Roads and highways are often constructed along the seacoast and river valleys just above the high water or normal flood stage elevation. This can pose technical problems when the river bank or seacoast is so narrow that new construction or widening of existing roads encroach on the river or the sea. Under these conditions, retaining structures are required which will be in permanent or temporary contact with either fresh or salt water.

It is common knowledge that during storms or floods, the combined forces of water and water borne debris can be highly destructive. Therefore, the design and construction materials used in retaining structures along river and coastlines must allow for the risks associated with this special environment.

Reinforced Earth™ is a proven alternative to other construction methods and materials used to build marine structures including highways and railways built along waterways and across dam spillways. It is easily adapted to these complex situations and has performance characteristics that have made it universally accepted in more traditional civil engineering applications. The worldwide use of Reinforced Earth as a standard construction technology has resulted from these inherent advantages:

- economy, which increases with the height of the structure.
- flexibility, whether on moderately compact or heterogeneous foundation soils.
- speed of wall construction and backfill operations.

The largest Reinforced Earth marine structure in the world supports and protects a coastal highway on Reunion Island in the Indian Ocean. Built during 1974 and 1975, this 11-km long wall (72,000 m³ of facing) has withstood the punishment of five cyclones, and continues to perform as designed.

In addition to roads and highways, Reinforced Earth is also used in the construction of dams and spillways. The first Reinforced Earth dam was built in 1973 near Hyères in Vallon des Bimes in France. The structure, 9m high with a downstream facing of 200m², creates a reservoir used to fight forest fires.

In 1984, the largest Reinforced Earth dam in the world was built in the United States at Rangely, Colorado. The dam measures 16.5m high and 165m long and retains 17 million m³ of water. The spillway and side walls are constructed of 3,500m² of Reinforced Earth facing.

Reinforced Earth marine structures have traditionally been constructed under dry conditions or during periods of low tide. Now, the underwater construction of quay walls has been successfully and economically demonstrated with the completion of three structures in Canada and the Solomon Islands.
Design procedures for Reinforced Earth marine structures are essentially the same as for non-marine structures. However, in many instances, special precautions are required in the choice of backfill and other construction materials to ensure good drainage within and from the reinforced volume of the structure.

Reinforcements
In structures either partially or fully submerged in fresh water, standard galvanized steel reinforcements are normally used. Uncoated steel reinforcements, 8 to 12mm thick manufactured from steel commonly used in marine piling, are required for coastal projects subject to inundation by seawater (saline).

Facing
The facing consists of standard, precast concrete panels and, in some cases, special panels designed to resist unique conditions such as unusual tides or stresses caused by wave driven lee or erosion. Structures often include panels designed for functional requirements such as wave deflectors.

Backfill
A major concern in the selection of backfill material is ensuring the long-term durability of the reinforcements. When standard Reinforced Earth galvanized steel reinforcements are used, the physio-chemical parameters of soils are somewhat more restrictive than those for ordinary dry land structures.

Good geotechnical design practice requires the use of materials that ensure adequate drainage, especially if the structure may be subjected to sudden rapid draw down and other variations in water level. Such drainage conditions can be achieved with backfill materials which contain less than 5 percent fines (< 74 μm) or in which the permeability coefficient exceeds 10^-7cm/s.

Materials with good drainage characteristics also exhibit a high degree of friction. Any backfill material used in an underwater structure must meet internal friction criteria defined by the properties of the fill when saturated.

Drainage and Protection
If permeable fill cannot be used for the entire mass, a free-draining layer of highly permeable material is often placed directly behind the panels. Filter cloth is used on panel joints to prevent sand from seeping through the joints. As in traditional marine construction, riprap or gabions are used to protect the toe of the structure.

Hydraulic Engineering
In structures with effective drainage, the water level inside the reinforced volume equals the river, dam or sea outside the structure. This will be the case even under conditions of tidal flow, rapid draw down of water level, or sudden discharges of water. If the structure is not essentially free draining the free water surface and pattern of flow through the reinforced volume at various stages or levels of water outside the structure must be estimated.

