TER-VOILE Retaining Works

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The TER-VOILE concept is a process for building retaining walls. A thin shell structure provides stability through the high level of interdependence between the mass to be retained and the structural elements. The basic structural element is the thin membrane. It is a spatial, U-shaped cell that opens towards the backfill. This unit can be made from curved or straight corrugated steel sheet, mesh, or from a sheet-mesh combination. The combination of several membranes and their backfill constitutes the retaining wall. The formation of arches on the horizontal plane within the membrane creates the soil-structure interdependence that makes the TER-VOILE structure a single monolithic mass.

The TER-VOILE® process is used to create structural units that are satisfactorily able to resist vertical and horizontal pressures. This resistance is achieved through the high level of interdependence between the cellular structure formed by the thin, factory-produced membrane and the large volume of earth on the site. The earth-structure combination results in a monolithic composite mass, similar to concrete gravity walls.

The basic structural element is a thin membrane (the "voile") which is designed to produce a U-shaped cell opening towards the backfill. The TER-VOILE structure uses materials of adequate tensile strength.

Figures 1 and 2 show a TER-VOILE cell with its characteristically curved central portion (the "facing") and the two straight end edges (the "restraints"). The basic cell is made of sheet metal or mesh, or of a sheet-mesh combination.

The U-shaped membranes are placed side by side as shown in Figure 3 to form the TER-VOILE structure. Successive layers of backfill (soil) inside the cells ensure interdependence between the structure and backfill, thus completing the soil-cell structure (Figure 4). The TER-VOILE structure is subject to constant tension and utilizes the mechanical properties of the construction materials to the fullest extent.

The thin membrane structure is specially selected and custom made. The backfill is taken directly from the construction site. This backfill is generally good-quality granular materials from borrow pits and already used in construction. In certain cases, laboratory testing may be required. In practice, construction will be facilitated by taking at least 2 m for the width of each cell. Assembly may then proceed by bolting together the face plates and the restraints (or anchors).

This description is based on classical soil mechanics as applied to TER-VOILE structures, supported by tests on numerous scale models (1,2) as well as by observations on the structures at University of Sherbrooke and Grandes Piles (2). However, the description does not enter into the special anchoring required for wire-mesh TER-VOILE structures.

In short, TER-VOILE creates composite structural units based on the interdependence between the structure and the mass to be retained. Backfilling completes the procedures.

THEORETICAL BASES

Cell Geometry

For this study of a retaining device, a basic unit will be examined consisting of a cell formed by a facing, two restraints, and a reference plane (fictional) (Figure 5). The system of coordinate axes and geometric characteristics are also shown in this figure.

Earth Pressure

Earth pressures are important factors in the calculation of TER-VOILE retaining structures. The effect of these forces is derived from well-known theories that are widely documented (3,4).

With regard to TER-VOILE structural units, earth pressures are considered to be applied within the structural cell—on the facing and restraints in particular. The TER-VOILE cell, with backfill confined to the inside of the cell, is then subject to earth pressures on the structural cell coincident with the back of the restraints.
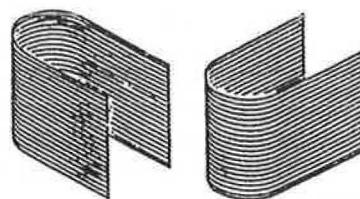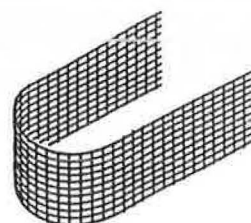

FIGURE 1   Thin shell (plate).

