Chapter 2

LITERATURE REVIEW

2.1 HISTORY OF SOIL REINFORCEMENT

Reinforced soil is a term, which means to enhance the shear strength of marginal as well as good quality soils by including some kind of reinforcing materials whose tensile strength must be greater than that of the soil. The soil or the backfill material ranges from heavily over-consolidated clay to the granular material. While the reinforcing materials include bamboo, geotextiles and galvanized construction steel. Throughout the world, natural reinforcing materials were used from old times. Babylonian constructed ziggurats made of soil mixed with plant stems more than 3000 years ago. Chinese constructed tide embankments by the use of fascine. Romans used mats made of ditch reed. The Gabion was introduced to Japan in 6th century. Dutch used the fascine widely to treat soft ground around the 14th century. Shingen Takeda used various kinds of "ushiwaku" (ox frame), 'ryogyo”, "daiseigyu', which were combinations of bamboo gabions and logs for river improvement. Earth reinforced with timber, straw and reeds, etc., were used from old times in the east and west. Wooden piles were used to prevent a landslide mass in Japan 200 years ago. Originally straw bags filled with soil were used for forming embankments withstood slopes in Japan. The "sumo" wrestling ring began to be constructed using such sandbags since about 400 years ago (Masami Fukuoka, 1988).

A modern method of reinforcing earth is invented by Henry Vidal, a French architect and engineer. His method is named 'terre armee' in French. Thus a new era in soil reinforcement has started with the first retaining walls have been constructed in 1964 and the first paper to have been published in 1966. Reinforced soil is one of the most promising new materials to have emerged in the last 30 years or so, from the intensive research that has been carried out into the alternative construction materials, which would offset the increasing cost of traditional materials. It is being successfully used for ground slabs and foundations, embankments and retaining walls, which constitute its largest application. The former is used in the military as remedial measures against bogging down of the vehicles in weak soils while the latter is used in public works such as slope stability and retaining walls etc.

Reinforced soil is a composite material in which the strength of the engineering fill is enhanced by the addition of strong tensile reinforcement. The basic mechanism of reinforced soil involves the generation of frictional forces between the soil and reinforcing material as was thought in the times of Henry Vidal for strip reinforcement.

But now other agencies for increased shear strength of the composite have been brought to light, like bearing resistance due to the transverse members of the reinforcement, especially grid reinforcement (Chang et al., 1972) and suction forces (this method not yet fully established) between the volcanic clayey ash of Kanto as fill material (water content ranging from 100% to 120% with a degree of saturation of about 80% to 90%) and polypropylene non-woven geotextile (Tatsuoka et al., 1990).

Geotextiles have very well performed as drains by maintaining a high suction at their levels, positive pore pressures were measured during rains. The suction contributed significantly to the stability of the structure by increasing the shear resistance of the soil. The direct contribution of the geotextile on the stability through its tensile resistance is thus increased by an indirect influence through the increased shear resistance of the soil itself. Similar measures have been done in France on a full scale wall constructed using a silt as fill material. Even if these preliminary studies give very interesting results, several points need more research. For example, how is the coupling between the drainage and reinforcements functions, both at short and long term, taken into account in the design. On the short term high suctions develop but they reduce with time. However, they are partially compensated by the improvement of the mechanical properties resulting from the consolidation of the soil. Taking into account the suction in the design may be a delicate point. On the contrary, it is possible to account for the improvement of the soil properties due to consolidation process by assuming full saturation (Goffeland, 1991).

In reinforced soil structures, the tensile forces developed in the reinforcements are considered either to decrease the forces tending to cause movements leading to instability or to increase the forces resisting these movements (Matsui & San, 1988). These forces are manifested in the soil in the form analogous to an increased confining pressure, which enhances the strength of the composite. A typical reinforced soil structure is shown in Figure 2.1.

Formerly, a reinforced soil structure usually had three ingredients: the selected granular backfill material, the galvanized steel reinforcing strips and the precast concrete panels of the facing. But now these specifications are improved upon. And a poor quality backfill material can be stabilized; other shapes are replacing strip reinforcements and materials and facing panels have also been eradicated in some cases (Chang et al. , 1972).

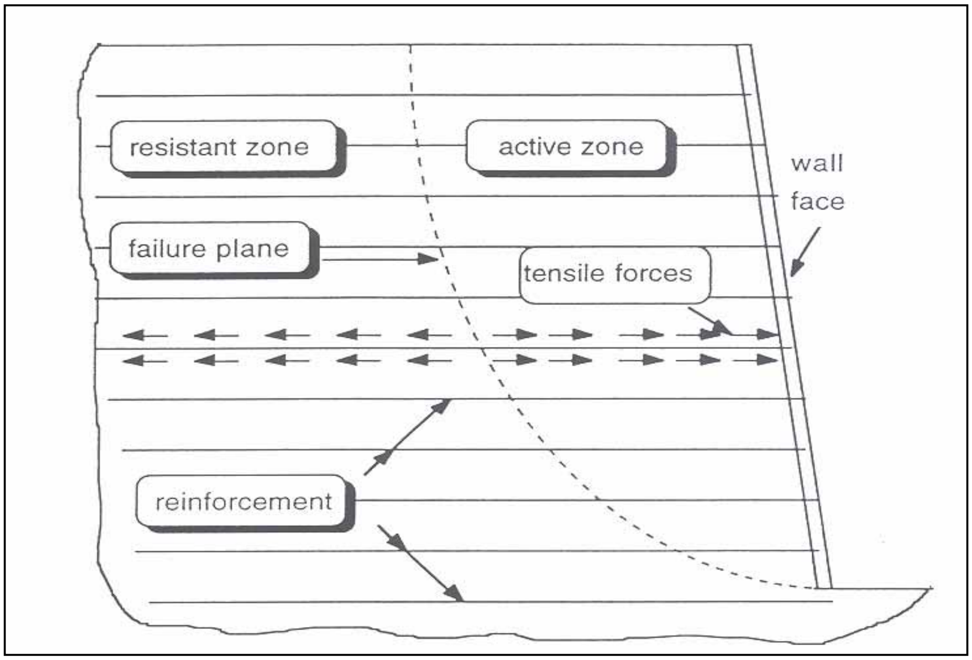

FIG. 2.1. Typical Reinforced Soil Structure

The rapid development of reinforced soil would not have been possible without substantial and continuous research and testing, both on the laboratory reduced models and in full scale experiments on actual structures. Since the beginning, reduced scale laboratory models were found to be an economical and efficient working tool for parametric studies on the behavior and failure mechanism; consequently they have been widely used in the development of the first approaches to the design of reinforced soil structures. Therefore, in the later stages of research, full-scale experiments were used to complete and verify the results of the laboratory models in order to establish appropriate design methods. The initial stages of the research were the following:

1960-67	Three-dimensional models	(Vidal)
1967-70	Two-dimensional models	(LCPC)
1970-73	Three-dimensional models	(Bacot, INSA)
1971-73	Three-dimensional models	(Lee, UCLA)
1972-75	Three dimensional models	(LCPC, TRRL)
1968-75	Ten full-scale experiments	(LCPC)

Many researchers have tried many combinations of reinforcing materials, type and geometry with different soils in laboratory model tests as well as in the field. In order to improve the performance, the reinforcement must adhere to the soil or be so shaped that deformation of the soil produces strain in the reinforcement. Reinforcement can take many forms depending largely upon the material employed. Common forms are sheets, bars, strips, grids and anchors. The reinforcement has no initial effect; it is only after that it has been strained. As the soil strains, it mobilizes the strength to resist the shear loads. Soil strain causes strain in the reinforcement: strength is improved until a limiting value is achieved; with further shear displacement the improvement remains constant.

2.2 ANCIENT STRUCTURES

The concept of earth reinforcement is not new, the basic principles are demonstrated abundantly in nature by animals and birds and the action of tree roots. The fundamentals of the technique are described in the Bible (Exodus 5, v. 6-9), covering the reinforcement of clay or bricks with reeds or straw for the construction of dwellings. Constructions using these techniques are known to have existed in the 5th and 4th millennia BC.

