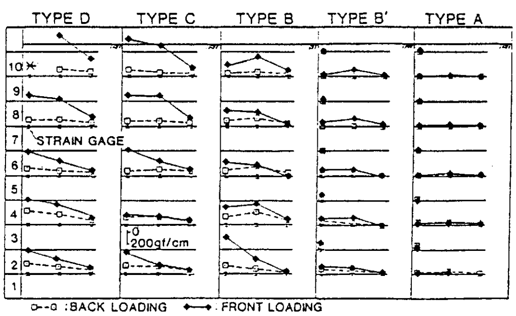


Figure 2.13 Observed tensile force distributions along reinforcement corresponding to different facing rigidities (*Tatsuoka et al.,* 1989)

Tatsuoka et al. (1989) studied the effect of facing rigidity in a set of GRS-RWs model tests having facing Types A~D. The test result reveals that the location of failure surface moved from an intermediate elevation to the bottom of the facing depending on the facing rigidity. The ratio of earth pressure p_f on the back of the facing to q_u remained almost constant with the facing rigidity. Similarly, the tensile force just behind the facing is greatly influenced by the facing rigidity (see Fig.2.13). Location of T_{max} (Fig. 2.11) approaches back of the facing with increasing facing rigidity. Thus, the contribution of the facing rigidity on the stability of the reinforced soil structure was clearly demonstrated and similar conclusions are also reported by several other researchers (e.g., Juran-Schlosser, 1978, Bolton-Pang, 1982, and Koga et al., 1992).

2.7 TYPICAL CURRENT DESIGN METHODS

For the analysis and design of reinforced soil structures numerous approaches have been developed. All methods are either empirical in nature or based on limit equilibrium analysis. These methods don't consider either the stress-deformation characteristics of the structure or the interactions between the wall components e.g. the soil, the reinforcement, the facing and the foundation. Their main purpose is to compute the factor of safety against several modes of failure. In general, the design methods use the allowable strengths (corresponding to each components) which are significantly lower than the ultimate strengths and further partial safety factors are applied to account for the uncertainties in the behavior of the reinforcement and soil/reinforcement interaction mechanism. As a consequence, these methods are lagging in adequately describing the real behavior of the reinforced soil structures. Hence, their application typically introduces an extra level of conservatism. Rimoldi (1988) based on eight case histories reported that current design methods are conservative.

Most of the current design methods can be divided into two main categories. The first category use simple force equilibrium analysis where the horizontal forces developed in the reinforcement balance the destabilizing horizontal force from the soil. The forces considered in these methods are: a. the vertical soil stress, b. the horizontal soil stress, c. the stress in the reinforcement and d. the horizontal resistance to pull-out of the reinforcement behind the potential failure plane. Two independent factors of safety, for reinforcement rupture and pullout resistance, are calculated for each layer of reinforcement.

The methods in the second category evaluate the force and or moment equilibrium on an assumed failure surface similar to conventional slope stability analysis but with the inclusion of the balancing force/moment developed in the reinforcement.

2.7.1 Force Equilibrium Methods

Some of the widely used force equilibrium methods for the design of numerous reinforced soil structures are as follows:

1. Jewell method (1987)- This method was proposed and applied first to predict the performance of Royal Military College trial wall in 1987. In this method, the reinforced soil structure is divided into 3 zones based on the reinforcement force as shown in Fig.2.14

   Zone-1: The zone between the wall face and the most critical surface where the reinforcement force required to maintain equilibrium is constant (i.e. between the surface and wall face). Thus, the most critical surface was defined as a surface through the toe that requires the greatest total reinforcement force to maintain equilibrium on this surface. The surface in vertical wall case is inclined at an angle $\theta=(45+\phi/2)$ to the horizontal as shown in Fig.2.14

   Zone-2: This zone is confined between the aforesaid most critical surface and the locus of zero required force as shown in Fig.2.14. A surface beyond which no additional stresses are required from the reinforcement to maintain equilibrium is called the locus of zero required force. Ideally beyond this zone the reinforcement can be truncated and equilibrium can be maintained by soil itself. Such length of the reinforcement is called the ideal reinforcement length.

   Zone-3: The zone beyond the locus of zero required force is in equilibrium without requiring any reinforcements.

Jewell (1987) proposed uniform spacing and ideal spacing pattern for reinforcement spacing. He further explained a truncated length concept and consequences of the truncation in the design. He also provided several design charts.