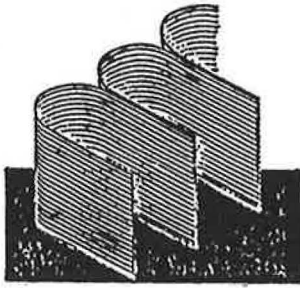**FIGURE 2   Thin shell (wire mesh).**
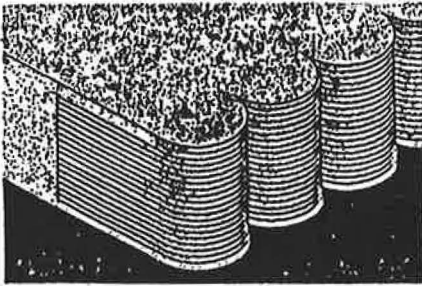
FIGURE 3   TER-VOILE cells.
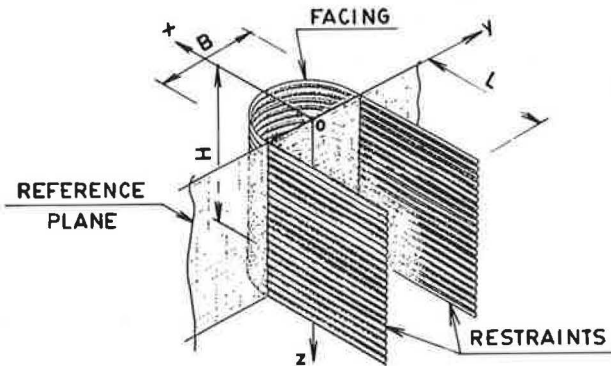

FIGURE 4   TER-VOILE structure.

FIGURE 5   TER-VOILE geometry.

DIMENSIONING

The TER-VOILE structure must be designed to ensure (a) resistance to the worst combination of exterior pressures and (b) behavior as an integral unit of earth and thin element. Overall stability must be ensured as for any gravity structure.

Internal Stability

The TER-VOILE structure shown in Figure 6a is considered to be subject to earth pressures on the reference plane (Figure 6b). Similarly, earth pressures are exerted within the unit on the restraints (Figure 6c). It should be noted that according to measurements (5) earth pressures exerted on the reference plane are compatible with the (constant) coefficient of pressure at rest. At the current stage, the use of a constant K_o is proposed by the author.
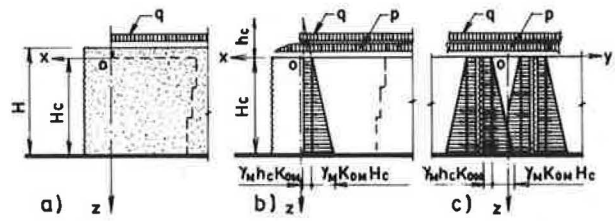

FIGURE 6   Thrust from inside a cell.

Consequently, stresses within the TER-VOILE structure at depth z are as follows:

1. The vertical unit stress (a function of depth, z):

$$\sigma_z = \Phi(z) \tag{1}$$

and

2. The horizontal unit stress in all directions:

$$\sigma_x = \sigma_y = K_o \, \sigma_z \tag{2}$$

K_o is the at-rest pressure coefficient, which is calculated as

$$K_o = 1 - \sin \phi \tag{3}$$

where ϕ is the internal angle of friction of the backfill.

Unit stresses in the thin membrane of the TER-VOILE cell are determined using the following methodology (Figure 7):

Step One

The semicircular facing used in this example may be compared to a cylindrical shell whose reference plane coincides with a diameter.
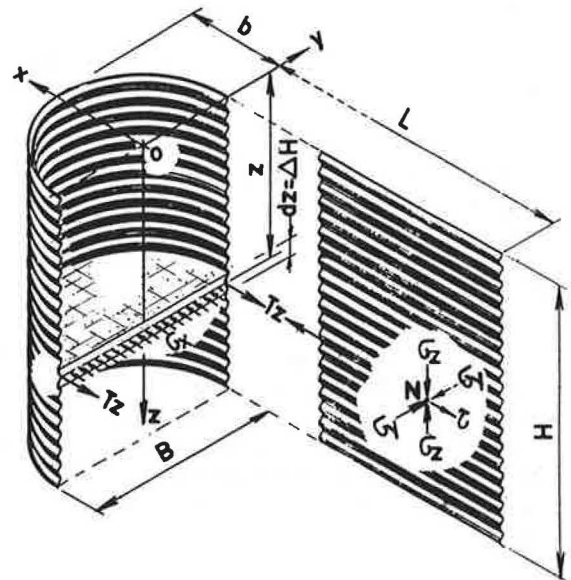

FIGURE 7   Forces on structure.