The earliest remaining examples of soil reinforcement are the ziggurat of the ancient city of Dur-Kurigatzu, now known as Agar-Quf, and the Great Wall of China. The Agar-Quf ziggurat, which stands five kilometers north of Baghdad was constructed of clay bricks varying in thickness between 130-400 mm, reinforced with woven mats of reed laid horizontally on a layer of sand and gravel at vertical spacing varying between 0.5 and 2.0 m. Reeds were also used to form plaited ropes approximately 100 mm in diameter which pass through the structure and act as reinforcement (Bagir, 1944). The Agar-Quf structure were also used to 45m tall, originally it is believed to have been over 80m high; it is thought to be over 3000 years old. Other ziggurats are known to have been built, among them being the structure at Ur, which was completed circa 2025 BC and the Sanctuary of Marduk at Babylon, sometimes known as the Tower of Babel, which was completed circa 550 BC (Copplestone, 1963). The Great Wall of China, parts of which were completed circa 200 BC, contains examples of reinforced soil; in this case use was made of mixtures of clay and gravel reinforced with tamarisk branches (Dept. of Transport, 1977).

The Romans also are known to have used earth-reinforcing techniques, and reed-reinforced earth levees were constructed along the Tiber. A recent discovery in London of a first-century Roman Army project of a wharf for the Port of Londinium has shown that past construction techniques are markedly similar to present day methods. The timber wharf, parts of which have been preserved in the Thames mud for 1900 years, is believed to have been 1.5 km in length. The 2m high structure was formed from oak baulks measuring up to 9 m in length, having a vertical face held in place by timber reinforcing elements embedded in the back fill, Figure 2.2 (Bassett, 1981).

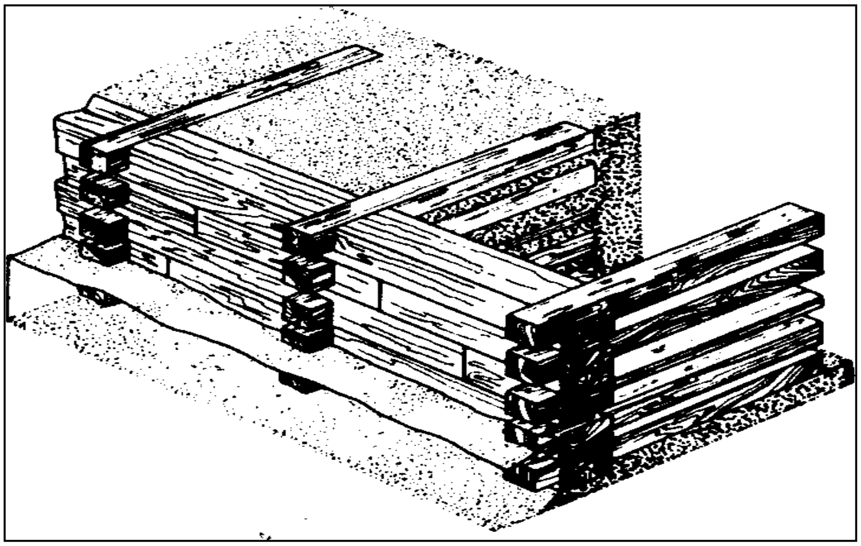

FIG. 2.2. Roman Wharf

In parallel with the Romans, the Gauls also made use of earth reinforcement technique in the construction of fortifications, the technique being to form alternate layers of logs and earth fill (Duncan, 1855).

Reinforcing techniques for Military earthworks appeared common up to the last century, although there is little reference in published texts. A notable contribution was made in 1822 when Col. Pasley introduced a form of reinforced soil for military construction in the British Army (Pasley, 1822). He conducted a comprehensive series of trials and showed that a significant reduction could be made in the lateral pressures acting on retaining walls if the backfill was reinforced by horizontal layers of brushwood, wooden planks or canvas; similar observations were made with modern reinforced earth backfills over 150 years later (Saran et al. , 1975).

In the past, most use for reinforced soil structures appears to have been in the control of rivers through training works and dykes. Early examples of dyke systems using reed reinforcement and clay fill are known to have existed along the Tigris and Euphrates, well before the adoption of the technique by the Romans. The use of faggoting techniques by the Dutch and the reclamation of the Fens in England are well recorded, as is the construction of the Mississippi levees (Haas and Weller, 1952). The basic technique is illustrated in BS Code of Practice CP No. 2.

The reinforcement of dam structures was introduced at the beginning of the twentieth century, by Reed (1904) who advocated the use of railway lines to reinforce rockfill in the downstream face of dams in California. A similar technique, but using grids made up of three-quarter-inch diameter steel bars, was used as late as 1962 in Papua (Fraser, 1962). Other applications of the latter system have been reported in South Africa, Mexico and Australia. Recently, the construction of reinforced earth dams has again been found to be economical.

A significant development to the modern concept of reinforced soil structures was made in the United States in 1925 by Munster (1925). He produced an earth retaining wall using an array of wooden reinforcing members and a light facing. Munster minimized the problem associated with the settling of the backfill by using sliding attachments, between the reinforcing members and the facing. Although the materials and details suggested by Munster would not find favor in modern construction, the techniques inherent in this system are valid and form the core of one of the construction techniques used today, Figure 2.3. In the 1930s, French developments came to the fore; first Coyne (1927) introduced the *mur a echelle* (ladder wall), in which the retaining wall consists of a mass of granular filling unified by a row of tie members each having a small end anchor, together with a thin cladding membrane. Settlement of the fill was catered for by the use of flexible tie members, one form of which was a galvanized flat iron strip.

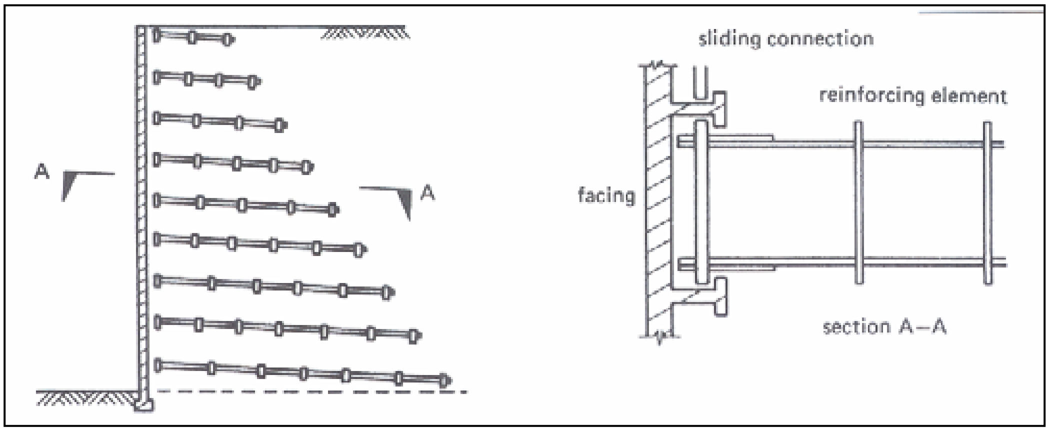

FIG. 2.3. Munster Earth Retaining Structure

Coyne also recognized that the surface cladding needed to be designed for settlement of the fill and advocated the use of flexible gaskets between facing slabs, elsewhere he used a form of overlapping slabs which could move relative to one another, Figure 2.4. Although Coyne's structures mostly used an anchor block at the end of the tensile reinforcing member, in 1945 he recognized that provided the fill possessed good frictional properties, the ties themselves could provide the necessary bond with the fill without the use of end anchors.

