EARTH WALLS

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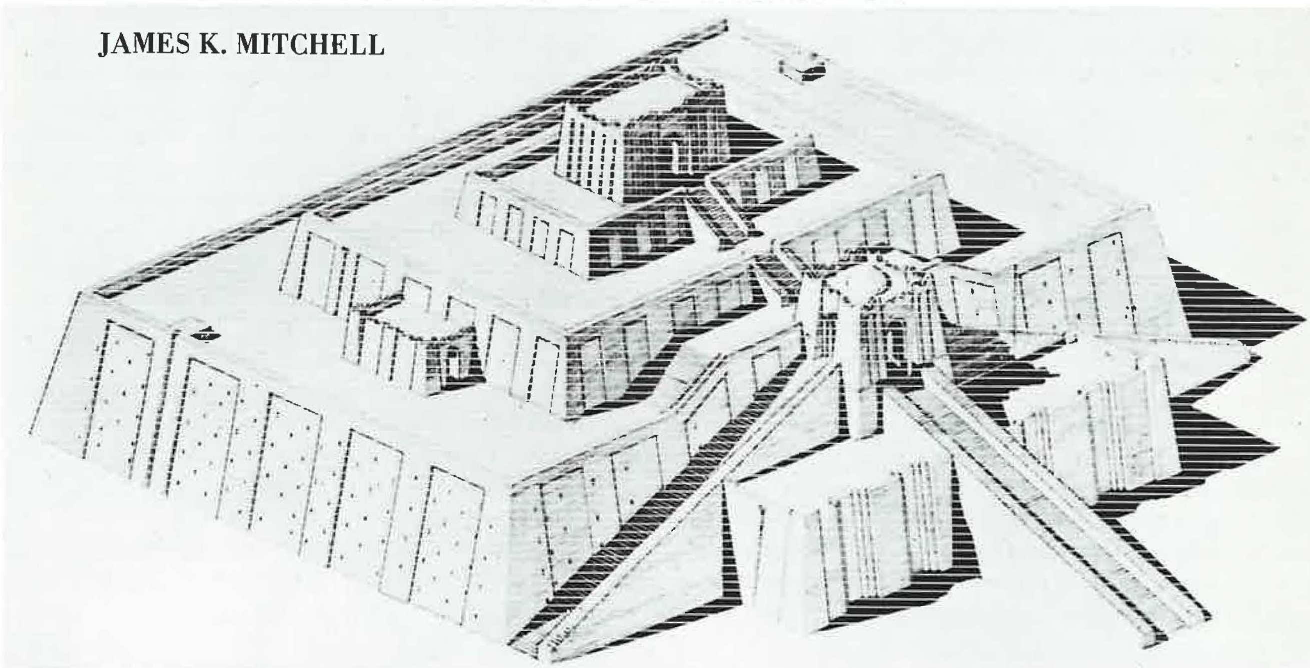
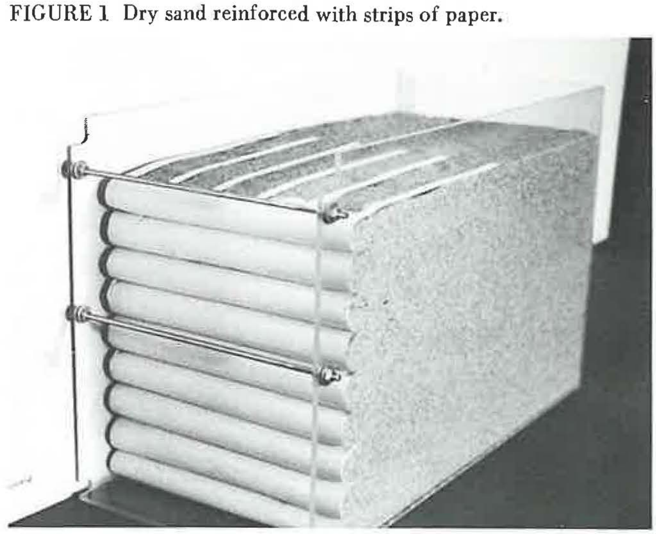


Ziggurat of Ur in Mesopotamia about 2500 B.C.

Soil is our most abundant and least expensive construction material. The range of soil types and possible states for any soil type is almost limitless. At a suitable density and moisture content most soils can be strong enough in compression and shear to be structurally useful.

FIGURE 1 Dry sand reinforced with strips of paper.