The cylindrical facing shell is very thin compared to the radius of curvature. Consequently, the stresses can be calculated with high precision by assuming that tensile stresses are uniformly distributed across the thickness of the shell.

The half cylinder that forms the facing and is subject to earth pressure may also be considered to be a very long, thin-walled cylindrical reservoir. Its tensile stress can be calculated for a unit with height ΔH at depth z as the following transmitted to the restraints:

$$\tau_z = \frac{1}{2} \sigma_x \cdot B \cdot \Delta H \qquad (4)$$

The restraints are acted on by two contiguous facings.

Step Two

The internal angle of friction ϕ is a characteristic of the backfill. The soil-structure angle of friction ψ depends on the surface of contact. From the observations on scale models (5) and the structures already built, this angle is relatively high. This high angle results from the creation of arches (discussion to follow). With current knowledge, the design criteria (6) used do not allow for an angle ψ in excess of 75 percent of the angle ϕ.

However, by using high-adherence (embossed) surfaces for soil-structure contact, ψ may be taken equal to ϕ, and this assumption will be made in what follows.

The coefficient of friction may be written as

$$f = \tan \psi \leqq \tan \phi \qquad (5)$$

The stresses on the restraint plane at a point N are shown in Figure 7.

The values of σ_x, σ_y and σ_z are given in Equations 1 and 2.

To determine unit tangential stress, Coulomb's linear law for noncohesive materials has been taken:

$$\tau = \sigma_y \tan \phi \qquad (6)$$

Given that the restraints may be thought of as an extension of the facing elements, they must be capable of transmitting force into the backfill mass by friction or by shearing. It must be ensured that friction exists without sliding at every point of contact between the structure and the soil. This results in the following equation:

$$f = \tan \phi = \frac{\tau}{\sigma_y} \qquad (7)$$

Using Equation 4 and referring to Figure 7, we can see that the tensile stress in the facing is transmitted to the restraints and must equal the sum of the tangential stresses. To express this, point N (Figure 7) will be isolated as a fragment of surface $dl \cdot \Delta H$, as shown in Figure 8. Integration of the equilibrium equation along the restraint gives the required length of the restraint:

$$l = \frac{Tz}{f \cdot \Delta H \cdot \sigma_Y} = \frac{B}{2f} \qquad (8)$$

In practice, a factor of safety must be added to this equation, depending on circumstances (6). This should be at least 1.5 at every level as well as overall.

A very important feature of the TER-VOILE structure is the formation of arches in the horizontal plane. This is the key factor in the soil-structure interaction that ensures the entire block will function as a unit. Consider a horizontal plane at a certain depth within the TER-VOILE structure. The interaction between the soil and the structure is illustrated in Figure 9.

Earth pressure in both directions is represented by σ_x and σ_y. The stresses σ_y cancel each other, whereas the stresses σ_x tend to destabilize the structure (Figure 9a). To achieve equilibrium, displacement of the structure will result in friction τ (Figure 9b), which counteracts and cancels σ_x. In addition, the sum of stresses $\bar{\sigma}_y + \bar{\tau}$ represents the reactions of the horizontal arches in the backfill. The same action occurs in silos, but in a vertical plane.

The formation of arches is the basis of the monolithic character of the structure and the backfill mass. In TER-VOILE structures, the creation of arches has been proven in laboratory tests on scale models and on the Grandes Piles prototype.

Numerous laboratory tests are available for analyzing the monolithic nature of TER-VOILE cells. Failure has been found to occur when the ratio of restraint length to wall height (L/H) is less than 0.3. With an L/H ratio of 0.4 or greater, deformations are tiny (see Figure 10).