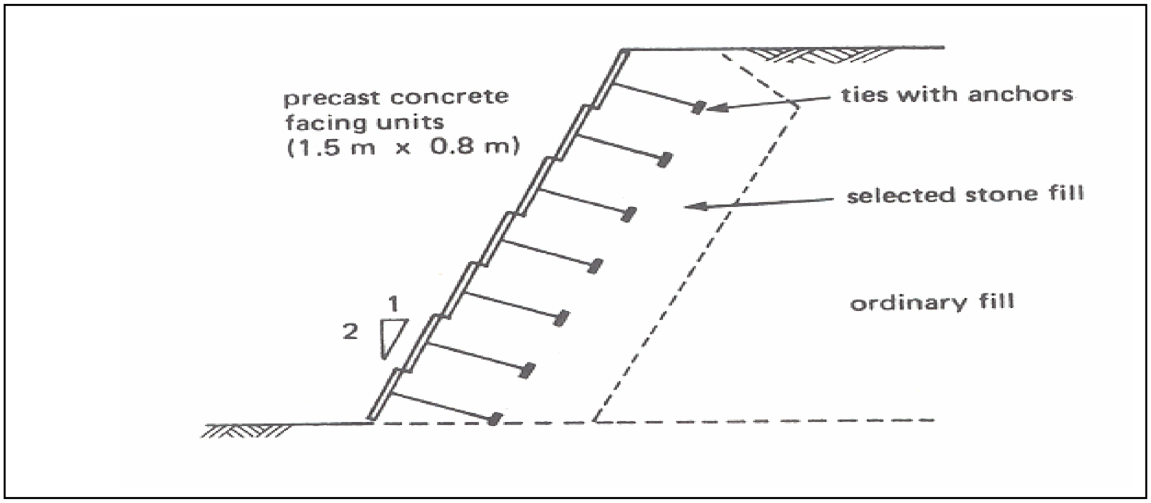

FIG. 2.4. Coyne Retaining Wall

2.3 MODERN STRUCTURES

The modern concept of earth reinforcement and soil structures was proposed by Casagrande who idealized the problems in the form of a weak soil reinforced by high-strength membranes laid horizontally in lavers (Westergaard, 1938). The modern form of earth reinforcement was introduced by Vidal in the 1960s. Vidal's concept was for a composite material formed from flat reinforcing strips laid horizontally in a frictional soil, Figure 2.5, the interaction between the soil and the reinforcing members being solely, by friction generated by gravity. This material he described as ‘Reinforced Earth’, a term that has become generic in many countries, being used to describe all forms of earth reinforcement or soil structures. In some countries, including the United States and Canada, the term is a trademark. The first major retaining walls using the Vidal concept were built near Menton in the South of France in 1968, although Vidal had built structures earlier, starting in 1964.

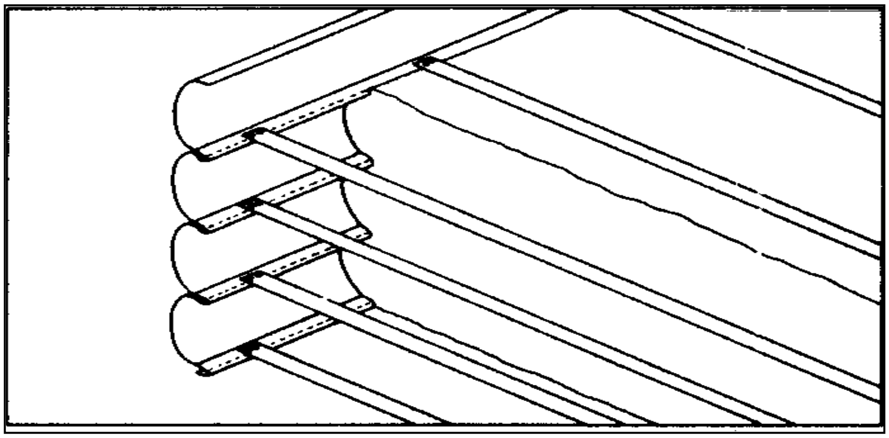

FIG. 2.5. Vidal Wall

The first structures used a pliant surface cladding made up from horizontally laid U-shaped sheet metal channel members. In 1970 an alternative cladding using a cruciform reinforced concrete member was introduced; concrete-faced structures are now used widely, Figure 2.6. The first use of Vidal's form of earth reinforcement in the United States was to correct a landslide in California in 1972, while the first reinforced earth structure in the UK was completed in 1973. In the same year another form of construction, the York method, having similarities with the earlier Munster technique, was introduced in the UK, having been developed on behalf of the Department of Transport, Figure 2.7. The York method has been the subject of continuous development for a period of 15 years and has evolved as a construction philosophy rather than a single technique. Central to the philosophy is that it uses common construction materials wherever possible and can be adapted to use any form of reinforcement or anchor.

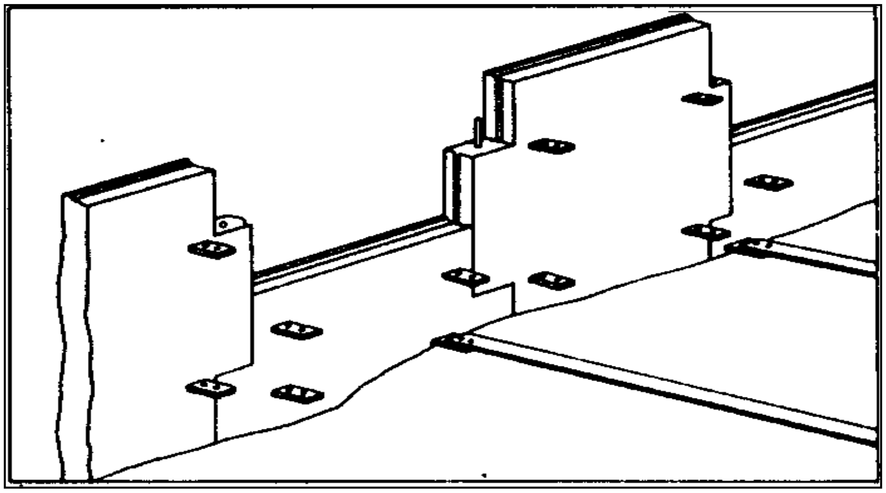

FIG. 2.6. Concrete Cruciform Faced Wall

The introduction of the Vidal structures led to rapid development. Much fundamental work was sponsored by various national bodies, notably at the Laboratoire des Ponts et Chaussees (LCPC) in France (Schlosser, 1978), by the United States Department of Transportation (Walkinshaw, 1975) and by the United Kingdom Department of Transport (Murray, 1977). This work led to the introduction of improved forms of reinforcement and to a better understanding of the fundamental concepts involved. Fabrics were introduced, although these materials have largely been confined to geotechnical applications other than soil reinforcing. In 1974 the California Department of Transportation introduced the use of mesh or grid as the reinforcing element in retaining walls, which has led to further developments (Forsyth, 1978).

Material development is interrelated with soil structure developments. Whereas the early structures were formed using organic materials such as timber, straw or reed for reinforcement, Pasley recognized the potential of more advanced forms of reinforcement, particularly in his use of canvas as a reinforcing membrane. Canvas could only have been expected to have a limited life before deterioration and Pasley's structures would not have been expected to last for long periods; in the nineteenth century, organic reinforcements still remained superior.

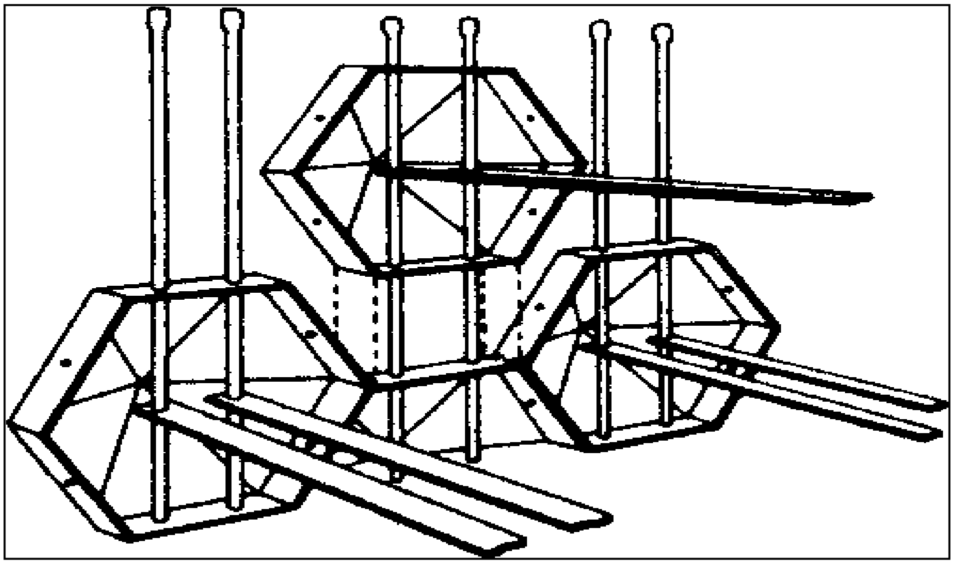

FIG. 2.7. York Method (After Jones 1978)

It was not until the necessary technical advances had taken place that artificial or engineering materials could be used for reinforcement. Coyne in the first half of the twentieth century was notably conscious of the problems of corrosion, an attitude which is also reflected by Vidal and others. Some structures are not Susceptible to corrosion or deterioration of the reinforcement as they have a short life. An example can be found in the mining industry where, as early as 1935, steel wire netting was being used to reinforce roof packs in the Yorkshire coalfield in England (Brass, 1935). The