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On the other hand, like portland cement concrete, soil is very weak in tension, which limits its use for some applications, such as those requiring slopes steeper than the internal friction angle of the soil. But also, as is the case for reinforced concrete, the inclusion of reinforcements that are strong in tension yields a composite material that combines the best features of both components.

The inclusion of reinforcements within a sand can, as a result of stress transfers between the soil grains and the reinforcements, provide structures with vertical faces that are stable over long time periods. Figure 1 shows a dry sand in which strips of paper are incorporated as reinforcing elements. The paper used as the wall facing prevents running of the sand from the region between reinforcements; however, it does not assume a major structural or load carrying function. Without the reinforcements the vertical face would collapse, yielding a sand pile with a maximum slope equal to the angle of repose, or about 30 degrees to the horizontal.

Increasing use has been made, over the past 15 years, of earth reinforced in a manner similar to that shown in Figure 1 to construct new walls or to strengthen existing slopes. There are several reasons for this in addition to the low cost and abundant supply of earth: Little site preparation is required. Construction is simple and rapid. Reinforcements and facing elements can be prefabricated. Aesthetically pleasing structures are possible. Earth walls do not require unyielding foundation support, because they are tolerant of internal and external ground movements. Keen competition among the developers of different reinforcement systems has led to rapid technological development and continued cost reductions relative to both traditional types of reinforced concrete walls and other types of wall systems, such as crib walls, bin walls, and anchored walls.

EVOLUTION OF EARTH WALLS

That tensile inclusions in soil can provide reinforcement has been known for several thousand years. Large religious towers, called ziggurats, were built by the Babylonians between 5,000 and 2,500 years ago. These structures had walls faced with clay bricks in an asphalt mortar with blocks of sun-dried mud behind (see Figure 2). Layers of reed matting were laid as horizontal reinforcing sheets in the mud. In some ziggurats additional reinforcement was included in the form of ropes about 50 mm in diameter placed perpendicular to the wall and regularly spaced in the horizontal and vertical directions.

There is reference made in the Old Testament *(Exodus 5:6-9)* to the use of straw-reinforced bricks by the ancient Egyptians. Many primitive peoples used sticks and branches for reinforcement of mud dwellings. During the 17th and 18th centuries French settlers along the Bay of Fundy used sticks for reinforcement of mud dikes.

The modern development of earth reinforcement for walls was pioneered by the French architect and inventor Henri Vidal. The results of several years of study and experimentation led to Vidal's patent in 1966 for Terre Armee. The first highway use of a earth reinforced wall was near Nice, France (Figure 3). A schematic diagram of this type of wall is shown in Figure 4.

Earth reinforcement walls were first used in the United States in 1972 to provide support for California State Highway 39 along a steep slope in the San Gabriel Mountains north of Los

FIGURE 2 Ziggurat of Ur in Mesopotamia about 2500 B.C. Reinforcement is considered a major factor in its longevity. (From M. E. L. Mallowan, *Early Mesopotamia and Iran*, Thames and Hudson, London, 1965)

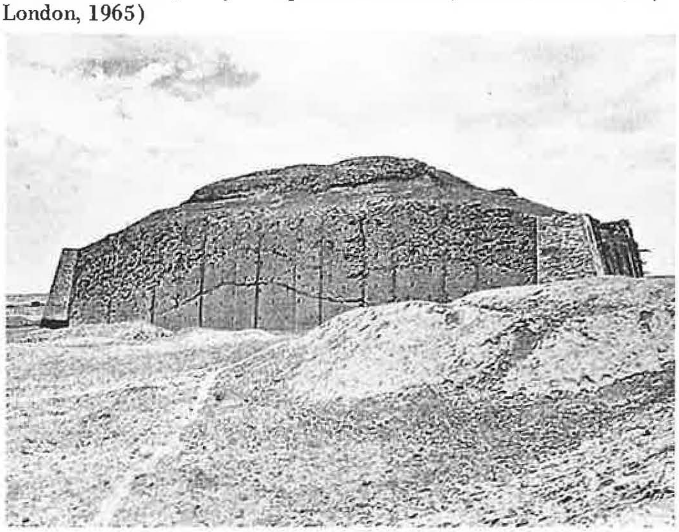
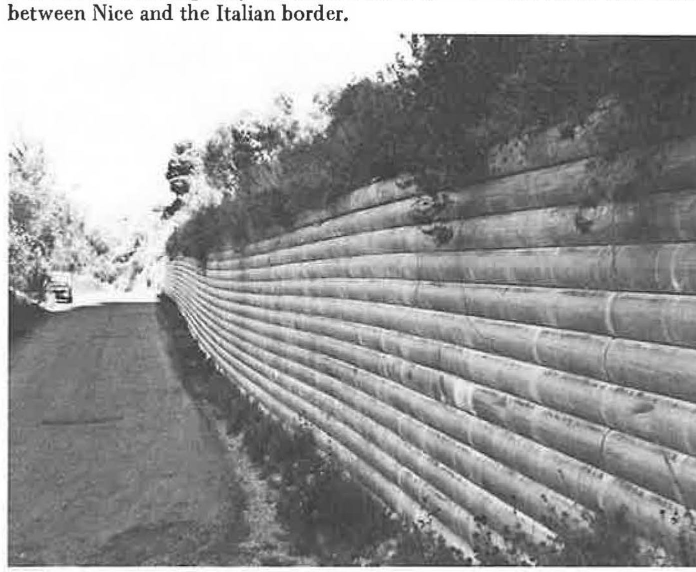