Based on current knowledge, the following formula for calculating dimensions is proposed:

$$L_m = (0.6 \text{ to } 0.7)H_c \text{ with } B \leqq 0.5H_c \qquad (9)$$

and

$$L_m \geqq 1.2B > \text{ with } B > 0.5H_c \qquad (10)$$

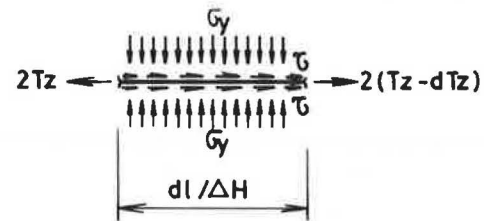The restraints of the experimental structure at Sherbrooke (each cell was 5.5 m high and 2.5 m wide) were fitted with

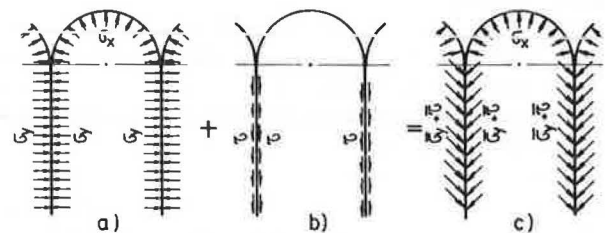**FIGURE 8   Equilibrium of a restraint.**

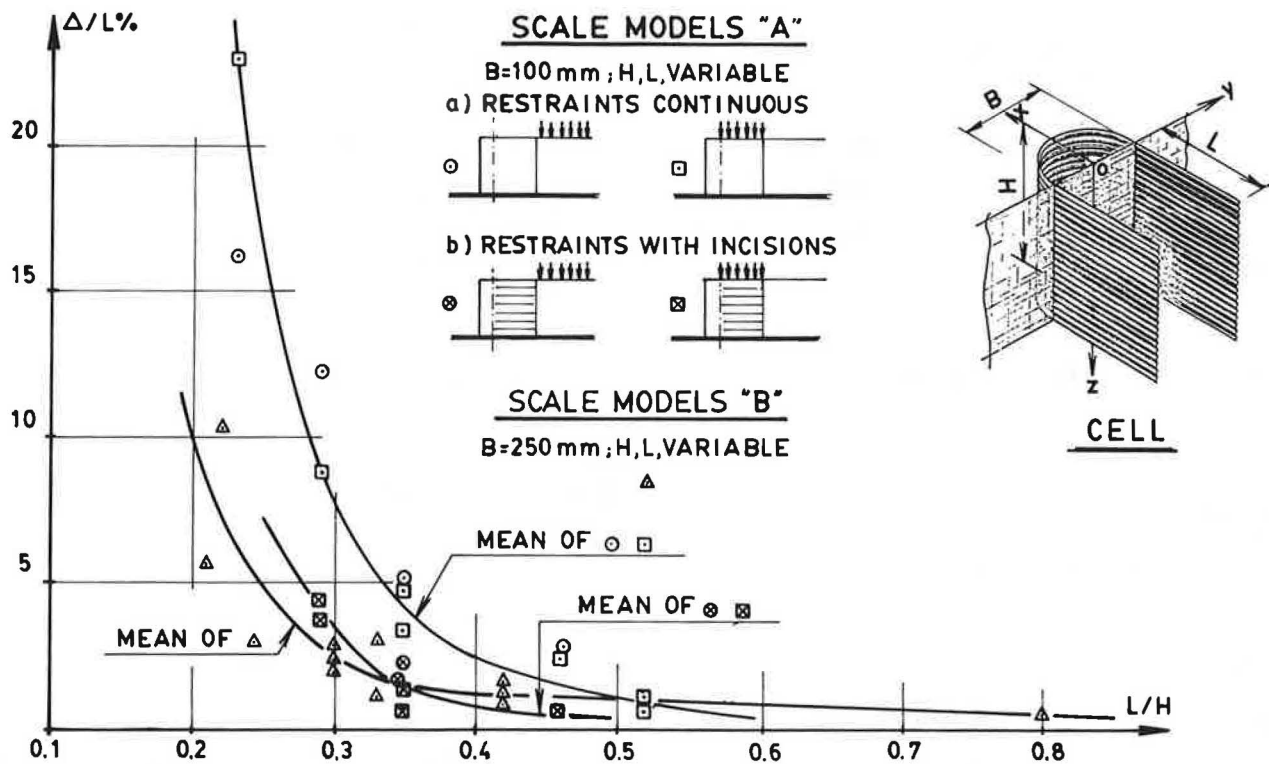**FIGURE 9   Soil-structure interaction.**