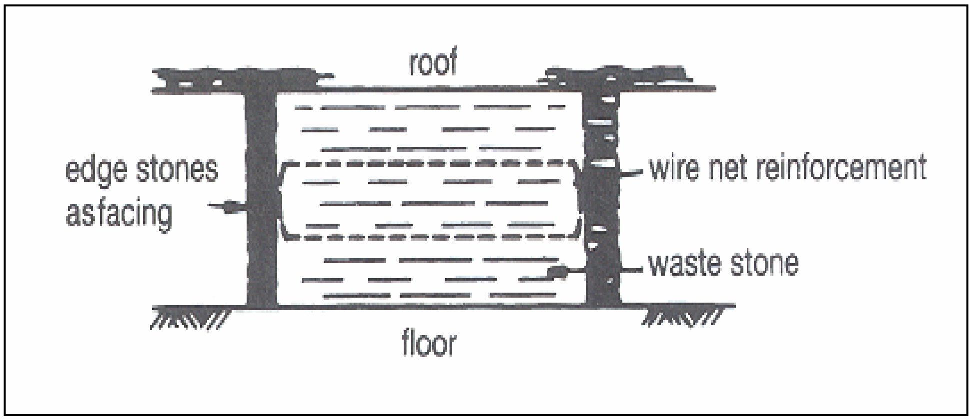

FIG. 2.8. Wire-Net Reinforced Roof Pack in Yorkshire Coalfield

reinforcement was laid in horizontal layers, dividing the pack into thinner slices, the frictional effect between the wire netting and the waste stone fill being relied upon for stability, Figure 2.8.

The use of textiles for reinforcement could not be contemplated until the development of synthetic polymer-based materials. Synthetic fabrics were known prior to 1940 but it was not until the late 1960s and early 1970s that the advances in synthetic fabric and geotextile developments led to the construction of reinforced soil structures. Fabric reinforced retaining walls have proved to be economical but are somewhat utilitarian in appearance, and the larger use of geotextile fabrics has proved to be in the areas of separation, filtration and drainage.

Geotextile materials can be divided into two categories: conventional geotextiles and specials. Conventional geotextiles are products of the textile industry and include non-woven, woven, knitted and stretch bonded textiles. Special geotextiles, usually referred to as geosynthetics, are not usually produced in a textile process. Two major forms have evolved geogrids and geo-composites. Geogrids have been used in civil engineering since the early 1960s, one of the first major applications being the use of high-density polyethylene grids in the construction of railways embankments in order to reinforce volcanic ash fill, and to enable higher levels of compaction to be attained (Yamamoto, 1966; Watanabe and Iwasaki, 1978). Around the same time, grid reinforcement was used to reclaim land for Nyeta Airport, Tokyo, and to improve the bearing capacity of weak subsoil (Yamanouchi, 1967). Following the examples of the California Highway Authority and the former West Yorkshire Metropolitan County in the UK, high-strength geogrid reinforcement is now used for concrete faced structures.

Geocomposites consist generally of high strength fibers set within a polymer matrix. One of the main uses for these very high strength materials has been as reinforcement of embankment structures over voids or as tension membranes. The development of Geosynthetic reinforcements is continuing, a recent innovation being the introduction of 'electro kinetic Geosynthetics' with advanced properties combining the functions of drainage, reinforcement and the concept of electro-osmosis.

In the 1980s a special type of reinforcement in the form of an anchor was evolved simultaneously in Europe, Japan and the USA. The multi-anchor system was developed by Fukuoka (1980) for the Japanese Ministry of Construction. The anchor is in the form of a rectangular steel plate, Figure 2.9.

The NEW retaining wall system, developed in Austria, is based on an elevated concrete facing and polymeric ties in the form of a closed loop (Figure 2.10) (Brandl and Dalmatiner 1986). In the USA and the UK, anchors formed from waste automobile tyres illustrated both the economic and the environmental benefits of reinforced soil. Steel anchors formed from a single piece of rebar were developed by the Transport and Road Research Laboratory in the UK (Murray and Irwin, 1981).

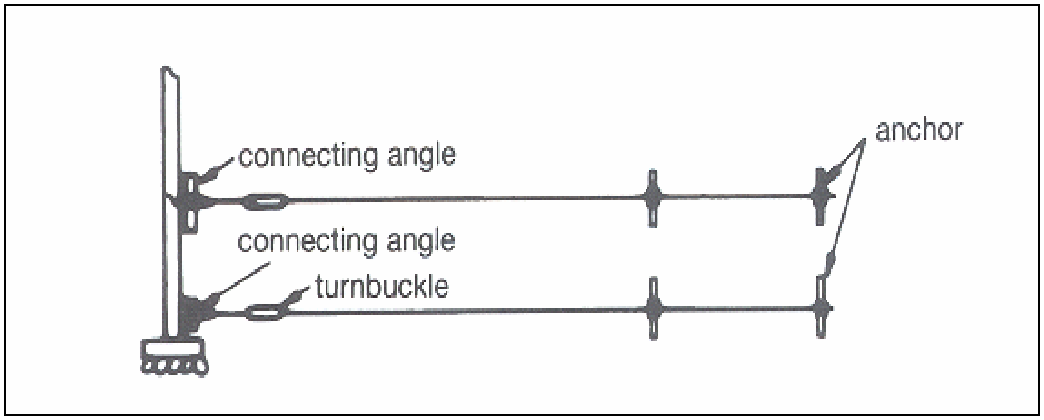

FIG. 2.9. Multi-anchor Wall (After Okasan Kogyo, 1985)

The first polymeric anchor was developed in 1992 (Jones and Hassan, 1992). In 1981, the development of soil structures advanced into a new area of application when synthetic grid materials were employed in the repair of cutting failures on the M1 and M4 motorways in England (Murray et al., 1982). The stabilization of cuttings by earth reinforcing formed in-situ, using techniques similar to those employed in ground anchor techniques, had previously been introduced in Germany and the USA.

These 'soil-nailing' or 'lateral earth support systems', together with the repair techniques developed on the M4 motorway, epitomize the present stage of earth reinforcing in which the technique is accepted as a conventional design option available for use in the design of geotechnical structures.

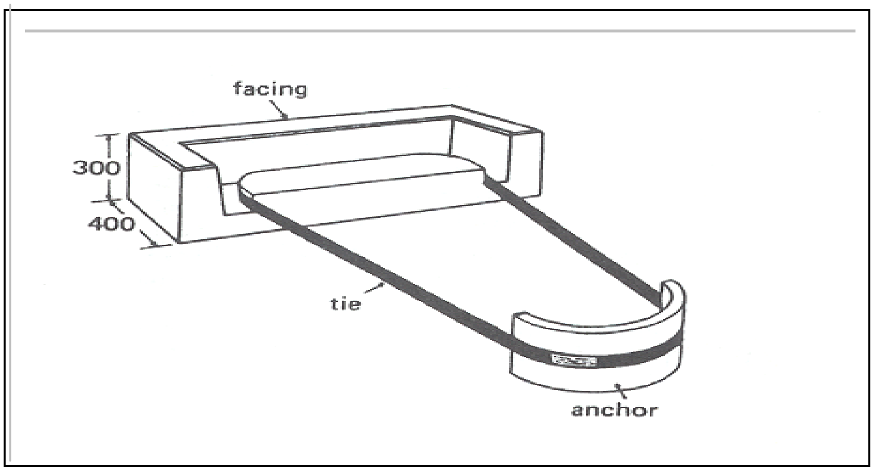

FIG. 2.10. NEW Wall System

Soil reinforcement acting as tension membranes supporting roads, buildings, embankments over voids or acting as construction aids in cases of extremely soft soil (super soft soil) were introduced in the 1980s. Yano et al. (1982) describe the problems associated with coastal areas including the bays of Tokyo and Osaka, where soft marine clay has been deposited over wide areas. This material has little or no bearing capacity but can be in a potentially prime location. Soil reinforcement in the form of grids is used to form a primary construction stage providing support for conventional ground improvement techniques.

The use of tensile reinforcing elements to support structures over natural or man-made voids has evolved to the point where the technique is described in the new British Standard on Reinforced Soil (BS 1995).

A multitude of hybrid systems -and techniques are now available, one of the most successful of which has proved to be the tailed gabion introduced by Jones and Templeman (1979), thus the stability of conventional gabion structures can be enhanced by the addition of reinforcement, Figure 2.11. NEW systems and developments continue to evolve, and even the advantages of prestressed reinforced soil have been demonstrated (Barashov et al., 1979).