FIGURE 3 First highway use of modern earth reinforced wall: in France between Nice and the Italian border.



Angeles (Figure 5). An earth wall was well suited for the site because of its ability to withstand substantial deformations without failure.

CURRENT REINFORCEMENT SYSTEMS FOR EARTH WALLS

During the past 10 years the Vidal reinforced earth wall has been the most widely used. Galvanized steel-reinforcing strips are connected to precast concrete facing panels, which have largely replaced the metal facings used in early walls. An example of walls with concrete facing panels is shown in Figure 6. For aesthetic reasons special finishes or panel designs can be used, as shown in Figure 7.

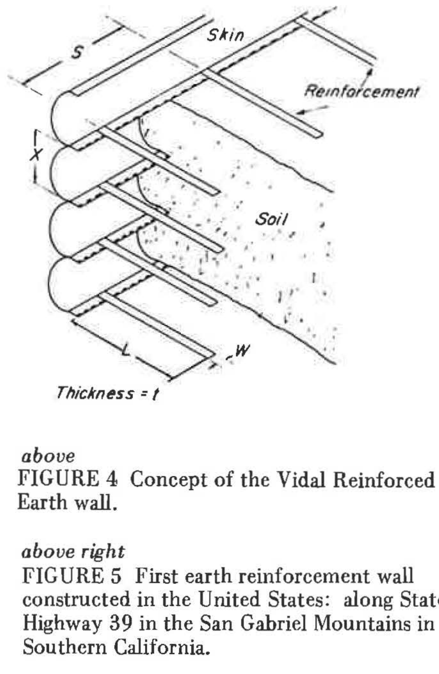
A number of other reinforcing systems and materials applications have been developed for earth walls as well. In the VSL retained earth system, horizontally placed wire or bar mesh systems are used (Figure 8). The Hilfiker welded wire wall uses wire-mesh reinforcement and a facing consisting of wire mesh covered by shotcrete (Figure 9).

Tensar geogrids are high-strength plastic composite grids that can be used in a variety of ways for containing, retaining, and reinforcing soil. Because the grids can easily be interconnected, a variety of combinations is possible. Large (1 x 1 x 1 m) earth- or rock-filled baskets similar to gabions can be stacked on top of each other to form walls or barriers. The plastic grids can be used during reconstruction of failed earth slopes to improve stability. An example of a brick-faced retaining wall using tensar geogrids is shown in Figure 10.

Synthetic fabrics for geotechnical use, termed geotextiles, have been used as earth reinforcement. They are particularly well-suited for relatively low walls along remote or relatively lightly traveled roads (Figure 11). A schematic diagram of the internal structure is shown in Figure 12.

The reinforced sacked concrete wall (Figure 13) is also a simply constructed system that is adaptable to remote sites. The facing consists of vertical reinforcing bars over which sacks full of premixed, but just wetted, concrete are placed by dropping the sack over the top of the bar. Wire-mesh or chain-link fencing is used as horizontal reinforcements in the manner shown.

