The Principle of Reinforced Earth

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•REINFORCED earth is a material formed by combining earth and reinforcement. The term "earth" covers all types of ground found in nature, or produced by physical or chemical means, including both granular soils and earth which exhibits some slight cohesion.

It can include all particle sizes (silt, sand, gravel, stones, and all sizes of rocks); it can be formed of prefabricated elements (concrete, for example). The word "reinforcement" is used to define all linear components which can withstand major tensile stresses. Thus, earth is a mass of constituents with compact shapes, close to a sphere or cube; as a result, we will call them "grains" or "particles". Reinforcing members are elongated elements, with one dimension clearly greater than the others.

Earth alone, or at least granular earth, according to the definition used in soil mechanics, is made up of non-cohesive particles, but when horizontal beds of flexible, rectilinear reinforcement are introduced into this earth, the whole mass exhibits some cohesion. It is a body of reinforced earth.

This cohesion of reinforced earth arises from friction of grains of earth against the reinforcing members. There is a transmission of forces by friction between the grains and the reinforcements, introducing true cohesion to the whole mass.

This assumes that there is grain-reinforcement friction without sliding; therefore, the reinforcing members must be so arranged that this condition is always met. Since reinforcement can be placed along the directions of the three axes of a trihedral, it can easily be understood that a reinforced earth body may present cohesion in all directions. Consequently, it is possible to build structures of reinforced earth in any desired shape.

In such structures, the stresses developed in the reinforcement depend on the sum of the contact actions between the earth particles. As a result, if the reinforcement is properly placed and designed, it is possible to avoid any shear and any sliding, so that the entire mass behaves like a cohesive solid capable of withstanding both internal and external forces.

In short, friction is the basis of the theory of reinforced earth. Once the proper contact between earth and reinforcement is established, the problem becomes one of calculating the stresses in the reinforcement and in the earth.

FRICTION BETWEEN EARTH AND REINFORCEMENT

To be effective, the reinforcing members must be connected to the earth. Since the reinforcing action results only from friction, it must be determined whether this friction exists without sliding.

Let us consider two grains of earth in contact with a reinforcing member (Fig. 1). If the contact force makes an angle α with the plane perpendicular to the reinforcement (f being the friction coefficient between grains and reinforcement) there must be the relationship $\text{tg}\ \alpha < f$. However, if the tension in a reinforcing member remained constant, it would transmit none of its stress to the earth and have no effect on α or the second grain. It would form no connection between two neighboring grains, such as in the case of tie rods.

Paper sponsored by Department of Soils, Geology and Foundations.

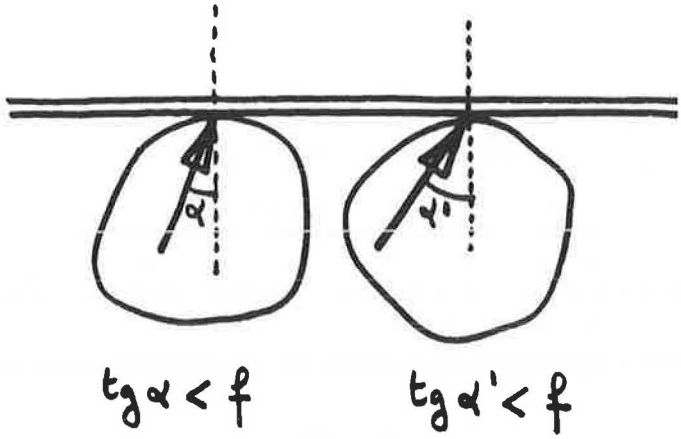


Figure 1.

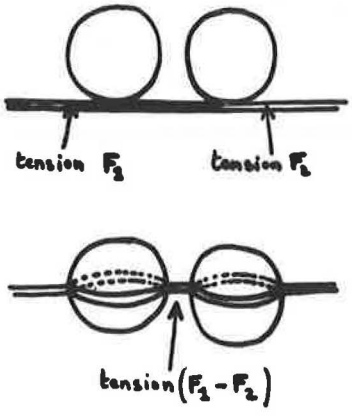
On the other hand, if the tension in a reinforcing member has a value of F_1 immediately in front of a grain (Fig. 2), and F_2 immediately after the neighboring grain, everything behaves as if the reinforcement were creating a connection between the two grains with a tension $F_1 - F_2$. For this connection actually to take place, this tension $F_1 - F_2$ must result from friction without sliding between the earth and the reinforcement. Let us call dl the distance between the two points where the tension has the respective values F_2 and F_1 (Fig. 3).

Over the length dl of the reinforcement, the stress varies by

$$dF = F_2 - F_1$$

If the stress in the earth perpendicular to the plane of the reinforcement (Fig. 4) has the value N (the force normal to the reinforcement over this length dl), and on two faces a value of 2 Ndl; it is then necessary to ascertain that friction is taking place without sliding, or

$$\frac{dF}{2\,Ndl} < f$$



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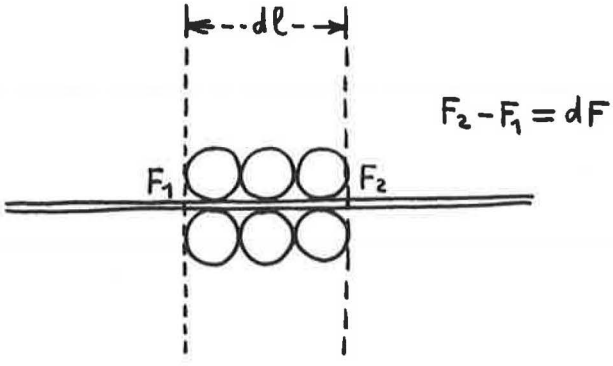

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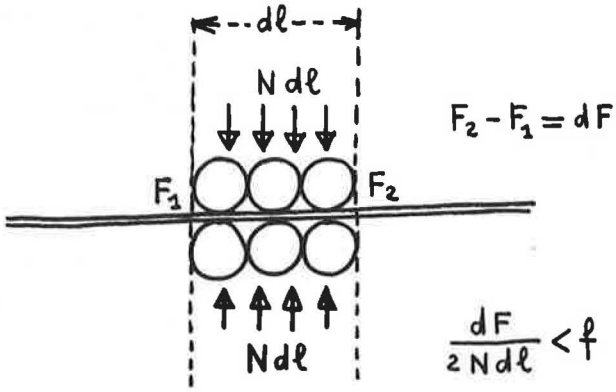

Figure 4.