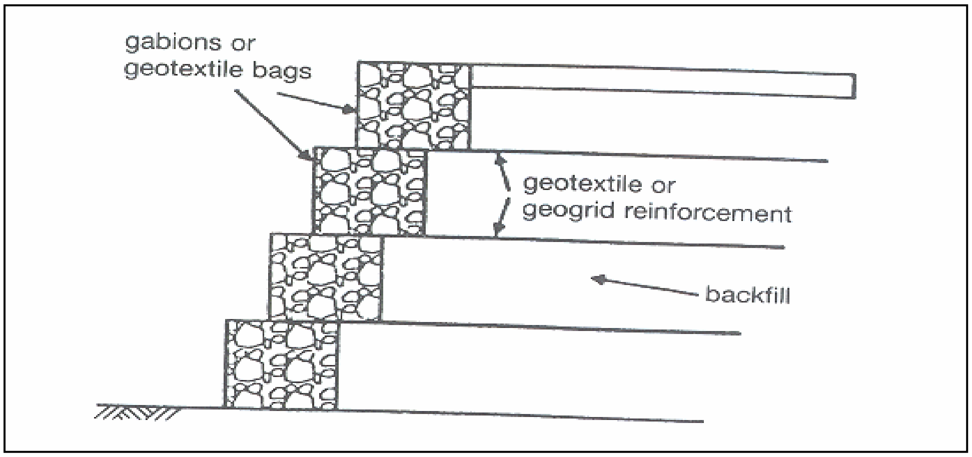

FIG. 2.11. Tailed Gabion

2.4 TYPES OF REINFORCEMENTS

Although a variety of reinforcing materials are now in existence but as in this study the nylon grid is used, therefore, only two types of reinforcements i.e. strip and grid reinforcements are described below. The interaction behavior of the anchor and grid types reinforcements may assume to be the same, therefore, the former is not included in discussion.

2.4.1 Strip Reinforcements: This type of reinforcement is the first to have been considered and included in soil reinforcing techniques.

$$\frac{\sigma_1}{\sigma_3} = \frac{1}{\mathrm{K}_0} = \frac{1-v_m}{v_m} \qquad (2.\ 1)$$

As can be from Eq. (2. 1) that greater the strain for material with high modulus of elasticity, E, the greater will be the reinforcing effect. Exploiting this high E, steel was considered in the form of sheet i.e. strip shape. Typical strip reinforcement is shown in Figure 2.12. To cause more straining, it is necessary that the surface area be larger and rougher. Moreover, for the same cross-sectional area, thickness, t, should be as minimum as possible to produce more surface area. That is the reason that normally; strip reinforcements are marketed in thinner forms. When interacted with soil under normal pressure, σ_n, the added cohesion i.e. improvement upon shear strength and movements is exhibited by such reinforcements.

2.4.2 Grid Reinforcements: As far as the effectiveness of these forces in straining the reinforcement is concerned, they can optimally be utilized by anchor type of arrangement on the longitudinal member. One of the methods of its achievement is to run bearing members across the longitudinal ones.

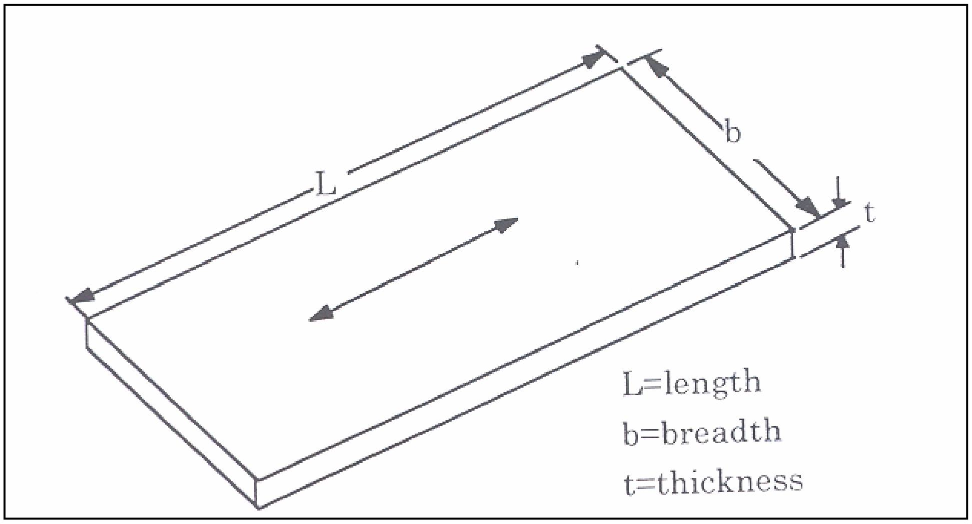

FIG. 2.12. Typical Strip Reinforcement

This idea was utilized by Chang et al. 1977 and carried out pullout tests on mesh type reinforcing mats. Reinforcements of mesh sizes of 200mm (longitudinal) X l00mm (transverse) x 9mm (diameter) and 350mm x 125mm x 9mm were used. The shape of the reinforcement thus obtained consists of a sheet with multiple grids and so is the name derived as "grid reinforcement" in which the added cohesion is many times enhanced. This agency for the increased enhanced confining stress comes from the bearing resistance of transverse members of the grid type reinforcement. This type of welded wire mesh reinforcement was first patented by Hilfiker Construction Company in 1978. It is a combination of longitudinal and transverse members, which are galvanized to resist corrosion during its active life. The size of the members and geometry of the grid are found to have relationship to pullout resistance of the reinforcement. This aspect has been studied by Bergado and Shivashankar (1993), Paimeira and Milligan (1989), Jewell and Milligan (1984) and others. Grid reinforcement is different from geogrids reinforcement mainly, in terms of materials, geometry and elastic properties. Grid reinforcements may be defined as any planar structure formed by a regular network of tensile and bearing elements with aperture or mesh of sufficient size to allow interlocking with surrounding soil. The geogrid is made of polymers and has almost a planar structure while the grid reinforcement, when in welded form, does not have the transverse and longitudinal members in the same horizontal plane. This definition may be applicable to welded wire galvanized grid reinforcement with the only difference that the longitudinal and transverse members do not lie in the same horizontal plane. The transverse members run parallel to the face of the reinforced structure. Typical grid reinforcement is shown in Figure 2.13. They act as stop footings parallel to one another separated by a, distance, along the longitudinal member direction, between them. This increase in elastic forces leads to more confining pressure. Because of this behavior of geogrid or grid reinforcements, even marginal or weak soils embankments have effectively been improved and stabilized. If on one hand it has superiority over the strip reinforcement in deriving more resistance from the soil, on the other hand it has complicated its understanding of interaction mechanism, which is not yet fully understood.

By now, different researchers have presented different theories about the pullout resistance mechanisms of geogrid and grid reinforcements. Since the apertures are small in size for geogrid reinforcements, the pullout resistance mechanism is based on the double shear, which takes place above and below the reinforcement in soil. In laboratory pullout tests, the planar extent (BL) of the reinforcement is considered as the shear area, where B and L are its breadth and length respectively. The concept of pullout resistance in such a system is the same as those for the strip reinforcement except the coefficient of friction may depend on the particle and aperture sizes. For the influence of particle and aperture sizes on the interaction mechanism, reference is made to the work of Jewell et al. (1985). If both sizes are such that the rupture surface is between soil-soil, then Ochiai et al. (1992) have elaborately investigated the evaluation methods based on different types of interaction mechanisms of the geogrid-soil composites.