FIGURE 10   TER-VOILE scale models.

dozens of strain gages. The measurements made did not enable a curve of maximum tensile stresses to be drawn.

The extensometers installed in the Grandes Piles structure showed monolithic behavior (no differential movement within the cells (see Figure 11). However, the same tests proved that relative motion did occur with respect to the rear of the unit.

In view of this, the hypothesis of a failed surface, in accordance with classical theory or even in the case of reinforced earth, has been rejected. In a TER-VOILE unit, loss of internal stability may result from (a) structural rupture, (b) the loss of frictional force between backfill and restraints, or (c) the destruction of the arches within the backfill.

The author assumes the destruction of the monolithic nature of the unit as a working hypothesis. This may occur as a possible rupture in the reference plane where facing and restraints are joined—the assembly section being weakest.

Between restraints, the surface of rupture should be located near the plane of reference.

In the present state of knowledge, the mechanism whereby the monolithic nature of the unit is destroyed is unknown. Laboratory tests are required to clarify this.

For a complete unit, a curved potential rupture surface is assumed in the interim. This is supposed to pass through point G_o (the centroid of the semicircular facing) at the base, and through point A_o at the upper surface. Practically speaking, the inclined plane through O_{Hc} and A_o may be substituted. This is located everywhere on the right side of the reference plane (Figure 11). In the limit, it will coincide with the reference plane in the case of cells of low height compared with their width.

Equations 9 and 10 are used to find point A_o, with L_m equal to L_z when $z = 0.5H_c$. In this case the surface subject to friction, which should be equal and opposite to the thrust from backfill, is equal to $l \cdot H_c$.
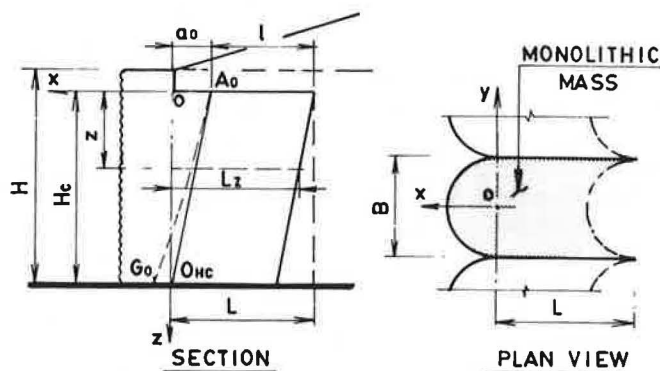
External Stability

Similar to a concrete gravity wall, the TER-VOILE structure is considered to be acted on by pressure from behind the structure (Figure 12) with a live load from above increased by 50 percent.

For practical purposes, a parallelepiped with rectangle $ABCD$ as its base and height H (Figure 12) may be taken as the stabilizing mass.

Note that distance C_1 defining the plane AB is given by

FIGURE 11   Analysis of internal stability.

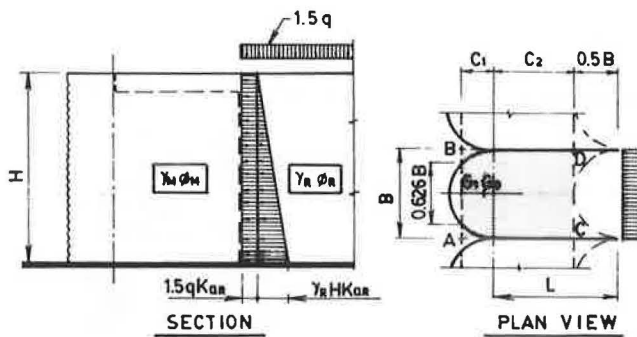$$C_1 \cdot B = 1/8 \, \pi \, B^2 \tag{11}$$

FIGURE 12   Analysis of external stability.