Since f is the coefficient of friction between earth and reinforcements, the coefficient 2 results from the friction on both faces of the flat reinforcement. As a result, if the relationship

$$\frac{dF}{2\,Ndl} = \frac{f}{s}$$

is verified, it can be assumed that granular friction on either side of the reinforcement is taking place without sliding, and with a factor of safety, s.

This relationship is somewhat similar to that of the bonding of the reinforcement in a reinforced concrete beam, only the bond stress is replaced by a pressure multiplied by twice a coefficient of friction. This formula assumes that the reinforcing members are flat and that a layer of reinforcement forms a complete plane. In reality, the reinforcements are in flat bands of limited width spaced at finite distances from each other (Fig. 5).

If K is the proportion of reinforcement per unit length, the formula becomes

$$\frac{dF}{dl} < 2\,KNf$$

The slope of the curve giving the stress in the reinforcing members as a function of their length must not exceed a certain value. In the case of the beam in reinforced earth with a shear force T, dF/dl = T, and it is enough to assure that

$$T < 2\,KNf$$

In the case of round reinforcements (Fig. 6), a similar formula will apply:

$$\frac{dF}{dl} < K\,\pi\,\phi\,Nf$$

where

ϕ = diameter of rod,
K = number of rods per unit, and
N = average pressure around the rod.

These two formulas are pessimistic because they do not take into account the arching effect between adjoining reinforcing bars.

In the preceding arguments, only the connection between a reinforcing member

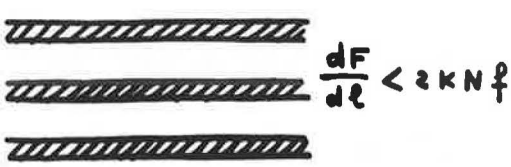

Figure 5.

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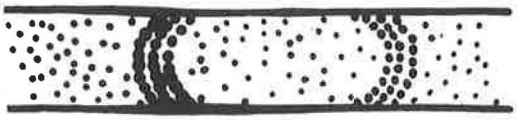

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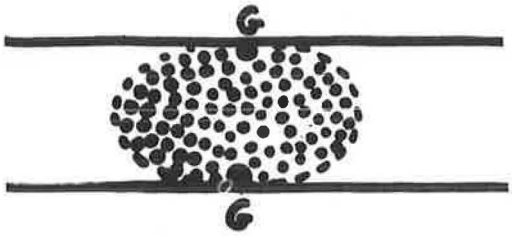


Figure 8.

and the grains of earth with which it has direct contact has been considered, but reinforcing layers generally lie at some distance from each other. Therefore, we must examine the manner in which the stresses in the reinforcement are transmitted from the grains in direct contact to those not in contact.

Although the manner of transmission is not known with certainty, it is assumed that this connection must be in some form of a strut or arch (Fig. 7). However the lack of such knowledge in the case of reinforced concrete has not hindered its development in the last 50 years.

In reinforced earth it is assumed that a grain G directly in contact with the reinforcement has an appreciable effect only on the grains between two layers of reinforcement over a certain radius related to the spacing of the reinforcing members (Fig. 8). Therefore, in making calculations, the earth particles can be considered as sacks of earth with a thickness equal to the distance between two reinforcement layers.

It is of little importance that we do not know exactly what happens within the sacks. If a structure actually consisted of sacks of earth, all the calculations would still be fully justified; opening the sacks by tearing the sides perpendicular to the reinforcement (Fig. 9) need not change the distribution of the stresses except in the immediate neighborhood of the tear. This should make no difference to the stresses on a grain A situated in the middle of the sack (Fig. 10).

Thus, it can be seen that the first condition for the existence of reinforced earth—friction between earth and reinforcement—can be met, and it can be checked by verifying a relatively simple formula. The calculation depends on the coefficient of friction between the earth and the reinforcement, on the stresses in the earth, on the geometric properties of the reinforcement, and on the rate of change of tension along each reinforcement.

Contrary to what might be thought, this condition of friction between earth and reinforcement has been achieved in all the numerous works which have been designed.

CALCULATION OF STRESSES IN EARTH AND REINFORCEMENT

It is now necessary to calculate the tension at each point in each reinforcement, together with the stresses in the earth, in order to verify that the mass always remains in equilibrium. Difficulty in calculating reinforced earth results from dealing with

Figure 9.

Figure 10.

a heterogeneous material that is generally non-isotropic and which, to all appearances, includes large plastic zones.

Although these special characteristics do not interfere with the validity of Mohr's circle, which makes it possible to represent the stresses in the earth around a point, it seems difficult at first to connect the stresses and strains in some simple manner—such as the theory of elasticity or of strength of materials. Nevertheless, reinforced earth can be calculated and may be considered as a material having a certain elasticity.

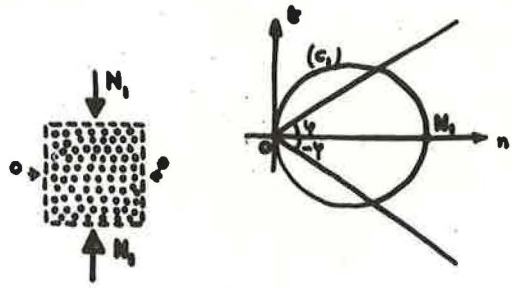


Figure 11.

As a first step, the fundamental cases of simple compression and tension will be studied. Then the elasticity properties of reinforced earth will be discussed, together with two methods of calculating the stresses in the most general case.

Pure Compression

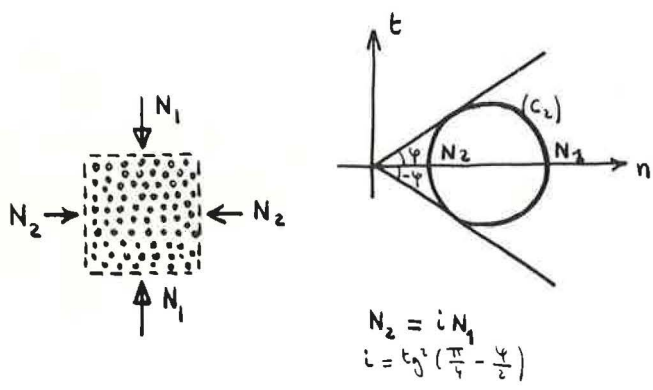
Material formed by a mass of particles without reinforcement has properties that are identical in all directions, since the particles are in a random arrangement. Therefore, the theory of the intrinsic curve (formed of two straight lines inclined at $+\varphi$ and $-\varphi$) is applicable.