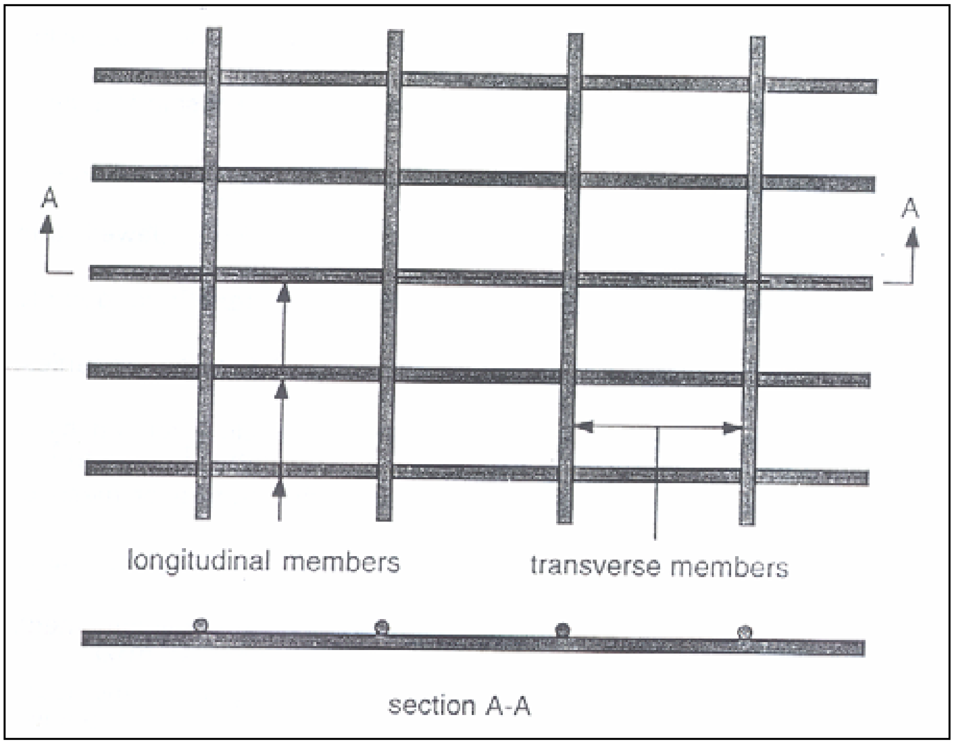

FIG. 2.13. Typical Welded Wire Grid Reinforcement

It has been found that the grid type of reinforcement can well be suitable in improving the stability. For example, one of the most successful methods of reinstating the failed slopes of heavily over-consolidated clay was to excavate all the slipped materials, add a small percentage of lime to improve its workability and recompact it into the slope with layers of geogrid.

2.5 INTERACTION MECHANISM OF SOIL REINFORCEMENT

2.5.1 Strip Reinforcement-Soil Interaction: When soil is pressed against the surface of the strip, relative movement can be effected by the application of some force according to the physics law of friction. In the field of soil reinforcement, the forces come from the lateral movement of soil and resisted by the friction between soil and reinforcement. In case of reinforced soil, this lateral movement, in addition to other causes, is brought about by geometrical shape and gravity, of reinforced soil structure, in which the face of the embankment or soil wall is erected at an angle more than the angle of repose of the soil. Vidal (1969) states that in the case of longitudinal reinforcement such as strip, the bond is derived from friction between the soil and the reinforcement. Vidal (1969) and Lee (1976) indicate that the reinforcement introduces“cohesion” to the granular non-cohesive soil. This added cohesion raises the Mohr's circle failure envelope and allows the stress condition to remain below the envelope. Vidal (1 969) states that this cohesion is exhibited because the reinforcement holds the soil essentially in place by friction bond which is, of necessity, a non-slipping bond. Such a state is exhibited in Figure 2.14 for a typical strip reinforcement on either side of the incipient failure plane of Figure 2.1 above.

For non-slipping bond, $\frac{dF}{dl} \le Nf$ where N is the normal stress per unit width of the reinforced structure and f, the coefficient of interfacial friction. When the reinforcement is stretched through adhesion forces by the soil movement, the elastic forces in the strip come into being and contain the soil with enhanced confining forces, dF, over an element, d*l* of the strip.

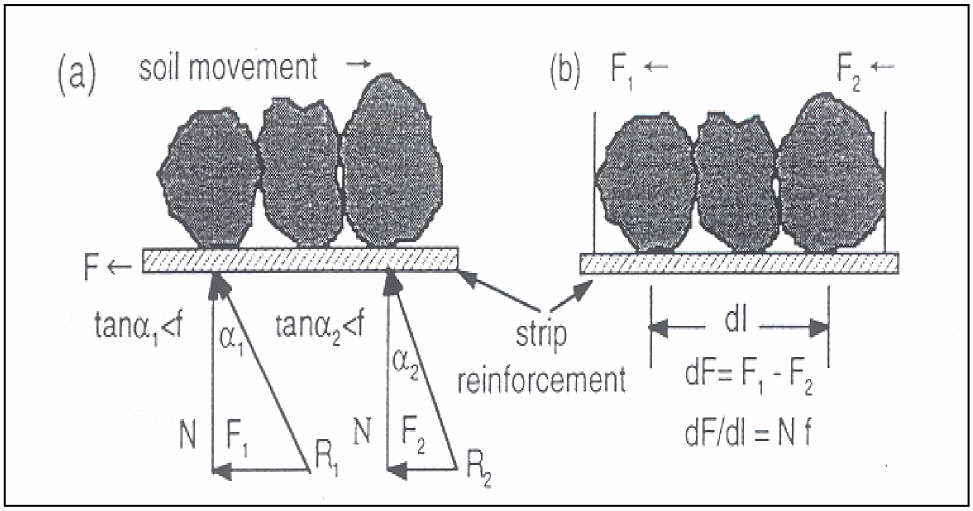

FIG. 2.14. Soil Strip Reinforcement Interaction Mechanism

It may be noted that the soil looses some of its rebounding properties i.e. it does not behave perfectly elastic, however, the reinforcement must be in the elastic range for the mechanism to work. This behavior of any point on the reinforcement may be compared to the stretched spring (Figure 2.15) to the surface of which soil is adhered through adhesive forces.

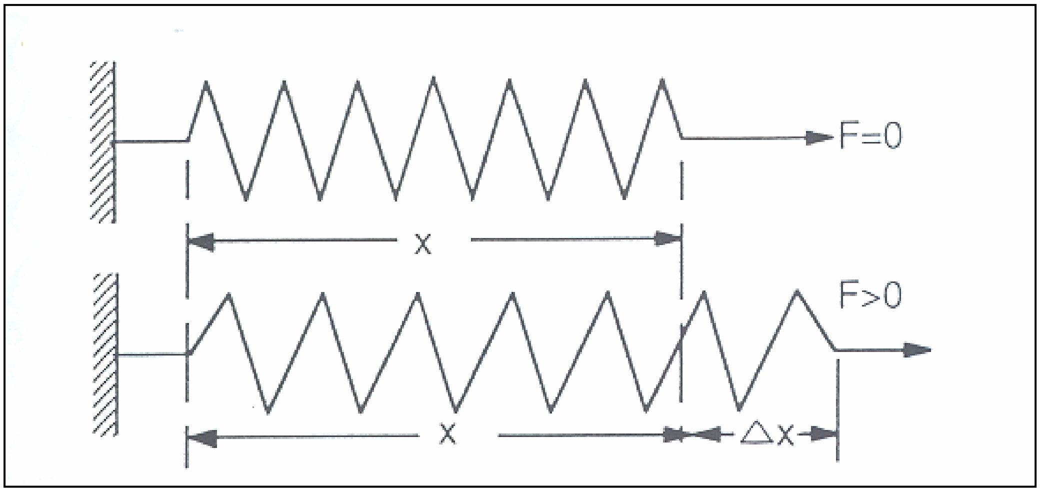

FIG. 2.15. Comparison of Strip Mechanism to Spring

When the lateral active movements occur, the spring is stretched by some distance Δx and the elastic forces, -Δxk, are developed which contain the soil movements. The negative sign shows direction opposite to the direction of soil movements and k is the elastic constant of the reinforcement.

According to Vidal, if the tension in the reinforcing member is constant (such as anchored rods), transmission of stress to the soil is impossible. If, however, the tension varies along the reinforcing member, different forces will be transmitted to the adjacent grains as shown in Figure 2.14(b). The contact angle will then be different for the adjacent grains (Figure 2.14(a)). This results in forces pushing the grains together, which is equal to the difference between the two forces transmitted by the contact with the reinforcement (Figure 2.14(b)). Thus a connection will be made between the grains by differential force, dF. For this to occur, the force, dF, distributed over the contact length of the grains with the reinforcement, dl, must be less than the maximum tensile force, fN. This is, by definition, a non-slipping bond. When this mechanism is applied to the reinforced soil, the stress state can then be represented by Mohr's circle shown in Figure 2.16.