If the size of the projects warrants, this problem can be solved using computer or analog models. Typically, however, a simple and conservative estimate is made, in which the free surface is assumed to be horizontal within the Reinforced Earth volume.

Structural Design
The first step in designing a structure is to define the mechanical characteristics of backfill materials to be used in the zone above water levels and in the submerged zone below the water level (see Table).

- In the summation of the structure weight and external forces, i.e., of components \( \Sigma V \) and \( \Sigma H \) and their moment \( \Sigma M \) with respect to the middle of the base of the Reinforced Earth mass, the Meyerhof formula can be used to compute the "effective" vertical stress in the fill:

\[

e = \frac{\Sigma M}{\Sigma V} - \sigma_z = \frac{\Sigma V}{L^2-2a^2}
\]

- With \( U_z \) being pore pressure at point A (a point along the line of maximum tension) the "total" vertical stress at this point is

\[
\sigma_z = \sigma_z + U_z
\]

- The total horizontal stress to be balanced by the reinforcements is

\[
\sigma_x = K_0 + U_x
\]

neglecting the effect of flow forces, which are insignificant under normal circumstances.
When dry conditions prevail along coastlines and river valleys, traditional Reinforced Earth construction procedures are used for building retaining walls or bridge abutments. During periods of low water, the foundation and the first few rows of panels are installed. Along the coast this first step of construction is typically accomplished at low tide. In such cases, tidal fluctuations will flood the project twice a day, but experience has proved that this causes no damage to wall construction in sheltered sites or harbors.

Special care must be taken to prepare a stable foundation under the facing. The leveling pad should rest directly on rock, if rock is present, or on a thick layer of drainage material, which also provides protection against ground seepage. Generally, the foundation is additionally protected using gabions or riprap sized according to the wave forces expected at the site.

Durability of Reinforcements

The durability of galvanized steel reinforcements must be considered when selecting backfill for structures which are temporarily or permanently exposed to fresh water. The following chemical and electrochemical criteria must be met:

<table>
<thead>
<tr>
<th>Fresh Water Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity, saturated</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>[Chlorides]</td>
</tr>
<tr>
<td>[Sulfates]</td>
</tr>
</tbody>
</table>

When designing permanent structures, the sacrificial thickness required under these conditions ranges from 1.5 to 2mm.

Projects directly exposed to salt water are subject to particularly harsh conditions. Regardless of the electrochemical characteristics of the backfill, the seawater itself is the primary determinant of the corrosion rate of the reinforcements. For such structures 8 to 12mm thick black steel must be used. The excess thickness used as a reserve against corrosion assures the structure’s service life. With respect to the thickness of the steel used, this design approach is comparable to structures built with sheet or bearing piles. Many older structures of this type have been inspected to assess the rate of corrosion. It has been consistently observed that the extent of corrosion on the fill side of sheet pile walls and in the strips is much lower than on the surfaces exposed to sea spray or to tidal fluctuations. As has been the case, the long-term performance of reinforcements used in Reinforced Earth structures is always based on conservative durability assumptions.

Case Histories

The coastal highway on Reunion Island is a good example of a seacoast project. In this part of the world, where tropical storms are frequent and particularly violent, it was necessary to protect the structures against damage from the constant impact of ocean waves (Figure 1). This project was completed in 1975 and the combination of tetrapods and riprap has proved to be structurally sound and effective. In February 1986, the cyclone "Erinesta" produced extraordinarily high waves that cut off all traffic for four days, even in the inner lanes. At several points the waves toppled the wall, crossed the road and ditch, and reached the foot of the mountain cliffs. A 175m section of concrete continuous traffic barrier, battered by storm driven water, was forced back over the roadway. At some points the barrier shifted as much as 2m. The waves also detached metal guard rails from a 250m section of the barrier's median strip. Throughout the storm, the Reinforced Earth walls suffered only minor damage, primarily along their top edge and only on those portions of walls at the most exposed points along the route.