A cube of earth (Fig. 11) subjected to a compressive stress N_1 on its two faces cannot remain in equilibrium, because the corresponding Mohr's circle (C_1) cuts the intrinsic curve. The cube can only be stable when compressive forces, N_2, which are at least equal to $i\,N_1$, act on its other faces (Fig. 12). As a function of the angle of internal friction, the coefficient of active lateral earth pressure, i, has a value of

$$i = \tan^2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)$$

Mohr's circle (C_2) then becomes tangential to the intrinsic curve. In the absence of reinforcement, these stresses N_2 can only be produced by external forces. It is no longer a case of simple compression, but of restrained compression.

Let us now examine how the reinforcement produces stability in a cube of reinforced earth subjected to simple compression.



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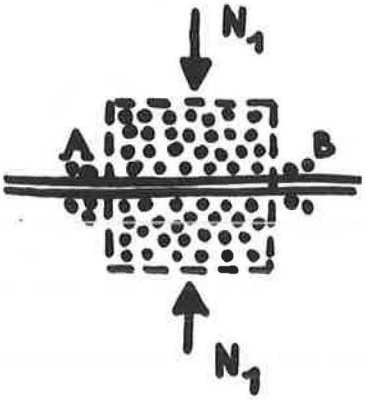

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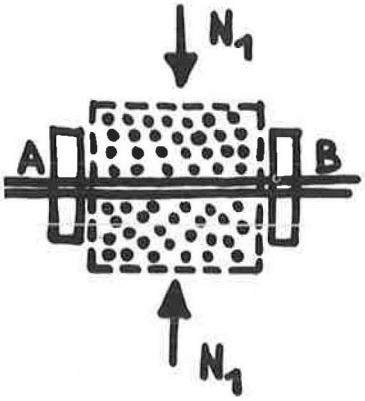


Figure 14.

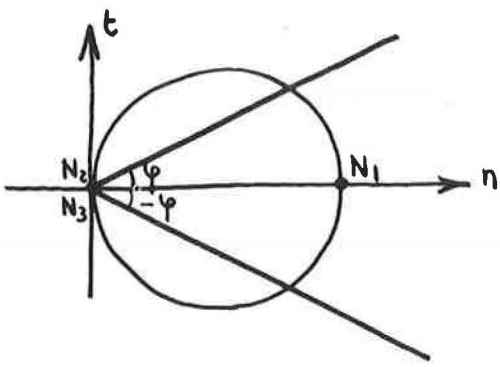
When considering an elementary cube of reinforced earth (Fig. 13), it is assumed that the reinforcement is arranged perpendicular to the direction of the compressive force N_1 in two directions at right angles. For this reinforcement to fulfill its function, it is assumed that there is no sliding between the reinforcement and the particles. Thus, the neighboring particles A and B are rigidly connected by the reinforcement.

If A and B are contained in the two portions of earth nearest to two faces of the cube (Fig. 14), but outside this cube, everything acts as if the two plates formed of the external particles, which can produce stress on these two cube faces, were connected by the reinforcement.

When the simple compressive stress N_1 is acting and when there is no compressive stress on the particles in the direction AB, sliding of the particles with respect to each other is automatically produced, since Mohr's circle passes outside the intrinsic curve (Fig. 15). The particles in the cube are in a plastic state.

But the elementary cube tends to compress in the direction of compression, and since the particle mass occupies a volume which is roughly constant, it tends to expand in the direction of the reinforcing members (Fig. 16). These expansions of the earth in the direction of the reinforcement are accompanied by extensions of the reinforcement. As a result, compressive forces, caused by the interconnection of the particle plates on either side, act on the faces of the cube.

The sliding of the particles within the cube is interrupted when the compressive forces become equal to i N_1 in such a way that Mohr's circle becomes tangential to the



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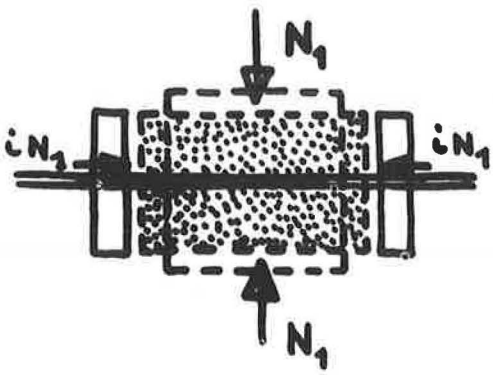

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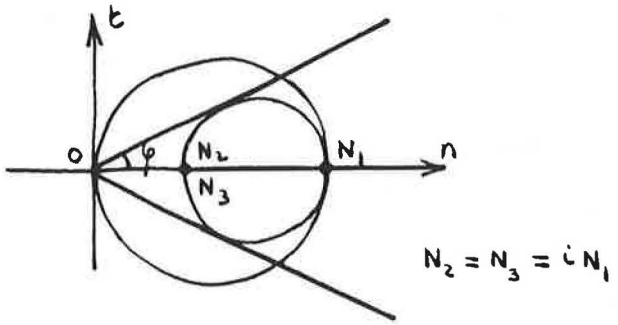

Figure 17.

intrinsic curve (Fig. 17). The complete reaction is that of an elastic body in compression, with a modulus of elasticity

$$E_t = \frac{ES}{2i}$$

where

E = modulus of elasticity of the reinforcements,
S = cross-sectional area of the reinforcements per unit area of earth, and
i = coefficient of active lateral earth pressure.

Pure Tension

In the case of pure tension, resistance to tension is provided only by the reinforcements. Assuming that there is no sliding of the particles with respect to the reinforcements, reinforced earth is elastic in simple tension, as if the reinforcement were there by itself, the modulus of elasticity being ES (E = modulus of elasticity of the reinforcement; S = cross-sectional area of reinforcement in tension per unit area of earth).