Reinforcing systems are also used to strengthen existing ground to improve existing slope stability or to enable slope steepening in excavations without internal bracing or active anchor systems. Soil nailing consists of the insertion, by driving or drilling, of reinforce-



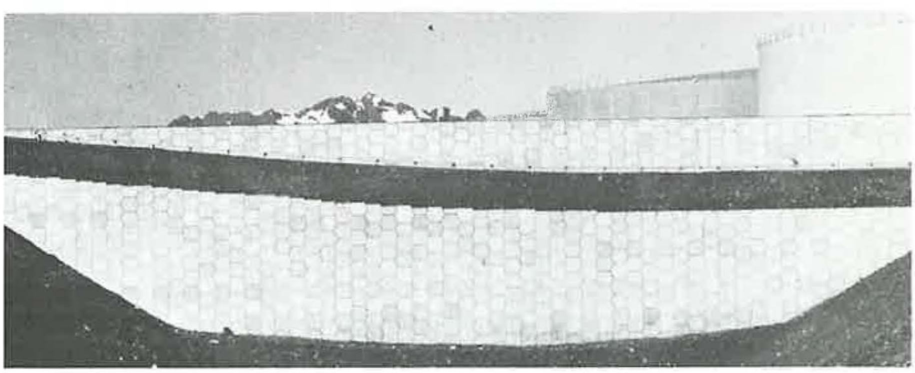


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FIGURE 4 Concept of the Vidal Reinforced Earth wall.

above right
FIGURE 5 First earth reinforcement wall constructed in the United States: along State Highway 39 in the San Gabriel Mountains in Southern California.

right
FIGURE 6 Earth reinforcement walls used at the Alaska Oil Pipeline Terminal at Valdez, Alaska.

ments into a natural or cut slope (Figure 14). Grouting around the reinforcements is often used to assure good bond between the soil and the reinforcements. Ground reinforcement of this type is distinguished from earth anchor systems in that the reinforcements are not prestressed, and bond between them and surrounding soil, in the form of friction or adhesion or both, is developed along their full length.

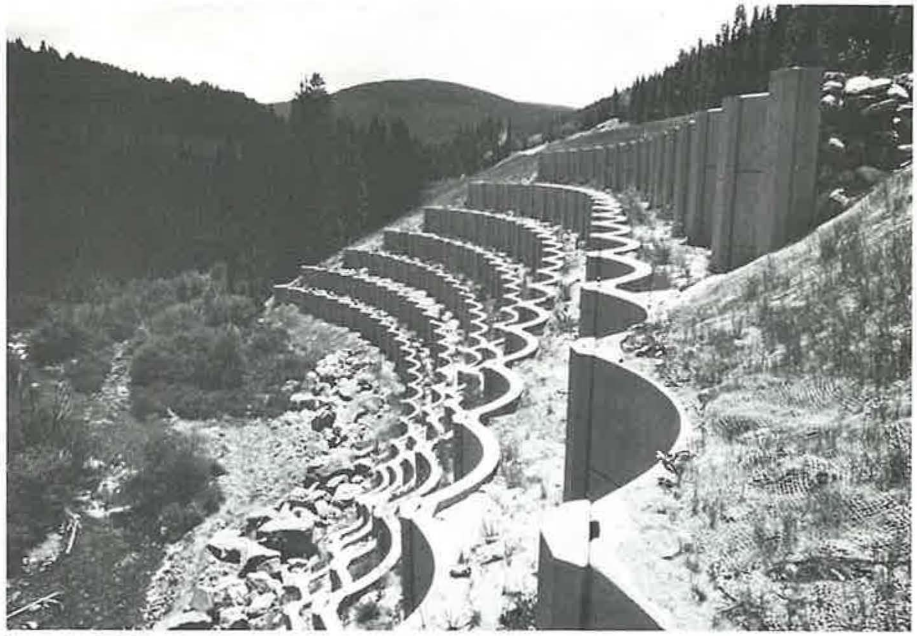


FIGURE 7 Special facing panels for reinforced earth wall along Interstate Highway 70 through Vail Pass, Colorado.

APPLICATIONS IN TRANSPORTATION SYSTEMS

Earth reinforcement systems of various types are being extensively used in transportation projects. Probably the two greatest uses are for retaining walls and bridge abutments, where they compete favorably, economically and

FIGURE 8 VSL retained earth system.