In the United States, four Reinforced Earth retaining walls, spanning a cumulative length of 3km and incorporating 23,500m³ of facing, support the Southern Tier Expressway along a section of road that runs between mountains and the Allegheny River in New York state. The use of Reinforced Earth reduced encroachment on the river to an absolute minimum while allowing the structure to blend in with the natural surroundings. The foundation consists of riprap that drops at a 2:1 slope toward the river. The embankment is protected by a concrete revetment. When the river recently reached its highest flood level in a century, the backfill was saturated and the water level rose to 3m within the structure.

Figure 1: Reunion Island. Typical section of highway built away from the cliff.
From 1978 to 1984, several sections of Highway 132 along the Gaspé Peninsula in Quebec, Canada were constructed on Reinforced Earth seawalls. In total, the project consists of over 55,000m$^3$ of walls extending over a cumulative length of 13,400km. Each winter, these walls are subjected to the build up of storm-driven pack ice. For added protection against the weather, the walls were built with 230mm thick, Z-shaped panels (Figure 2) that allowed for rapid construction (up to 700m$^3$ per day on this project) necessitated by the extreme tidal fluctuations experienced at that latitude. A special panel at the top of the wall deflects the pounding of ocean waves. The majority of these walls are built directly on rock, with no special protection at the foot of the structure.

In 1983, a parking area and boat launching ramp were built directly on reinforced earth walls at the port of Swansea on the southern coast of Wales in Great Britain. The maximum height of these walls is 10m; the tide can rise as high as 9.9m. At a depth of 1.3m, the wall rests on a bed of drainage material that was also used to replace pockets of soft clay. The footing, which is 1m in width, was prefabricated in 3m sections and secured to the lower half-panels, thus avoiding any need to pour concrete on-site.

The foundation was laid and the first row of panels installed during periods of low tide. At high tide, the job site was completely submerged. After construction in the tidal zone was completed, erection proceeded quickly, as on a land-based project. The base of the structure is protected against erosion by a stone embankment 1.5m thick. When designing the reinforcements of the structure, it was assumed that at ebb tide the difference between the level of the sea and the level of the water inside the structure was 2.5m, corresponding to one hour of tidal change.

Many other examples of Reinforced Earth marine structures built in or along the water can be found throughout the world. Currently, more than 300,000m$^3$ of Reinforced Earth walls or abutments have been built along rivers and coastlines.
The use of Reinforced Earth in the construction of earth dams allows the reduction or elimination of the structure's downstream slopes, resulting in considerable project savings. Reinforced Earth makes it possible to build a dam spillway with its sill at the very crest of the structure, eliminating costly gates and other flood control structures that would otherwise be required in addition to the dam. In the event of high water levels during construction, it is possible to allow a portion of the flow to spill over the unfinished dam. This provides added savings by minimizing the need for a temporary diversion of the water course.

These advantages may also be obtained with other types of vertical walls. However, Reinforced Earth has additional, unique benefits: structural flexibility on moderately compact or heterogeneous foundation soils, speed of construction, and the integration of embankment work with construction of the Reinforced Earth spillway.

**Design**

The stability of a dam and spillway depends on two essentially independent factors:

- computing the slope stability of the upstream embankment against failure
- computing the internal downstream stability of the Reinforced Earth volume.

The stability of the Reinforced Earth volume must be determined for two conditions:

- normal operations, for which a high level of security is required
- accidental (and unlikely) saturation, in which the dam ceases to be watertight and the drains become clogged.

In some cases, stability in two special conditions must also be examined:

- high water occurring in the course of construction and saturating all of the backfill
- the final phase of construction, in which interstitial pressures developed in impermeable fills might not yet have had a chance to dissipate.

In the latter three conditions, continued internal stability must be verified, although safety coefficients under these conditions may be reduced.

For each situation the process begins by defining "above water" and "saturated" zones. Next, loading conditions are determined from the weight of the structure itself, earth pressure, and hydrostatic pressures on the structure. It is then possible to compute the resultant of the internal and external forces and the effective vertical stress within the fill for each level of reinforcement. The resulting horizontal stress and the interstitial pressures determine the level of tensile stress in the reinforcements.

Pullout resistance of the reinforcements in the zone of resistance is then checked, taking into account effective vertical stress due to the weight of the earth and a friction coefficient that depends on depth and on whether or not the fill is saturated.