Elasticity of Reinforced Earth

As long as there is no sliding between the particles and the reinforcement, reinforced earth has an elastic behavior which is as effective in tension as in compression, but its elasticity is not the same in the two cases. Even if the density of reinforcement were uniform at all points and the same in all directions, the modulus of elasticity in tension would generally differ from the modulus of elasticity in compression, but not to a great degree. In practical applications this modulus of elasticity is generally small. Thus, although it may seem paradoxical, earth will often be as elastic as timber or reinforced concrete.

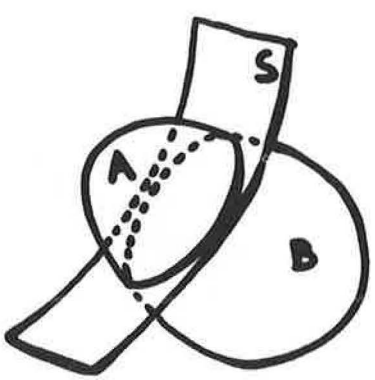

Figure 18.

But if earth shows elastic properties, it follows (in a very approximate way) the mathematical theory of elasticity, since the constant ratio between stresses and strains can vary with the direction of the stress and with the point under consideration. In tension, it varies with the area of longitudinal reinforcements; in compression, it varies with the section of transverse reinforcement. The exact mathematical theory of elasticity in the case of a non-isotropic material includes

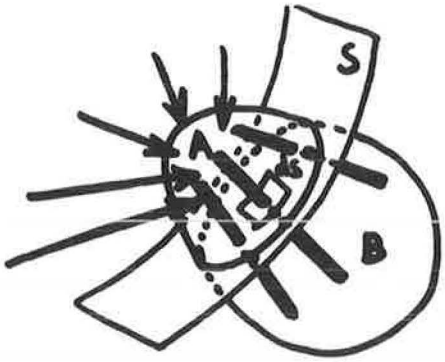

Figure 19.

too many parameters to permit its practical use without complicated calculations.

In fact, reinforced concrete also does not have the same elasticity in tension as in compression; moreover, in compression the elasticity of concrete varies with the value of the stress. Thus, there is never any proportionality between the forces and deformation at any point for a given direction, although this proportionality does exist for reinforced earth.

It should be remembered that when demonstrating the elasticity of reinforced earth in compression and in tension, it has been assumed that the particles were sufficiently compacted to eliminate cavities, so that during deformation the volume of a unit cube remained more or less constant. In actual practice, such may not always be the case, and the period of apparent elasticity of the reinforced earth may be preceded by a period during which collapse of the cavities and compacting of the grains produces an initial, non-elastic, permanent deformation, which would appear, for example in the case of a beam, as a permanent deflection.

The Design of Structures of Any Shape

For structures of any shape, two methods of design have been prepared.

First Method—In the first method, which is more practical, the volume of reinforced earth is cut by a surface S (Fig. 18) which divides it into two parts A and B. To prevent volume A from slipping with respect to volume B along surface S, under the action of forces acting on A and B, it is generally necessary to provide reinforcement connecting A and B. This reinforcement must be so arranged that there is no sliding of any element of surface dS anywhere on area S (Fig. 19).

Thus, it is assumed that over an element of surface dS, the result of the forces of A on B is R_1, making an angle greater than φ (Fig. 20) with the normal to dS. It is possible to arrange reinforcement connecting volume A to volume B with a tensile force F such that the resultant R_2 of R_1 and F makes an angle less than φ (Fig. 21) with the normal to dS.

Inasmuch as this arrangement can be provided for all the surface elements dS of the area S, reinforcement can prevent the sliding of A on B, and the size and spacing

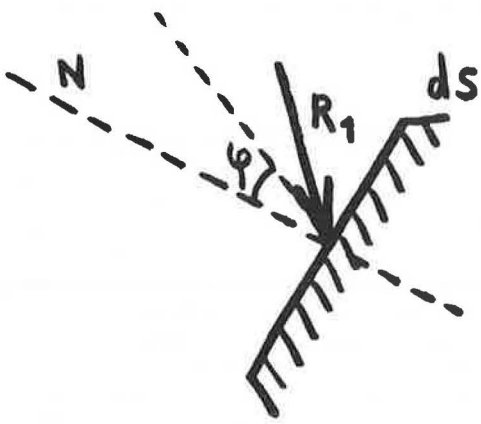

Figure 20.

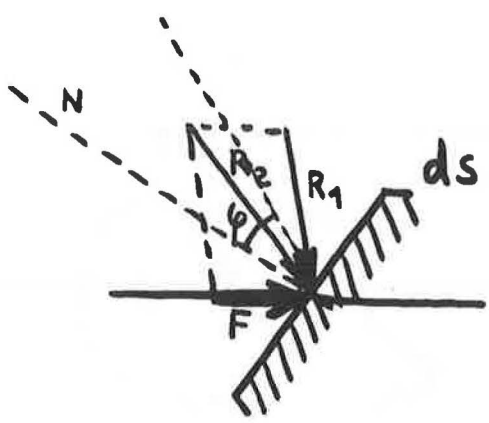

Figure 21.

of reinforcement necessary at each point can easily be calculated.

If this equilibrium condition can be achieved, for any area S cutting the volume of reinforced earth, then the entire mass will be in equilibrium.

In practice, the surface S is replaced by planes, and earth stresses in these planes are usually known with sufficient accuracy by assuming a linear distribution of forces of contact along these planes.

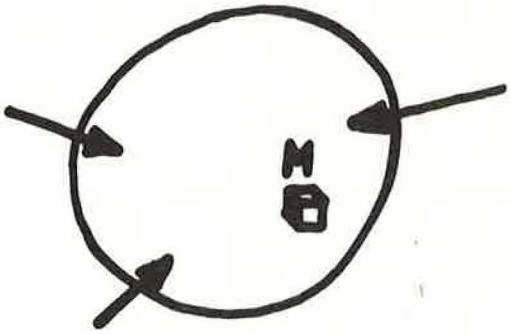

Figure 22.

Second Method—The second method calculates the stresses by the theory of elasticity (Fig. 22). A body of reinforced earth is elastic according to Hooke's law, that is to say that at a point M the deformations are linear functions of the stresses. For a body of any shape, it would theoretically be possible to determine the stresses at any point, as functions of the external forces—as if the body were following this law of elasticity. This law, moreover, takes into account the arrangement and size of reinforcement within the volume under consideration. In practice the calculation would generally be almost insoluble.