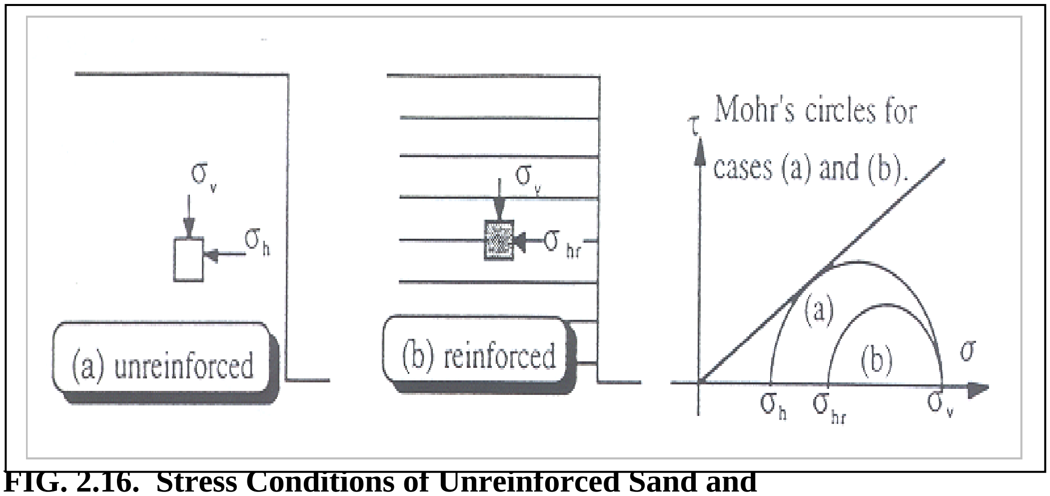

FIG. 2.16. Stress Conditions of Unreinforced Sand and Reinforced Soil Structures

The magnitude of added cohesion depends upon the value of non- slipping bond, the elastic properties and orientation of the reinforcement. The magnitude of this non-slipping bond is proportional to the lateral active movement of the soil and attains its maximum value of tan$\phi_{M,}$, where ϕ_M, is the angle of mobilized friction between soil and reinforcement. The strain will be maximum in the reinforcement if:

(a) For the same cross sectional area, the horizontal contact area is maximum and

(b) The reinforcement is in the direction of tensile maximum strains in the soil structure (After Milligan, 1974) i.e. if the reinforcement bisects the tensile arc (Figs.2.17 (a) & 2.17(b)).

Therefore, the strip reinforcement is more effective than the square or circular bar of the same cross sectional area. And the direction of tensile maximum strain is found to be horizontal in a vertically faced reinforced soil structure. It is interesting to note that the horizontal placing of the reinforcement changes the trajectories of the failure lines in the reinforced structure as shown in Figure 2.17(c) (After Basset and Last, 1978). But in case of embankment, the direction of tensile strain is not horizontal and the problem is that of determining or predicting the directions of the compressed strain trajectories and the α and β zero extension lines. Failure to do this procedure could result in tensile reinforcement being placed in a position of compressive strain, or along a potential rupture plane.

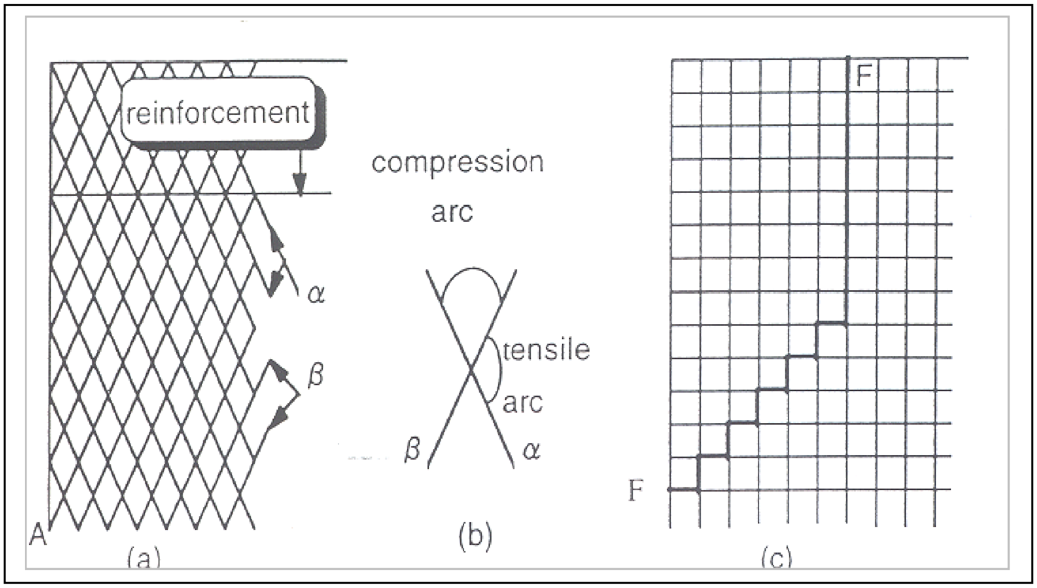

FIG. 2.17. (a) α and β Characteristics of Reinforced Soil Fill Produced by the Wall Rotating about A (After Milligan, 1974), (b) Strain Arcs, (c) α and β Characteristics for Reinforced Fill. β Direction Aligned with Horizontal Reinforcement (After Bassett and Last, 1978)

Predictions of the α and β planes can be obtained from centrifuge tests, Basset and Homer (1977), from model tests, Roscoe (1970), by using mathematical models, Sim and Jones (1979), or from limit equilibrium methods. The task is eased by using the observation that under monotonic loading conditions, the axes of principal total stress and incremental strain coincide. The idealized zero-extension characteristic fields through and beneath an embankment, together with the directions of the principal compressive stresses are shown in Figure 2.18(a). By inspection, it can be seen that reinforcement placed horizontally in the majority of the embankments would be advantageous, but horizontal reinforcement restricted to "C" would be potentially dangerous. Reinforcement at the base of an embankment can be achieved by two methods. Horizontal reinforcement (A-A) can be placed at the base in a manner similar to the technique with vertical walls as shown in Figure 2.18(b), which will create a condition of horizontal restraint on the plane of the reinforcement (Binquet and Lee, 1975).

Alternatively, reinforcing tendons can be introduced into the foundation soil beneath the embankment, aligned with the principal tensile strain directions (8-6) Figure 2.18(b).

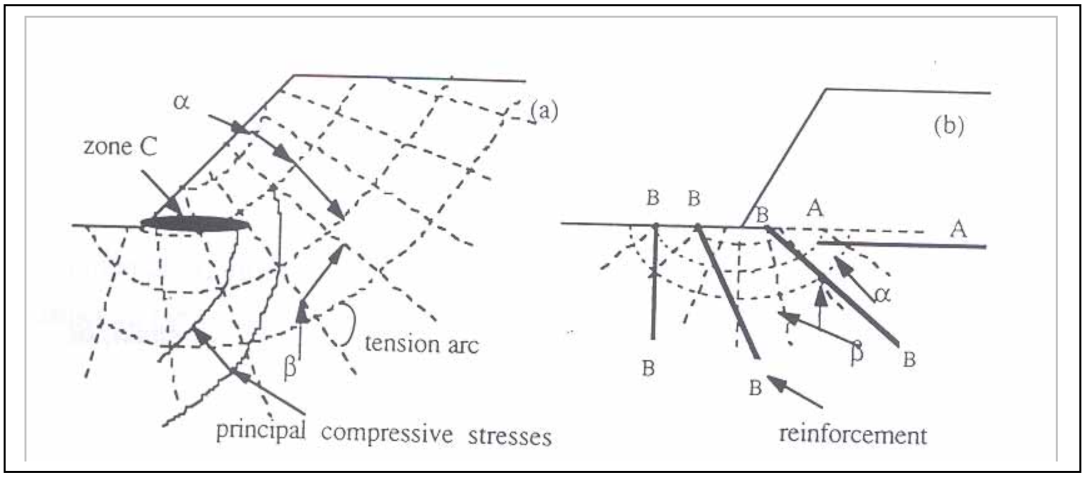

FIG. 2.18. (a) The Idealized Zero Extension Characteristics Field Through and Beneath an Embankment (b) Possible Reinforcement Placing

2.5.2 Grid Reinforcement-Soil Interaction: In grid reinforcement, the longitudinal members are indirectly responsible for the soil containing effect. Because these members are strained by the forces not directly developed by them but by the bearing forces due to bearing/transverse members if the frictional forces on longitudinal members are neglected (which often constitutes less than 8% of the total pullout resistance). On the other hand, the strains developed in the strip reinforcements are due to the forces of friction produced over its own body and the mechanism is simple enough to understand. But the interaction mechanism between the bearing members of reinforcement and soil is still under research.