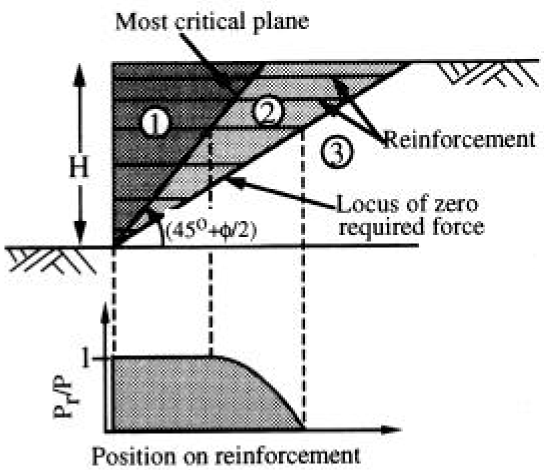


Figure 2.14 Reinforcement layout and force distribution for ideal length case.
(*Jowell, 1987*)

2. Bonaparte et al. method (1987) - In this design method, the extensible and inextensible reinforcements are clearly distinguished. Then, the influence of reinforcement extensions is evaluated by defining hyperbolic relations between K~ε_h. Detailed explanation about the method may be referred to Bonaparte et al.(1987).
3. Tie back design method (1978)- Tie back method was originally developed by the U.K. Department of Transport (1978) and is based upon limit equilibrium methods. It is independent of the reinforcement material and is used with both inextensible and extensible reinforcement and with anchors.

2.7.2 Slope Stability Methods

Many basic methods have been derived from the conventional slope stability studies; the most widely used (Rowe and Ho, 1992; Smith, 1992) being the Fellenius or Bishop methods or the Wedges methods. There are three noticeable differences among these methods as follow: a. the shape of the failure surface b. the distribution of force in the reinforcement and c. the means by which a surcharge is considered. Typical slope stability methods are as follows:

Fellenius Method:

In this method, it is assumed that for each slice the resultant of the interslice forces is zero. Taga et al.(1992) have summarized all the possible combination of various forces based on the Fellenius (simplified) method used in the analysis and design of reinforced soil structures where the basic computational formula used is as follows (*refer* Fig. 2.15):

$$\textit{Sliding Safety Factor, } F_s = \frac{\textit{Force resisting sliding}}{\textit{Force inducing sliding}} = \frac{\sum\left[cb + W\cos a \tan f\right]}{\sum W \sin a} \qquad \text{...(2.1)}$$

where,

W: weight of sliced blocks
b: length of sliding plane in sliced block
f: Internal friction angle of sliding surface
c: cohesion of sliding surface
α: inclination of sliding surface with horizontal.

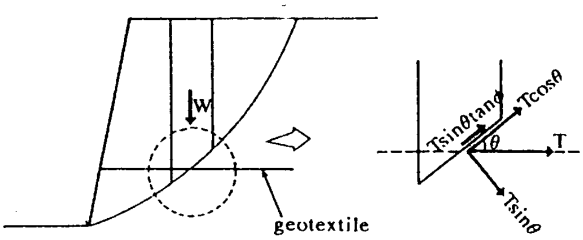


Figure 2.15 Fellenius method of analyzing reinforced soil structures

There are two reinforcement effects of the tensile force generated in the reinforcements in the sliding surface (see Fig. 2.15).

(1) Anchoring effect, T $\cos\alpha$

(2) Confining effect, T $\sin\alpha$. $\tan\phi$

Regarding the confining effect (2), involves the equation, Eq.(2.1), and regarding the anchoring effect, two possible conditions arise, it may be considered as a resisting force (numerator) and as a sliding forced (denominator). Sometime, both effects are considered simultaneously together depending on the problem. Thus following five combinations can be derived by coupling these two effects with the Eq.(2.1).