On the other hand, elastic calculations in which the materials are assumed to be isotropic and homogeneous are conventional calculations in a certain number of simple cases. For cases of complicated volume, the stresses and strains may be evaluated by photoelasticity.

Finally, in the case of an elongated body which can be compared to a beam, the stresses may be calculated still more easily by the theory of strength of materials.

It is thus tempting to try to apply the conventional theory of elasticity to a body of reinforced earth, if one could be sure that this comparison did not lead to major errors.

But it is even more tempting to do so, when one sees this theory of elasticity currently applied to concrete, which is not elastic since its deformations do not vary in a linear way with respect to the stresses; it is sometimes applied to reinforced concrete; and it is applied to many other non-isotropic materials.

If the stresses at any point are known in the case of an elastic body, according to the forces acting on the body, it becomes a question of seeing how these imaginary stresses make it possible to determine the stresses in the earth and in the reinforcement. These imaginary stresses at any point M may be represented by the corresponding Mohr's circle, C′ (Fig. 23). Since there is generally no reason for this circle to lie inside the intrinsic curve for the earth, equilibrium will not generally occur with granular earth.

Inclusion of reinforcement modifies the stresses in the earth in such a way that the new Mohr's circle at this point, corresponding to the earth alone, lies inside the intrinsic curve.

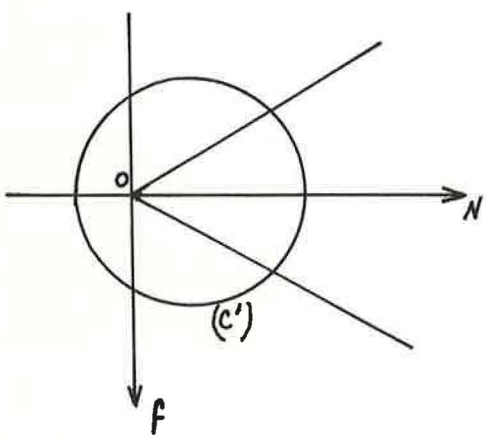

Figure 23.

Figure 24.

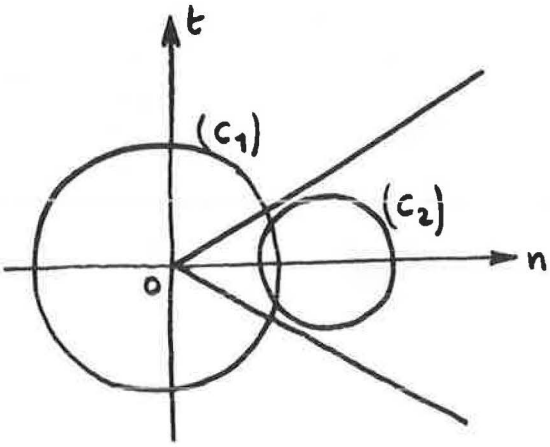

Figure 25.

In practice, during the course of general elastic deformation, the particles cannot remain in equilibrium without reinforcement, and slide in such a way that the reinforcement is placed in tension (Fig. 24).

If it is assumed that the connection at A and B between the particles and the reinforcement is done without sliding, and we have concluded that everything acts as if the two faces A and B of the elementary cube of earth formed two plates rigidly connected to the reinforcement.

The reinforcement is placed in tension between A and B with a tensile force F equal to the compressive force exercised by the plates on the grains. Thus, the effect of the presence of the reinforcement is to introduce an additional compressive force in the grains, parallel to the reinforcement and equal to the tensile force in the latter; the corresponding compressive stress has a value of n_a such that F equals S n_a, where S is the area of action of the reinforcement on the particles perpendicular to the direction of the reinforcement.

Taking into account this additional compression in the earth, a new Mohr's circle can be drawn (C_2) which represents the stresses in the earth alone around the point considered (Fig. 25). For the earth to be in equilibrium, this new Mohr's circle must lie inside the intrinsic curve for the earth.

The graphical construction which makes it possible to find the value F of the stress in the reinforcement is simple, and this method can be used to calculate all the stresses in the reinforced earth body.

CONCLUSIONS ON THE THEORY OF REINFORCED EARTH

The fundamental calculation for the friction between earth and reinforcement, which is the basis of the cohesion of reinforced earth, is extremely simple. When the stresses in the earth and the reinforcement are known, only a simple formula is needed for computation.

Insofar as the calculations for the earth and the reinforcements, it can be said that they are fairly close to the calculations which are made for conventional structures and materials.

The principal cases of pure compression and pure tension are calculated with the same degree of accuracy as for conventional structures. On the other hand, for work of no specified shape the calculations are fairly difficult—as is the case with other materials.

It is because structures of this nature may be encountered fairly frequently in reinforced earth that the two very different methods have been prepared for their design. And when these two methods have been applied to the design of the same work, the results have been very close in agreement.

But there is one point at which reinforced earth leaves all conventional materials far behind. This is the possibility of checking the most difficult calculations by means of scale models. These scale models are very simple to construct, and they will always offer a very effective method of checking the theoretical calculations. Therefore, they should advance the accuracy of this theory.

CONSTRUCTION OF REINFORCED EARTH STRUCTURES

In actual construction, the reinforced earth structures are composed of earth and reinforcing elements in the form of strips disposed in horizontal layers. In these

layers, the strips are set at certain intervals. On the facing of the structure, a certain type of boundary, or skin, is required to retain the earth particles that are not in contact with reinforcing strips.

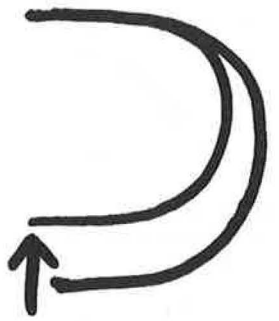

Figure 26.

The Skin

The skin must have certain qualities. First, it should have sufficient local resistance to retain the particles of earth contained between two adjacent reinforcing members close to the surface. But it must also have sufficient flexibility to follow all deformations of the mass, by forming an integral part of the mass. If the skin were rigid, it would find itself in contact with members external to the reinforced earth mass—the supporting ground for example. It would also transmit large additional external forces (about which little would be known and which would make it necessary to increase its rigidity even more). This would completely deprive the reinforced earth of its homogeneous quality.