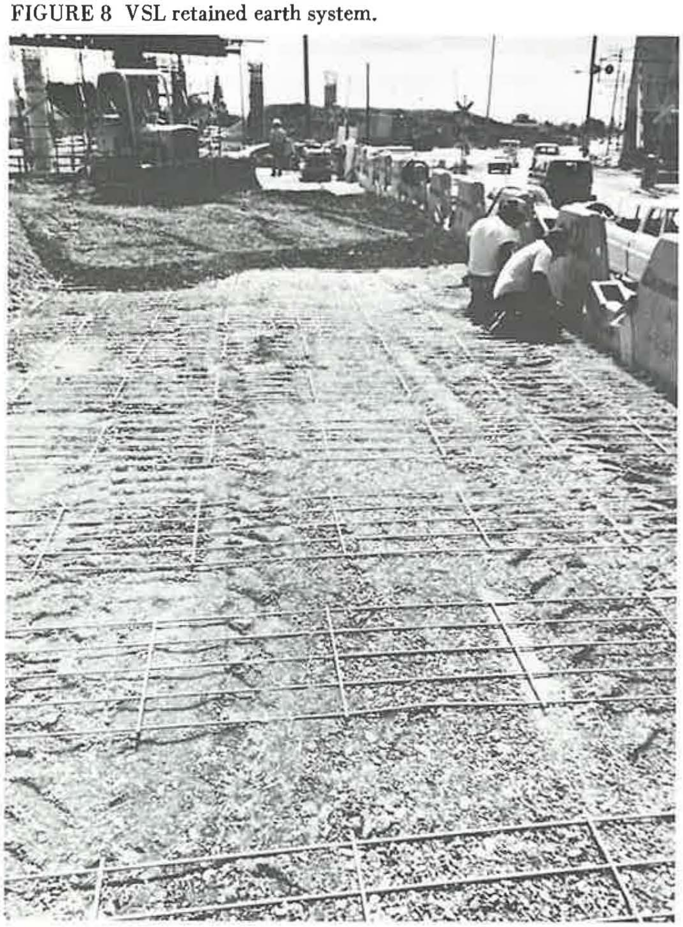
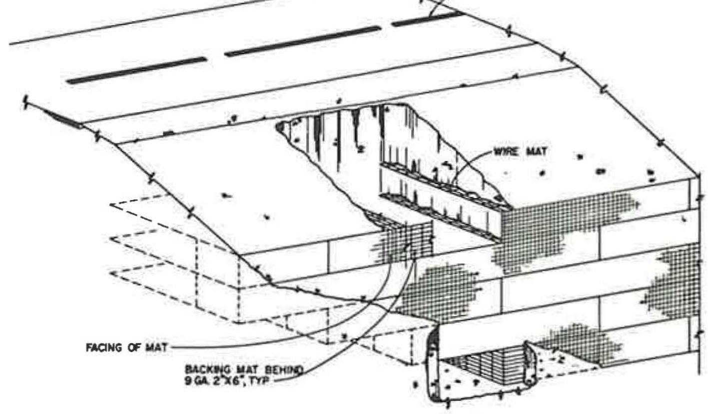


FIGURE 9 Schematic diagram of Hilfiker welded wire wall.



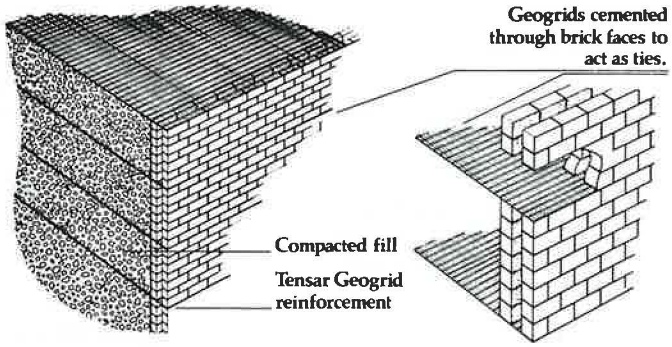
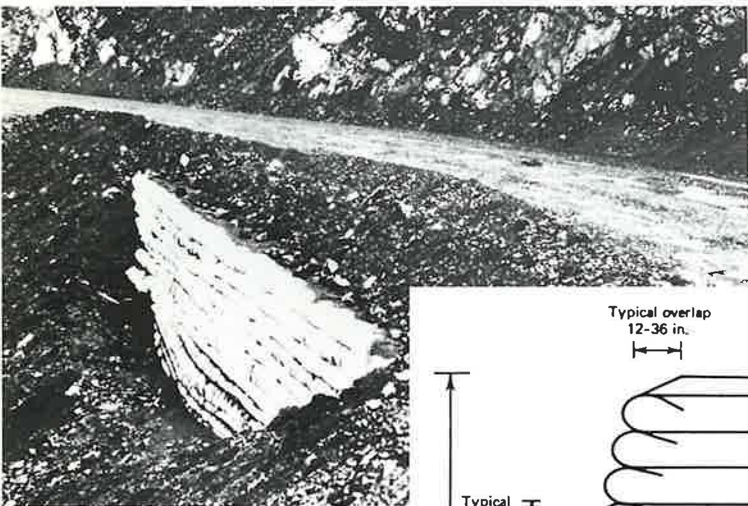


FIGURE 10 Tensar geogrids used to reinforce a brick retaining wall.