2.6 THEORIES OF MECHANISMS OF SOIL-STRIP REINFORCEMENT

To advance the work of Vidal and other pioneers, Schlosser and Long (1973), Haussman (1976), Chapuis (1972) and Yang (1972) further investigated the mechanism of soil-strip reinforcement interaction. Their works are briefly noted down.

2.6.1 The Enhanced Confining Pressure Theory: Chapuis (1972) of the Institute de Mechanique de Grenoble and Yang (1972) of university of California, Los Angeles based their works on the assumption that the horizontal plane could not be the principal plane because there was a shear stress induced between the soil and reinforcement. Similarly the vertical plane could not be the principal plane. In addition, the internal stress was found to be far from uniform. Both authors appreciated that within the reinforced sample, the minor principal stress was higher than the applied stress, while the major principal stress was increased, resulting in the shifting of the Mohr's circle of stress. The size of the circle was also increased. This circle for the reinforced sample will also be tangent to the failure envelope of the unreinforced sample. Therefore, the failure envelope was the same for reinforced and unreinforced samples as shown in Figure 2.19.

The conclusion was that the additional strength for reinforced soil resulted from the enhanced confining pressure effect.

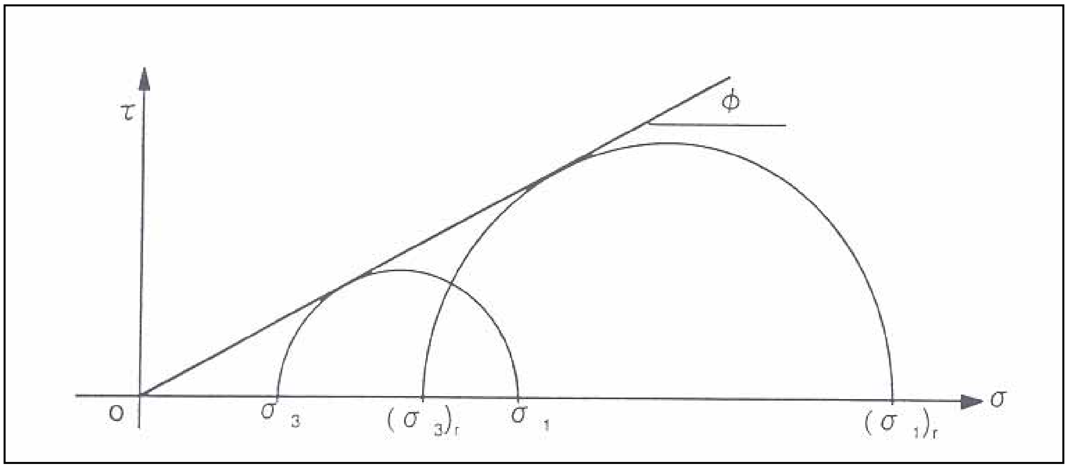

FIG. 2.19. The Enhanced Confining Pressure Concept (Ingold, 1982)

2.6.2 The Anisotropic Cohesion Theory: This concept was first proposed by Schlosser and Long (1973) as the "LCPC cohesion theory". A series of triaxial tests were performed on aluminum foil disc reinforced sand sample. The conclusion was that for tensile reinforcement failure, the envelope of both reinforced and unreinforced sand had the same internal friction but additional strength imparted by the reinforcement could be represented by an apparent anisotropic cohesion, C_r, as shown in Figure 2.20.

This intercept becomes an imaginary one under zero normal pressure and which may be associated to composite property. This property is not an inherent one like the cohesion of clayey soils.

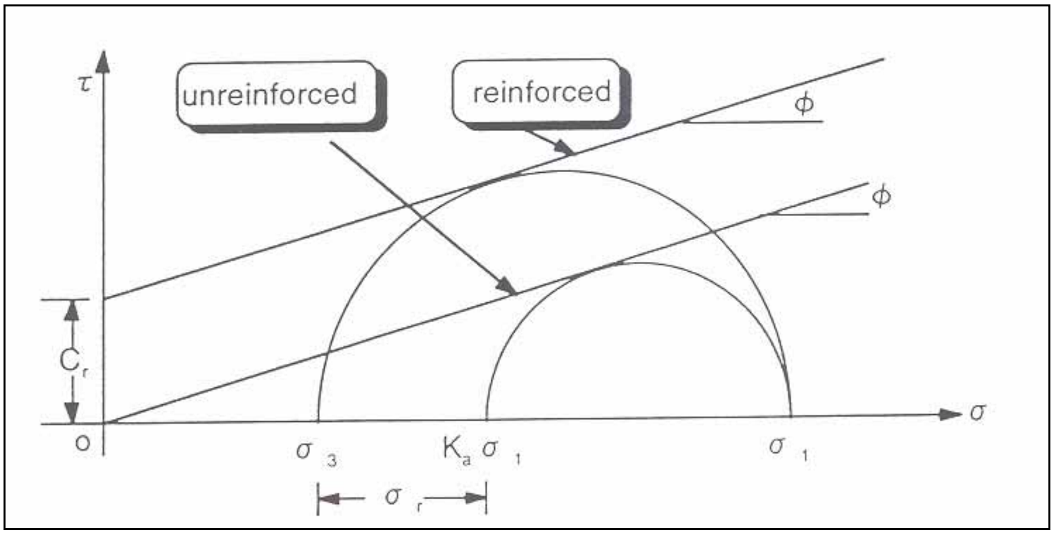

FIG. 2.20. The LCPC Cohesion Theory (After Haussman, 1976)

Haussman (1976) postulated a more unified anisotropic cohesion theory, called "the New South Wales Cohesion Theory". This theory consists of two parts. Firstly, the failure of reinforced soil occurs by tensile failure of reinforcement at high stress level as shown in Figure 2.21. In this part, there is an apparent anisotropic cohesion for reinforced soil mass and the angle of internal friction is the same for reinforced and unreinforced soils. Secondly, failure of reinforced soil occurs by slippage between the soil and the reinforcement at low stress level as shown in Figure 2.21. There is no apparent anisotropic cohesion intercept but the additional strength of reinforced soil is achieved by increasing of internal friction angle due to friction developed between soil and reinforcement, which is proportional to vertical stress. The anisotropic cohesion concept is based on the assumption that the major principal stress is constant while the minor principal stress is decreasing. Therefore, the failure envelope of reinforced sand sample will lie above that of unreinforced.

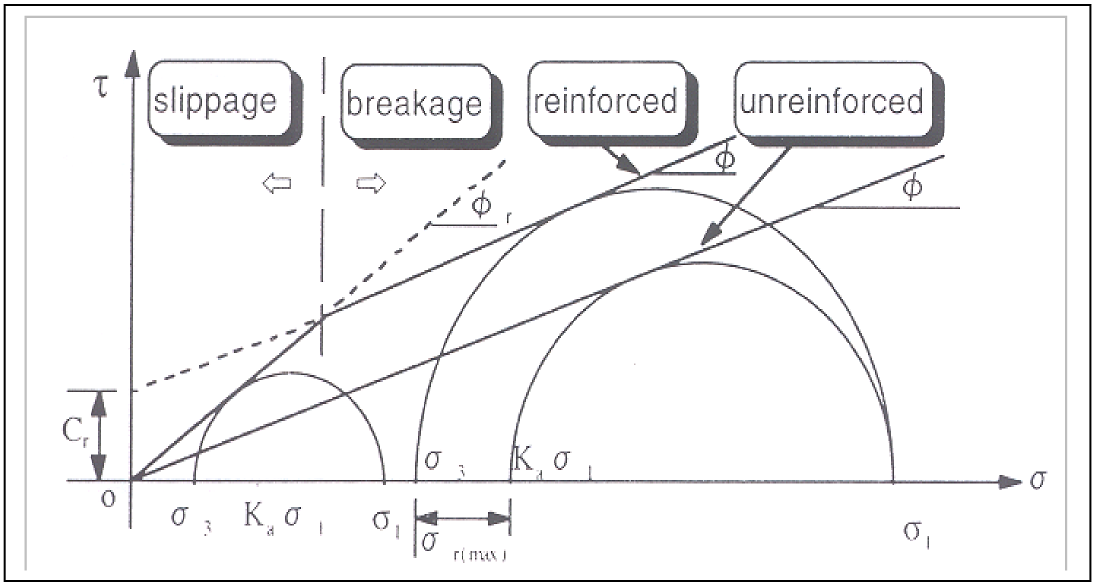

FIG. 2.21. The NWS Cohesion Theory (After Haussman, 1976)