Thus, walls made with sheet piling with tie rods and anchoring blocks are not reinforced earth structures, because their tie rods (wherein the tension is constant) have no similarity with reinforcement in which the tension varies and which links together particles in the earth mass.

The boundary skin must have the particular property of adequate local resistance, combined with overall flexibility. It must act as a protection by offering resistance to shock and abrasion; it must be in a material or of a color which is acceptable. It must be of a sufficient degree of tightness or must provide drainage. It must be designed in such a way that its placing, together with that of the earth and the reinforcement, is very simple. Finally it must have a high resistance to corrosion.

The skin may be plane, and may deflect through the simple elasticity of the material, just like rubber sheets. It can also be formed of rigid elements overlapping one another, as in the shells of numerous insects or crustacea (and there are several types of skin derived from this idea). But it may also be flexible by making use of curved areas (Fig. 26) with overall flexibility due to large curved surfaces.

The semi-elliptical cylindrical elements or skins arise from this principle. Starting with this basic element, it is always possible to construct a body of any required size in reinforced earth, because the surface of the body can always be broken down into a pattern of elementary rectangles (Fig. 27). This basic element, which can have widely differing dimensions, is economical since it works in tension under most filled conditions. It is stable, and its stability is guaranteed regardless of the forces in the earth, its characteristics, or its settlement.

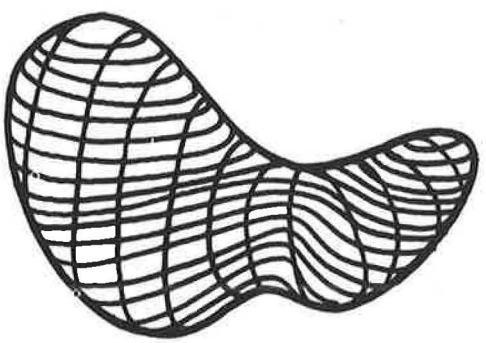

Figure 27.

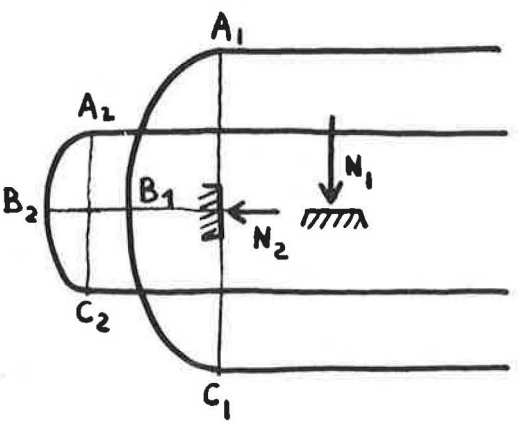

Figure 28.

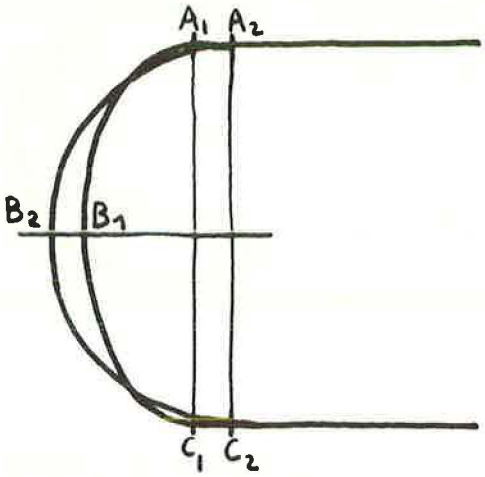

Figure 29.

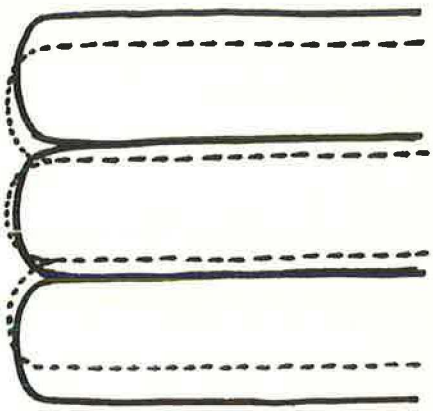

Figure 30.

The result can be shown on a scale model (Fig. 28). It can also be demonstrated mathematically by making the assumption that the stresses in the earth contained inside a skin element comply with a state of equilibrium similar to that of Rankine; that is to say, that the principal directions N_1 and N_2 are at all points parallel and perpendicular to the general line of the surface of the skin, and that the ratio of these principal stresses $N_1/N_2 = i$ is constant.

Under these conditions it has been verified, by the membrane theory, that the stable shape for a skin member is a semi-ellipse, with a ratio between the axes of $\sqrt{i}$.

When the value of i changes (Fig. 29), or does not comply with $\varphi = 30$ deg, chosen for the initial ellipse, the ellipse changes shape slightly until the ratio between the axes returns to $\sqrt{i}$, corresponding to the actual angle of friction of the earth. In practice, these two phenomena occur at the same time, and there is an adjustment with a change in the value of i (Fig. 30). The local radius of curvature of the skin then varies enormously.

It has been verified that with this special form it is possible for this deformation to take place and still give a factor of safety which is always greater than 2. This holds true no matter what the material chosen and for high values of skin tension. It is concluded that, from a purely mechanical point of view, the skin needs only a very small thickness to resist the forces acting on it. Other factors, such as corrosion, lead to increased skin thicknesses.

Corrosion is a factor to be taken into account. Galvanized steel or aluminum magnesium alloy have already been used in structures. Plastics have been tested. In the future, new types of metals, such as weathering steels, will certainly be used.

Outside the initial protection given by a coating such as galvanization, or various types of chemical coatings, one way to fight corrosion is to in-

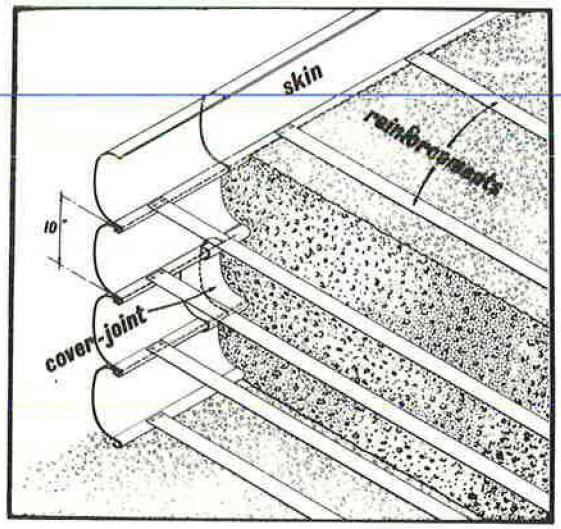

Figure 31.

troduce in the skin and reinforcements the necessary extra thicknesses of metal.