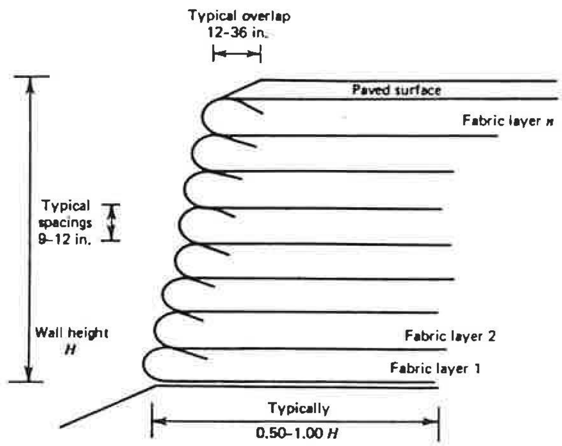


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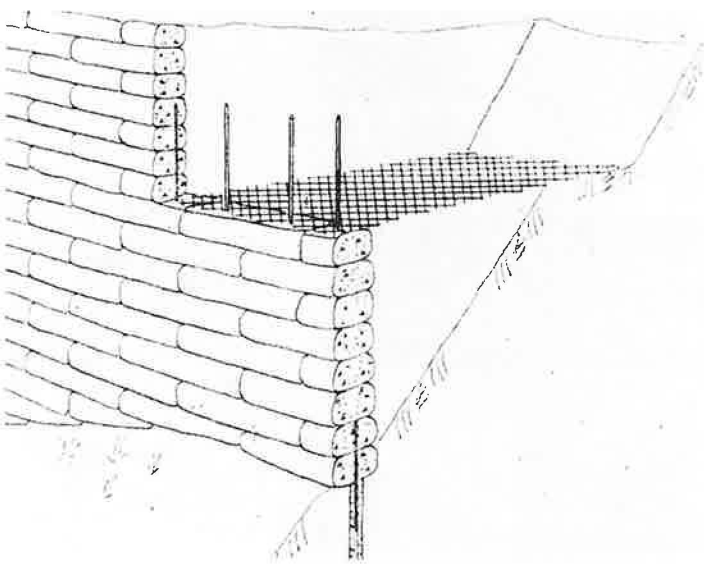
FIGURE 11 Fabric-reinforced earth wall.
right
FIGURE 12 Schematic diagram of fabric-reinforced earth wall.
below
FIGURE 13 Schematic diagram of reinforced sacked concrete wall.



aesthetically, with reinforced concrete. A bridge abutment application is shown in Figure 15. Earth reinforcement systems are useful for rail networks. The need to rehabilitate and expand existing road and rail systems in urban areas portends increased use in rights-of-way presently containing earth slopes that will have to be steepened or removed in order to provide the needed space. Any situation requiring an elevation change of more than a few feet is potentially suitable for application of an earth wall.

Earth walls have also been used for waterfront structures; for example, quay walls. Here the facing elements play an additional role: erosion protection for the soil behind. Geotextile and grid cell reinforcement systems are now being used for embankment reinforcement and for the support of embankments over soft foundations.

DESIGN CONSIDERATIONS

Earth walls are subject to the same external design criteria as is a conventional retaining wall: (a) they must be stable against sliding due to the lateral pressure

below
FIGURE 14 Soil nailing for improving cut slope stability.

of the soil retained by the wall; (b) they must resist overturning; and (c) there must be safety against foundation failure. Classical methods of soil mechanics have been satisfactorily used for the analyses necessary for this part of the design.

The internal design of the wall itself must ensure against

- Failure of reinforcements in tension,
- Pull out of reinforcements, and
- Loss of reinforcements by corrosion or other forms of deterioration.

To ensure against the first two failure modes requires knowledge of soil-reinforcement interactions, which depend, in turn, on soil type, reinforcement type and geometry, and stress state of the soil. The inclusion of linear, sheet, and grid reinforcements having high strength and tensile stiffness transfers load to the surrounding soil in two basic ways: friction and passive soil resistance. Figure 16 shows these two types of resistance for a bar mesh type of reinforcement. The relative contributions of friction and passive resistance depend on the sizes and configurations of the reinforcements, the soil type, the soil overburden pressure, and the strain in the system.

Little specific data about the relative contributions of the two types of resistance or the stress states in the soil are available. Nonetheless, it is clear that the reinforcements act to restrain soil deformations, which, in turn, increases the strength and stability of the soil component of the composite material.