Formula (a)

$$F_S = \frac{\sum\left[cb + W\cos a \tan f + T\cos a\right]}{\sum W \sin a} \qquad \text{...(2.2)}$$

Formula (b)

$$F_S = \frac{\sum\left[cb + W\cos a \tan f\right]}{\sum (W \sin a - T\cos a)} \qquad \text{...(2.3)}$$

Formula (c)

$$F_S = \frac{\sum\left[cb + W\cos a \tan f + T\sin a \tan f\right]}{\sum W \sin a} \qquad \text{...(2.4)}$$

Formula (d)

$$F_S = \frac{\sum\left[cb + W\cos a \tan f + T\cos a + T\sin a \tan f\right]}{\sum W \sin a} \qquad \text{...(2.5)}$$

Formula (e)

$$F_S = \frac{\sum\left[cb + W\cos a \tan f + T\sin a \tan f\right]}{\sum (W \sin a - T\cos a)} \qquad \text{...(2.6)}$$

Bishop's Method:

In this method, it assumed that the resultant forces on the sides of the slices are horizontal. Thus, moment equilibrium is checked in this method as follows (refer Fig. 3.16):

$$Fs = (M_R + \Delta M_R)/M_D \qquad \text{...(2.7)}$$

where M_D = sliding moment, M_R =resisting moment of soil, ΔM_R =resisting moment of geogrid, ΔM_R =R? T_i, R=radius of slip circle, and ? T_i =sum of tensile strengths of geogrid. A typical formula for computing the factor of safety based on Bishop's Method is:

$$F_S = \frac{\sum\left[cb+(W-ub+P+T\sin g)\tan f\right]}{\sum\left[W\sin a+P\sin a-T\cos(a+g)\right]} \qquad ...(2.8)$$

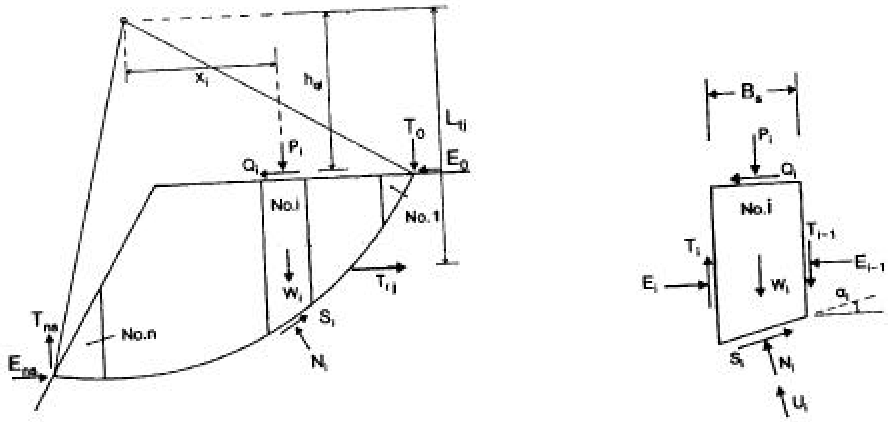


Figure 2.16 Bishop's Simplified Method of analyzing reinforced soil structures

***Trial Wedges Method**:*

Slip surfaces in the trail wedge method can be assumed to be two straight-line slips caused by the horizontal earth pressure, similar to the experimental data.

$$F_S = \frac{\sum T_i}{P_H} \qquad ...(2.9)$$

In this equation, P_H = horizontal earth pressure and $\sum T_i$ = sum of tensile strengths of the geogrid. Total horizontal earth pressure components P_H, of the two straight-line slips, divided into two areas, Zone-1 and Zone-2, as shown in Fig. 2.17, can be obtained based on the concept of force polygons. It can be determined that the embankment is stable when the external force of restraining wall acting is larger than P_H.

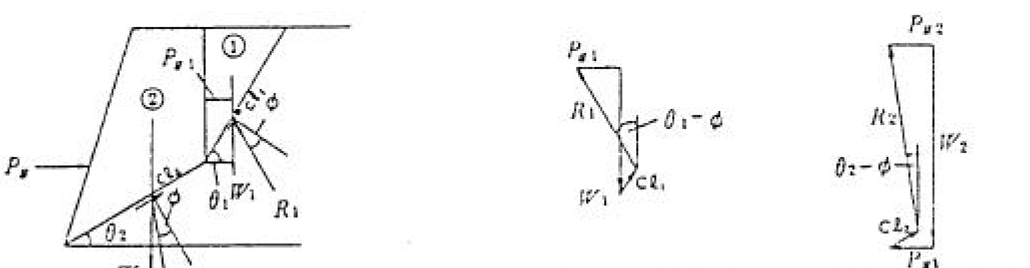


Figure 2.17 Trial wedge method of analyzing reinforced soil structures (*Taga* et al., 1992)

2.7.4 Failure Modes

Sometimes several possible failure modes are checked in reinforced soil walls depending on type of the structure itself and the field conditions. Generally, five independent types of failure (i.e. limit) modes are suggested sufficient enough for most of the geotechnical design problems (Bolton, 1989). These failure modes are grouped into two (external and internal) stability criteria. Typical failure modes that are checked (Jones, 1993) in the design of reinforced soil structures are as mentioned below:

External Stability (Fig. 2.18~19)

a. Vertical and horizontal deformations resulting into unacceptable differential settlement.
b. Lateral sliding of reinforced soil.
c. Overturning failure due to rotation about toe of the wall.
d. Bearing capacity failure (punching) of the foundation soil under the reinforced soil.
e. Overall collapse of the reinforced wall or embankment or nailed slope.