External stability is expressed via the following two equations:

Equation 12 shows stability against overturning:

$$F_r = \frac{M_s}{M_r} \qquad (12)$$

where

F_r = factor of safety against overturning,
M_s = stability moment, and
M_r = overturning moment.

In overturning, there must be an axis of rotation of the TER-VOILE cell at foundation level. The precise position of this axis is unknown. The plane of reference is too conservative and the front of the semicircular facing is not realistic. The author suggests an axis of rotation located between G_o (centroid of the semicircle) and G_1 (G_1 is on the line AB) (see Figure 12).

For these reasons, the factor of safety against overturning F_r should be 1.5 with respect to an axis passing through G_o, and 2.0 with respect to one through AB.

Equation 13 shows stability against sliding at the base:

$$F_g = \frac{W}{P} \tan \phi_1 \qquad (13)$$

where

F_g = factor of safety against sliding,
W = weight of entire retaining structure,
P = earth pressure, and
ϕ_1 = internal friction angle of foundation soil.

In practice, we suggest a factor of safety against sliding of at least 1.5.

FOUNDATION AND BACKFILL

The site where a retaining wall is to be erected is never a free choice. Similarly, the foundation soil comes part and parcel with the site and must be accepted with all its shortcomings as well as its positive qualities.

The high structural elasticity of TER-VOILE retaining walls makes them adaptable to very poor foundation conditions. In fact, when the terrain is uniform, is relatively unaffected by

water, demonstrates great strength, and has good drainage, retaining walls do not even require a special foundation.

In the construction of retaining walls, two types of backfill must be distinguished. The first, in-cell backfill material, is placed within the cell and provides the necessary structural interdependence with the membranes. Its physical characteristics (Figure 12) are identified as γ_M and ϕ_M.

The second is rear backfill material. The space between the wall and the natural ground slope can be filled using the same material as that used within the cells or with another material of poorer quality. This type of backfill will exert pressure on the in-cell backfill and may produce external instability of the structure. Rear backfill is identified in Figure 12 by γ_R and ϕ_R.

DURABILITY OF STRUCTURAL MATERIALS

As previously stated, the structural element is a thin membrane (the "voile"). Because this membrane is manufactured, its characteristics can be selected as needed. The material used to make the membrane must have high tensile strength and meet architectural and environmental requirements. In addition, the materials used and their coatings must be selected according to the nature of the backfill.

The main materials suitable for the manufacture of TER-VOILE structural elements are

- Galvanized or nongalvanized steel,
- Stainless steel,
- Cor-ten steel,
- Steel alloys,
- Aluminum alloys, and
- Composite plastic materials.

The most widely used material for retaining structures is mild steel in the form of galvanized or nongalvanized, corrugated sheet metal (or mesh), or aluminum alloys. Aluminum alloys should be of the type used for piping or piles. Aluminum alloys need careful attention, depending on the nature of the soil.

If, for better appearance, stainless or cor-ten steel is selected for the facing, galvanized steel may be used for the restraints. For example, stainless steel behaves poorly when it comes in contact with certain types of soil. On the other hand, the behavior of cor-ten steel in contact with soil is not well documented. Generally speaking, direct contact between both types of steel and soil is to be avoided. Bituminous coatings with polymers or the equivalent may be used.

Among other steel alloys, the best results have come from steel containing copper. This alloy has excellent fresh water resistance. Composite plastic will be an option in the future.

The structural elements forming the cell may be either a continuous membrane or a wire mesh used alone or in combination with poured concrete or gunite. Small precast concrete blocks can be combined in a variety of ways with the facing. Precast concrete panels can be used for the facings.