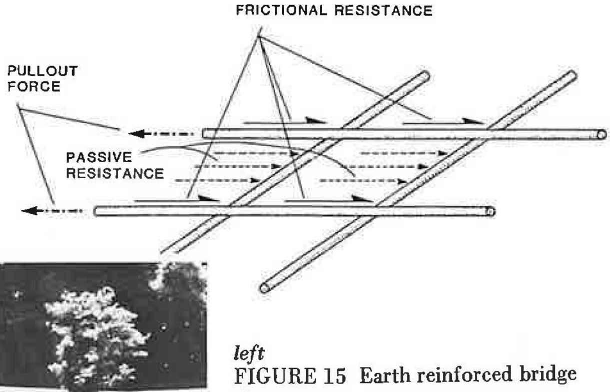
Many analytical, numerical, model, and full-scale field experiments have been performed to provide information on which the selection of needed parameters for design can be based. Sufficient information has been obtained from these studies and from experience with existing walls to ascertain that safe designs are possible for normal loading conditions.

The soil used in the reinforced zone of permanent-reinforced backfill walls is usually required to be cohesionless so that it will be freely draining, there will be a reasonable frictional strength, and there will not be problems owing to large creep deformations, as might be the case if a clay were used.

For the Vidal earth reinforced wall, the distribution of tensile stresses along reinforcements has been found to be about as shown in Figure 17. The locus of maximum tensile stresses as a function of depth is also shown. This geometry can be used with soil property and reinforcement data and suitable factors of safety in order to select length, cross-sectional area, and vertical and horizontal spacings of reinforcements. A similar methodology can be used for other reinforcing systems.

A generally accepted method for the seismic design of earth walls has not yet been developed. High-magnitude earthquakes were considered in the design of the walls at Valdez (Figure 6) and for other walls in areas of known seismicity. The design methodology led to a somewhat increased length of reinforcements and a higher density of reinforcements in the upper part of the wall. There appear to be no failures or significant distress of earth walls due to earthquakes.

Reinforcement durability is one of the areas of greatest concern at present. The rate of corrosion of metal reinforcements depends on many factors, most of which cannot be controlled over the long term in the ground; for example, local chemical concentrations and stray electrical currents.



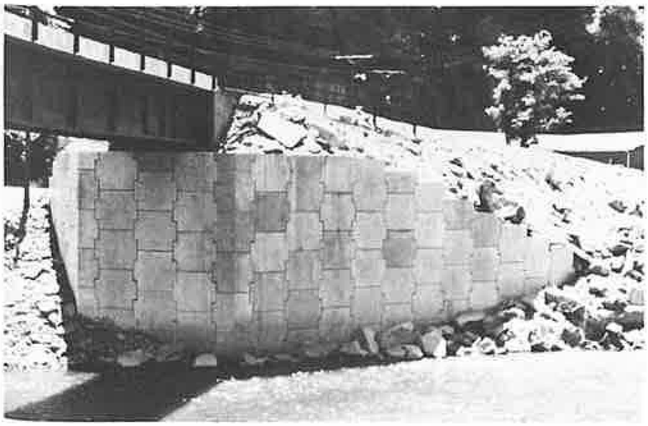


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FIGURE 15 Earth reinforced bridge abutment.

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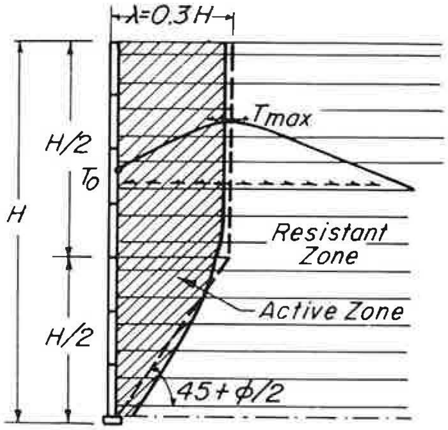
FIGURE 16 Frictional and passive soil resistance development by a bar mesh reinforcement.

right
FIGURE 17 Stress distribution along reinforcement and locus of maximum tensile stresses in a Vidal earth reinforced wall.



Galvanized steel has been extensively used. The by-products of zinc corrosion cover the base metal and tend to seal affected areas. A corrosion loss over the design life of the wall is taken into account in the specification of metal reinforcement cross sections. Epoxy-coated steel reinforcements have now been developed that offer the potential for high durability.

Nonmetallic reinforcing materials, such as geotextiles, fiberglass, plastics, and composites, while not susceptible to corrosion, may undergo other chemical and/or biological forms of deterioration. Unfortunately, many of the materials are new, and the effects of long-term burial and exposure to the elements are not known. Hence, durability emerges as an area of major concern, and further studies are likely.