Internal Stability

a. Rupture failure of reinforcement
b. Pull-out failure of reinforcement

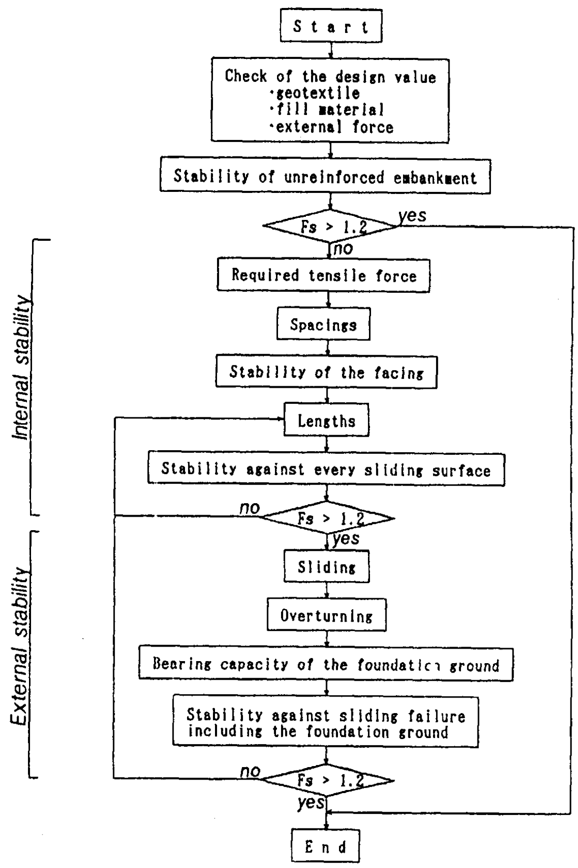


Figure 2.18 Typical flow chart for the analysis and design of reinforced soil structures. (*Onodera* et al., 1992)