As previously shown, only small metal thicknesses are necessary from a purely mechanical point of view. Generally speaking, the metal in reinforced earth structures is under low stress, whereas sheet or tube piling is under high stress and corrosion can rapidly become dangerous.

Thus, the metallic elements of reinforced earth can be calculated to last the design life of the structure.

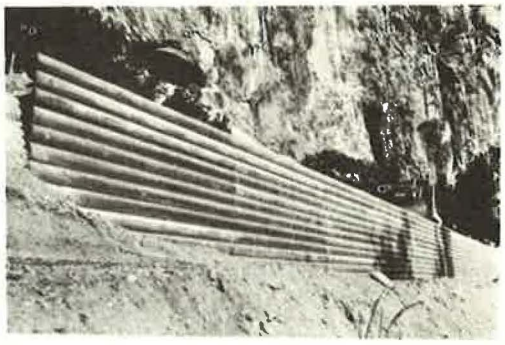

Figure 32.

Reinforcing Elements

Reinforcing elements can be made out of any material possessing the necessary tensile strength and in any shape giving the necessary friction surface in the required direction. Thus, strips, wire mesh, steel cables, aluminum alloy or plastic fabric have been and could be used. Most construction for walls has used elongated reinforcing strips made of galvanized steel or aluminum magnesium alloy. The strips are disposed in horizontal layers and tied to the skin elements (Fig. 31). They are set at calculated distances, depending on the forces acting on the structure.

The Earth

Between two horizontal layers of reinforcing strips, earth is dumped and, depending on the purpose of the structure, can be compacted or not.

"Earth" as used in this paper covers a great number of natural soils, composed mostly of granular material, with an amount of clay not exceeding a certain limit. This limit varies with the type of reinforcement used, the general condition being that sufficient friction exists between earth and reinforcement to generate the necessary tensile stresses in the reinforcement. With the conventional type of reinforcement generally used, this condition is met with earth having an international friction angle around 25 degrees.

When building reinforced earth structures, conventional testing methods for embankment materials are used.

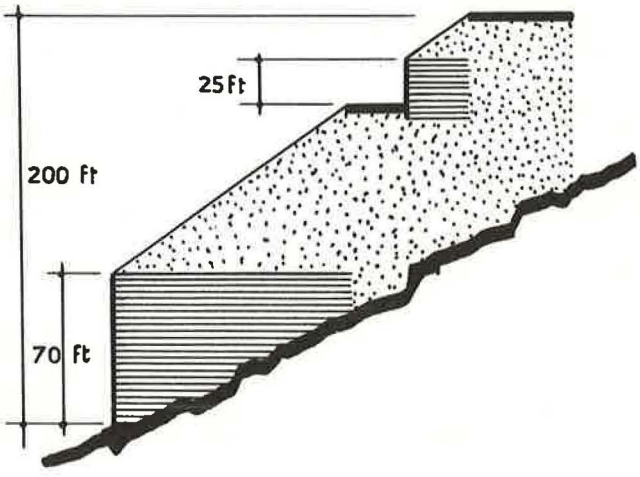

Figure 33.

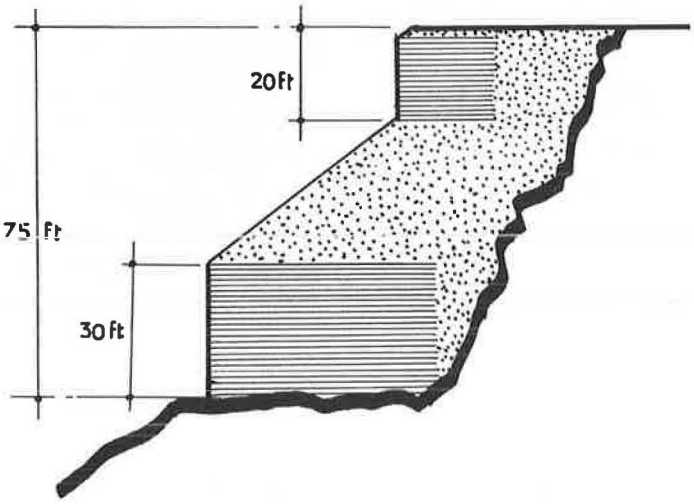

Figure 34.

Types of Reinforced Earth Structures

Most types of heavy foundation works can be built with reinforced earth as well as with concrete, the respective weights of these two materials being quite close. Thus, the volume of a reinforced earth structure can be similar to that of a comparable concrete one.

Earth-Retaining Walls—Figure 32 shows a typical wall, such as those on French-Italian or Normandy highways, constructed as an embankment to retain the adjoining land—thus reducing the necessary right of way.

Slope-Retaining Structures—Reinforced earth structures can be built on flat ground or on slopes (Fig. 33). The Peyronnet structure on the French-Italian highway was built to retain a large slope, 200 ft in height; an intermediate reinforced earth wall was built in the top section of the slope to provide a service road.

Platform-Supporting Structures—Figure 34 shows a typical example. The Vigna works, on the French-Italian Highway, consists of two reinforced earth walls, the top wall directly supporting the highway platform. The surcharge caused by the highway is taken into account in calculating the distribution and size of the reinforcements inside the structure. It is always possible to design a reinforced earth structure to support whatever external forces are exerted upon it.

Beams and Foundation Mats—The reinforced earth principle has been used in two works of this kind. One is a foundation mat to support a canal that had to pass over a section of ground containing gypsum beds where cavities could be expected to form due to flowing. The other is a roof over a uranium mine in Gabon. Both structures were made with wire mesh as reinforcement inside a mass of granular soil.