CONSTRUCTION

In general, the construction of earth walls is relatively simple, rapid, and straightforward. Equipment for placing and spreading the backfill soil and a roller for compacting are required. Many types of reinforcement can be carried and placed by hand (Figure 18). If precast facing panels are used, a small crane will be required for handling them (Figure 19). Some facing types, for example, geotextiles, do not require equipment for installation.

A significant advantage over reinforced concrete walls is that no formwork is required. On the other hand, construction of an earth wall requires considerably greater space behind the wall face, because the reinforcement lengths are usually at least 0.7 times the wall height, whereas the base width of a concrete wall is only about 0.3 times the wall height.

COSTS

The costs for earth reinforcement walls today are less, in constant dollars, than they were 8 to 10 years ago, because the technology is maturing and because of competition among different earth reinforcement systems. FHWA experience indicates that cost savings of up to 25 percent or more are being realized on highway projects through the bidding of alternate wall types: gravity walls, cantilever walls, anchored walls, and reinforced backfill walls.

The total cost in any case will consist of the costs for materials, erection, backfill soil (if the on-site soil is unsuitable), and any special aesthetic treatment of the facing that may be required. A reasonable figure for the cost of materials and erection for walls in the height range of 10 to 15 feet is about $15 per square foot. For walls 15 to 30 feet high, the cost increases to $17 or $18 per square foot.

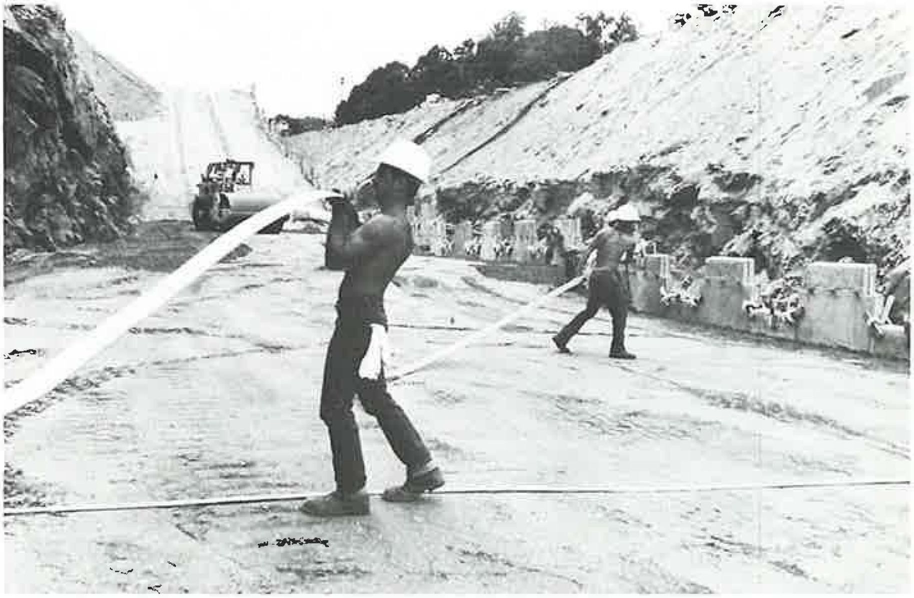
In urban areas reinforced concrete is likely to be more economical than reinforced earth for low walls up to 10 feet high. The two types are competitive for wall heights of 10 to 30 feet, and the earth wall is less expensive for heights greater than 30 feet.

THE FUTURE

A number of reinforcing systems have been developed for construction of earth walls. Some are best suited for permanent high walls; some are best for low walls; some have their best application in remote areas; and others must withstand the rigors of urban areas with high traffic volumes.

As experience broadens and uncertainties disappear concerning the durability question, it can be anticipated that earth reinforcement will see even greater use in surface transportation networks. The current competition among the manufacturers of different reinforcing materials and systems can only lead to more efficient designs.

FIGURE 18 Reinforcement placement.



The rapid development and growing importance of the field has been recognized at the federal level. Work on National Cooperative Highway Research Project 24-2, Reinforcement of Earth Slopes and Embankments, administered by TRB, is now in progress. An international team of experts has been assembled to evaluate and compare the major systems and methods. The results of this study, due to be completed in late 1984, will be disseminated in the form of a report providing the user with the information required to make the analyses, designs, and estimates needed for the rational choice of an earth wall system.

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FIGURE 19 Installation of facing panels.