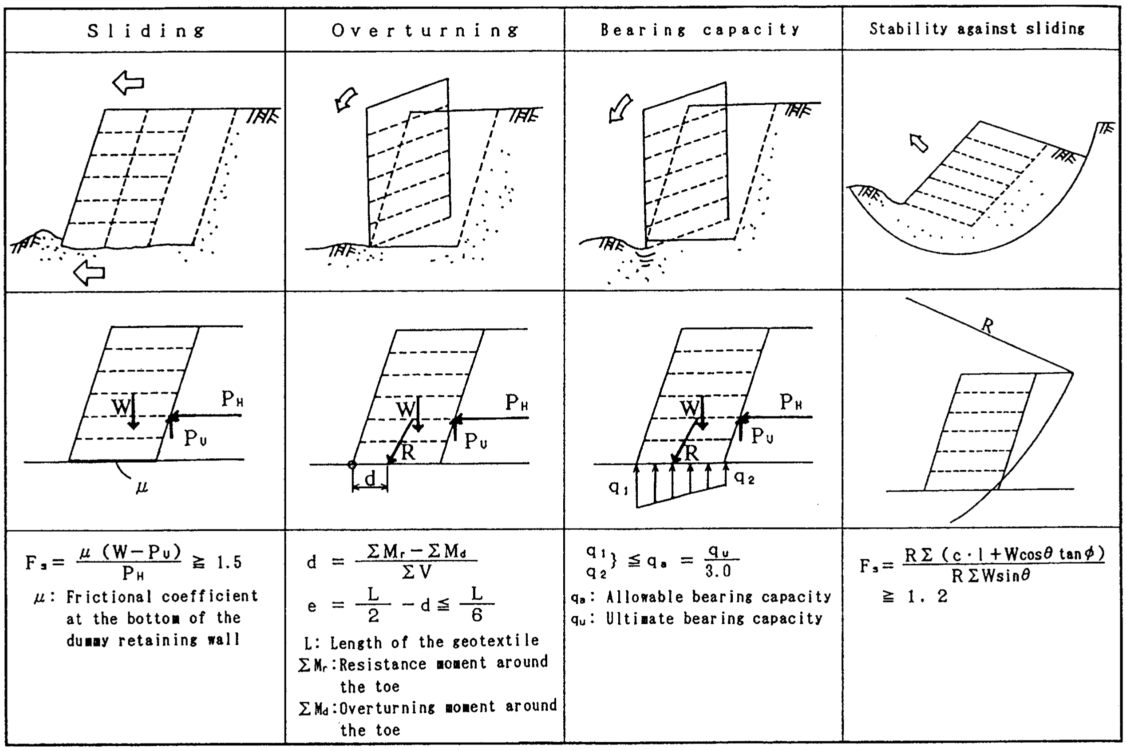
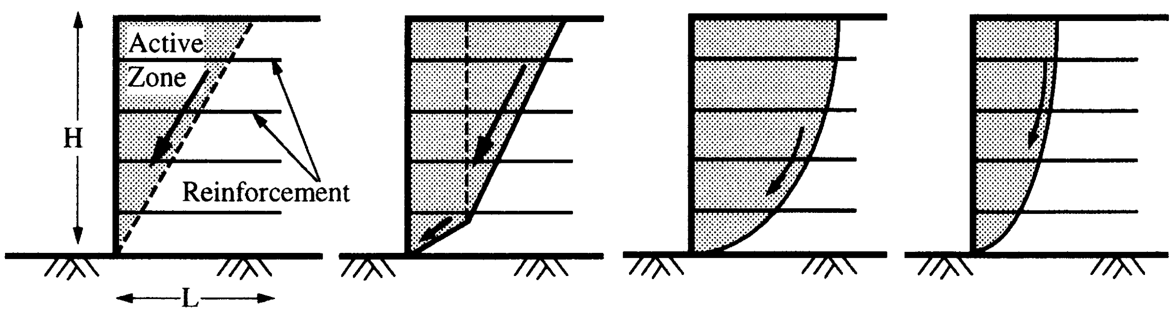


Figure 2.19(a) Typical failure modes to be examined in the design of reinforced soil walls (*Onodera et al.*, 1992)



(a) Straight wedge (b) Two-part wedge (c) Circular arc (d) Logarithmic spiral

Figure 2.19(b) Common shapes for potential failure surfaces for Limit Equilibrium Analysis techniques

2.8 FINITE ELEMENT ANALYSIS

Finite element method (FEM) is vigorous well known method of numerically solving boundary value problems which can accommodate highly non-linear stress-strain relations of materials including even creep, any geometrical configuration with complex boundaries, construction sequence, etc. FEM has been used as the standard tool for the design and analysis (e.g. prediction of safety factor and settlement analysis) of many geotechnical structures. Similarly, it is becoming a design and analysis tool for the reinforced soil structures. These features of FEM can be achieved only when material parameters, constitutive equations and boundaries are appropriately defined or modeled.

2.8.1 Modeling of Components: *soil, reinforcement and facing*

The incorporation of mechanism of soil-reinforcement-facing interaction in the FEM are greatly influenced by the construction method, compaction, propping of facing during construction and its release later including the boundary conditions (loading on top, etc.), thus, making it difficult to model the problem.

Soil: most researchers as pointed out by Gourc, 1992, have adopted non-linear elastic or elasto-plastic models. The initial deformation is sometime calculated using linear elastic constitutive models and failure load is calculated using limiting equilibrium methods employing appropriate constitutive models e.g. Mises or Mohr-Coulomb, Drucker-Prager etc.

Reinforcement: Reinforcement is generally modeled by linear bar element capable of taking only axial tensile forces. Behavior of extensible geosynthetic materials is generally nonlinear. Sometime metallic reinforcements are also modeled as continuous beam element (Kalikan and Xi, 1992) and the bending moment is calculated in addition to the axial force.

2.8.2 Modeling of Soil Reinforcement Interface

Several authors have proposed various types of interface elements to model the interface behavior. Most of the interface elements, originally developed in rock mechanics, are used in the analysis of reinforced soils. Interface elements can be classified (Gens et al.,1989) into the following categories:

a. Standard finite elements of small thickness
b. Quasi-continuum elements possessing a weakness plane in the direction of the interface.
c. Linkage elements in which only the connections between opposite nodes are considered
d. Interface elements in which relative displacement between opposite nodes are the primary deformation variables. They can have finite or zero thickness.