Underwater Structures—Underwater structures can be built with the same elements, using an aluminum magnesium alloy to prevent corrosion when working in seawater. Prefabricating techniques have been used to speed up the work, and entire wall panels, including skin elements and reinforcing strips, have been assembled on land and set in place under water as a unit.

Sand is then poured and the reinforcing strips released layer by layer (Figs. 35 and 36). Piers for harbors have been built in France, using prefabricating techniques.

Many other structures with varying shapes and sizes could be built. Walls to support highways or railways in urban areas, dams, cofferdams, and tunnels in embankments have been projected or tested, and calculations have been developed.

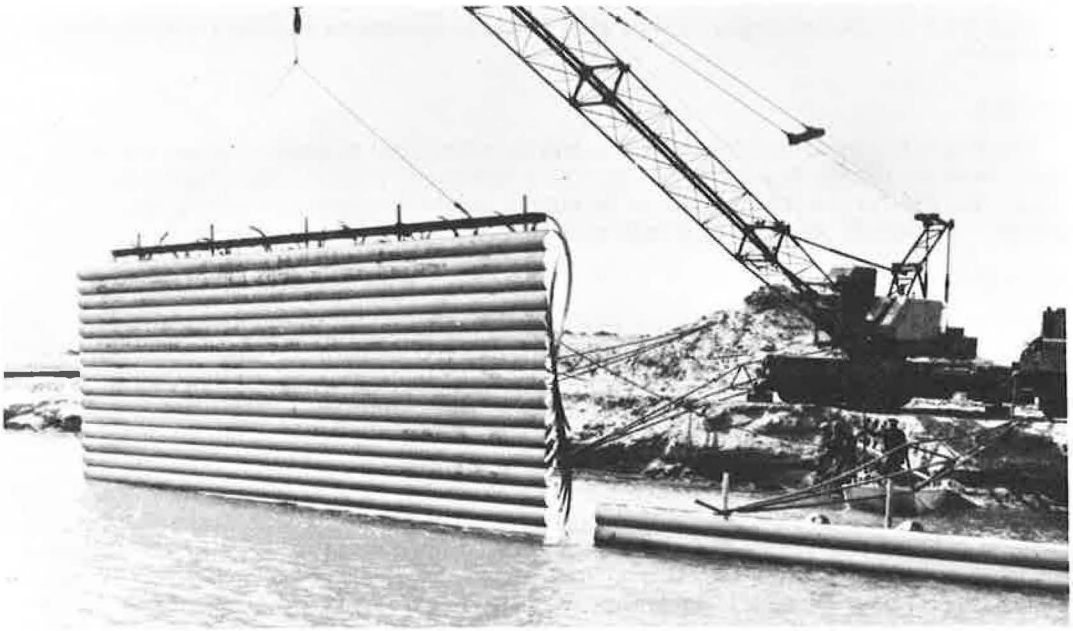

Figure 35.

REINFORCED EARTH PROPERTIES AND ENGINEERING PROBLEMS

The development of reinforced earth in civil engineering is recent; the first structures were built in 1964. Its use as a construction principle arises from several characteristics and indicates the place it is apt to fill in the future.

Heavy Weight

Reinforced earth is a heavy material like concrete. Heavy, solid structures able to resist high stresses or impact loads are often necessary and sometimes desirable for purely architectural reasons. Earth itself is being used in embankments, dams, highway supports, etc., but it requires handling large volumes and results in structures that occupy considerable surface lands that become costly in populated areas.

Reinforced earth has basically the same qualities, but with their vertical

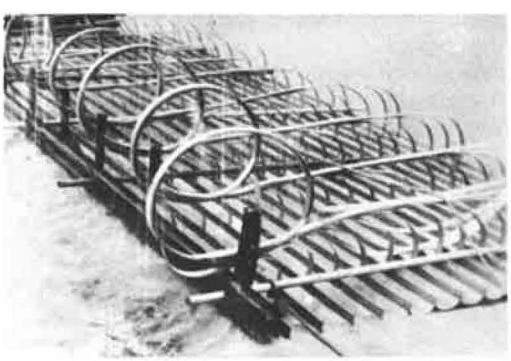

Figure 36.

Figure 37.

facings such structures reduce the amount of earth movement and the right-of-way necessary.

Strength

Unlike earth alone, reinforced earth can be calculated to resist almost any pressure, because the particles constituting the mass usually have a high crushing resistance, and the reinforcing strips can be placed inside the mass to resist external conditions. Figure 37 shows a very high wall built with a large safety factor.

Flexibility

The mass constituting reinforced earth being essentially granular in nature, deformations of the supporting foundation do not produce fissures or breaks, as would be the case with concrete. In fact, an infinite number of fissures or cracks exists in the mass, and movements of the ground cause these fissures to move. In such a case, the particles slide along the reinforcing elements to achieve another state of equilibrium—resulting in another stress distribution in these elements.

As long as the reinforcing elements are calculated to withstand these new loads, the whole structure remains stable. This phenomenon of plasticity with large deformation prior to rupture is an essential quality of every building material. Properly designed reinforced earth can possess this quality to such a high degree that resistance to earthquakes should be important. Naturally, stability to external forces induced by earthquakes should be considered, but reinforced earth should be more econimically favorable than conventional materials because of the necessity for a large horizontal base and inside dimensioning.

Simplicity

Building reinforced earth structures is simple and fast. There is no time factor for settlement and compacting is necessary only when it is desired to limit vertical settlement. Skin elements come in standard length, are easy to handle, and no heavy equipment is necessary. No special skills are required either.

Economy

Because of its relative simplicity, the economy achieved in comparison with concrete is great. The forces inside the mass of a structure are resisted by reinforcing elements placed according to calculations, and only in the direction required by the action of external forces. Concrete construction requires cement in all directions, making for an expensive and wasteful use of cohesive forces.

In French highway experience, reinforced earth structures cost approximately half what concrete structures would have cost for comparable uses. They were also less costly than all other types of retaining walls (crib or bin walls) that could have been used.

There is no height limit to structures made with the reinforced earth principle, and, indeed, its economic advantage increases with the height.

With these interesting characteristics, the reinforced earth principle can be expected to be used extensively in construction all over the world, filling a place between the large, heavy earth or concrete gravity works, and the ultra-elaborate reinforced or prestressed concrete structures.

Finally, it should be pointed out that the reinforced earth principle, and its applications, are patented in the United States and most other countries.