**Design of Reinforced Earth Dams and Spillways**

Upstream, the design of a Reinforced Earth dam is analogous to that of a conventional earth dam with respect to its impervious zones and the slopes required for the embankment. Downstream, however, the situation is different. Reinforced Earth structures have a vertical facing on the downstream side (Figure 3). Thus the volume of the dam can be reduced by half. The length of the intake and discharge channels and conduits are also reduced.

The upstream impervious barrier may consist of a surface membrane or of a core of impervious material placed behind, and possibly above, the reinforced volume. As usual, a drainage system, including a filter, is installed just behind the water barrier to absorb any leaks. When the reinforced backfill is not highly permeable, the system also includes a drainage layer directly behind the facing panels. The spillway is normally formed by a single reinforced concrete slab placed in a notch in the dam's crest, through which the water is conducted downstream. To protect the dam from harmful erosion, its foundation is built below the bottom of the settling basin, and/or the impact area of the water flow is covered with riprap (energy dissipation).
Construction
The Taylor Draw dam on the White River in Colorado (USA) is the largest and most complex dam and spillway built of Reinforced Earth (Figure 4). The dam is 380m in length and consists of these two sections: low embankment section from each abutment, and a central section of Reinforced Earth that supports the spillway. The wingwalls are also built of Reinforced Earth. The flow of the spillway can reach 1,850m³/s.

Imperviousness of the foundation and dam is assured by foundation injections and a core of impermeable material. The Reinforced Earth volume is drained by two vertical upstream and downstream drainage zones. In addition, a geomembrane covers the reinforced volume to prevent water penetration from above. The structure is capped by a reinforced concrete slab which ends in the slope of a flip bucket spillway.

The savings resulting from the use of Reinforced Earth on this project have been estimated at almost one and a half million dollars.

Increasing the Height of Existing Dams
Reinforced Earth can also be used to form a double-faced structure used to raise the height of an existing earth dam and increase the holding capacity of the reservoir it impounds (Figure 5). Compared to other materials, the advantages of Reinforced Earth are:
- its flexibility, which is important for structures founded on large embankments
- the uniform distribution of loads throughout the structure which results in the least possible impact on the entire structure
- the increased stability of the existing embankment.

Of course, a dam built in this manner must not be subject to overtopping.

The earth dam at Lake Sherburne in Montana (USA) is 60 years old and rises to a height of 26m. In 1983 it was topped with a double-faced Reinforced Earth wall 7.3m wide, 6m high, and 350m long, increasing the reservoir holding capacity to approximately 200 million m³. The Reinforced Earth solution was 35% less expensive than other methods for raising the dam, such as widening and raising the embankments which would have increased the risk of overloading the foundation.

Dam Restoration
The restoration of a 100-year-old dam in Jamesville, New York (USA) was required because of its precarious condition and recreational value to the local community. Economic considerations and public opinion dictated that the dam be strengthened rather than removed. Reinforced Earth was specified for stabilizing and improving the stability of the structure. This century-old dam is 15m high and retains 9 million m³ of water. Built of stone and cyclopic concrete masonry, the dam exhibited general bulging of the downstream facing and water seepage and occasional flows from open joints between blocks. Its renovation consisted of building a new high-water spillway of Reinforced Earth with a sloped facing that abuts the downstream face of the old dam, thereby strengthening and stabilizing it. A reinforced concrete slab covers the panels and seals out water (Figure 6).

Figure 4: Front face elevation and typical cross-section of Taylor Draw dam.

Figure 5: New section of earth dam at Lake Sherburne.

Figure 6: Cross-section of Jamesville, New York dam.

Lake Sherburne, Montana.
Conclusion

Reinforced Earth is a proven and effective construction material readily applicable to marine structures such as retaining walls, bridge abutments, quay walls, and dams and spillways. The use of Reinforced Earth offers significant project cost savings, design flexibility, and rapid construction. As an alternative to traditional materials, Reinforced Earth has demonstrated superior performance characteristics in almost any application, whether on dry land or submerged in water.