Several differences exist among these methods and the main argument concerns the physical existence of shearing band of soil around reinforcement. FEM methods are based on continuity of soils except the contact plane between soils and reinforcing materials. Goodman element

(1968) is the original interface element introduced in the geotechnical contact problems. This type of interface element is extensively used in the reinforced soil problems. A typical interface element is illustrated in Fig.2.20 below.

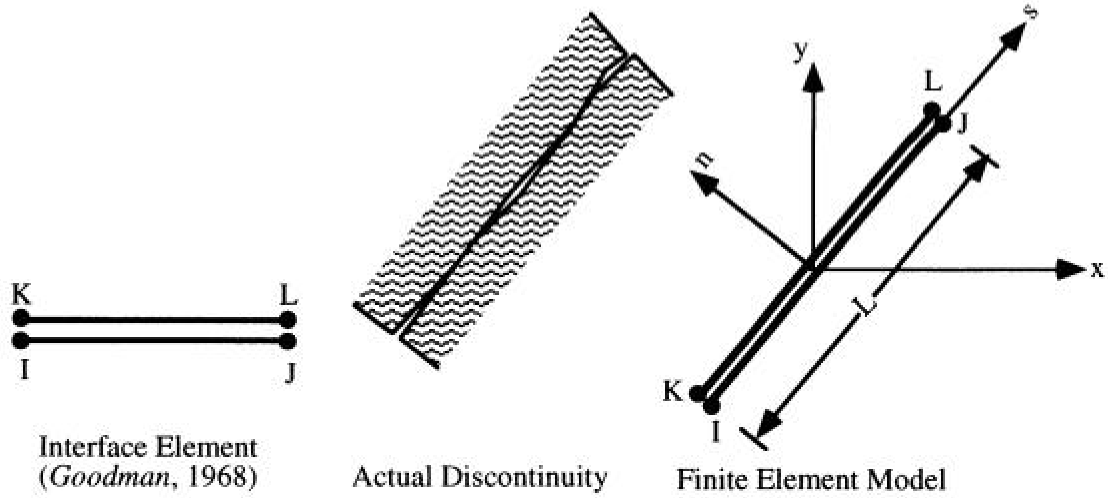


Figure 2.20 A typical interface element used in the modeling of the soil-reinforcement interfaces (*Goodman, 1968*)

2.9 SUMMARY AND CONCLUDING REMARKS

In this chapter, literatures on the existing philosophies of reinforced soil system have been reviewed. The review clearly shows a lot of progress has been achieved since the early publication of Vidal's (1966) concept of soil reinforcement. As Mitchell also pointed out that the research in this field of soil improvement technique has been leading extensively compared to other contemporary soil improvement techniques. In this chapter, the current patterns of the analysis and design of reinforced soil structures are illustrated. It shows similarity as well as diversity in the methodologies and interpretations of results. The following conclusion is drawn based on those preceding sections:

1. Overall strength of the reinforced soil structures increases substantially. Shear stress develops along the reinforcement axis, thus principal stresses also get rotated. The confining pressure and bond length control the maximum tensile force in the reinforcement, and thus, the failure mode of reinforcement is either slippage or rupture.
2. Real reinforcements lie in between two boundaries: inextensible and extensible, which controls the response of the reinforced soil structures. The horizontal earth pressure distribution in the former types (e.g. steel) approaches to K_O condition while in the latter type, it approaches to K_A condition. Creep also affect the structural response and varies with time.
3. Essentially two types of tensile force distribution patterns, with the stiff facing material and without facing material, exist in the literature. The real structure lies in between these two extremes because of yielding during construction.
4. The review by Tatsuoka (1992) on the role of facing has shown significant structural role of the facing in contrast to the conventional assumptions.
5. Force equilibrium and slope stability methods are currently used design methods with some minor modifications. Internal and external stability are checked. All most all the design procedures are over-conservative in nature because of two many unrealistic idealizations. It is because most of the design method are oversimplified and also consist of a lot of design parameters to model the reinforced soil structures. These parameters are difficult to quantify/ identify accurately in the design of real structures.
6. Finite element method (FEM) is getting popular, but, still confined in the research purposes compared to the analysis and design of reinforced soil structures in practice. There are no simple and realistic concepts on modeling the reinforcement and soil-reinforcement interaction and is the main reason for lagging in the application of the FEM into the design of real reinforced soil structures. This aspect is the main fulcrum of the present research.