The useful life of these retaining walls varies. The durability of the structural elements depends on the resistance to corrosion of the materials used. The rate of corrosion is closely linked to the compatibility between these materials and the surrounding environment, particularly the characteristics of the backfill soil.

The chemical and electrochemical characteristics of the foundation soil, along with the in-cell backfill, determine the degree of corrosion. In practice, it is possible to limit corrosion of structural metal by choosing appropriate backfill material. It is impossible to totally eliminate corrosion; however, it can be limited to within a tolerable range.

Protection against corrosion is closely related to the electrochemical nature of the deterioration process. The main types of protection are

- Coatings,
- Cathodic protection, and
- Additional thicknesses.

TER-VOILE STRUCTURES

Usual Structures

The basic TER-VOILE structure was discussed earlier in this paper (Figures 1 and 2). For reasons of aesthetics, strength, or durability, the structure may include a façade covering, such as injected concrete (gunite) (Figure 13).

If a relatively thick gunite coating is desired, the use of mesh is recommended. As shown in Figure 14, the mesh may be attached to the restraints, which are extended specifically for this purpose. This means that a very thin metal sheet (capable of withstanding earth pressures during construction) may be used as a facing. However, the mesh must be sized to take the full extent of earth pressures.

Structures with Joined Facings

A structure with joined facings or "junctions" combines the basic structure with the U-shaped elements joined at the façade by convex elements (Figure 15).
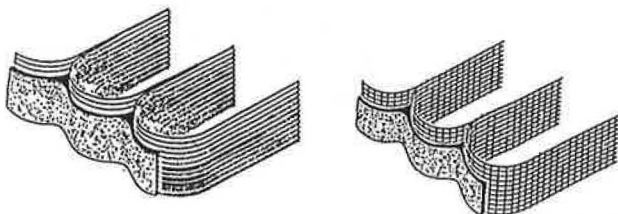

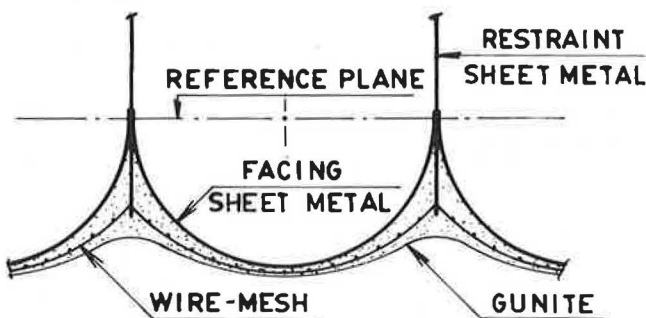FIGURE 13   Gunited structure: overall view.

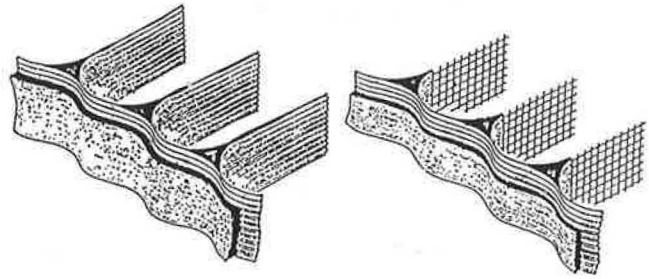FIGURE 14   Gunited structure: plan view.

FIGURE 15   Gunited junction-type structure: overall view.

The façade may be covered or bare. Figure 16 shows a plan view of the detail of a junction type structure. This structure has recesses that may be filled with concrete or reinforced concrete. This is a particular advantage for bridge abutments.

Coated Structures

These structures are specially designed so that a coating can be attached to the facing. The facings of these structures are circular arcs with a camber between one-third and one-half of the radius (Figure 17).

The facings and restraints are hooked together bar by bar or by using rods.

The structures shown in Figure 17 can be backfilled "as is" if rock fill is used, or by installing a membrane between the backfill and the mesh facing. The membrane, acting as a liner, prevents the passage of materials through the facing. It can be made of metal or plastic sheet or a thick geotextile.
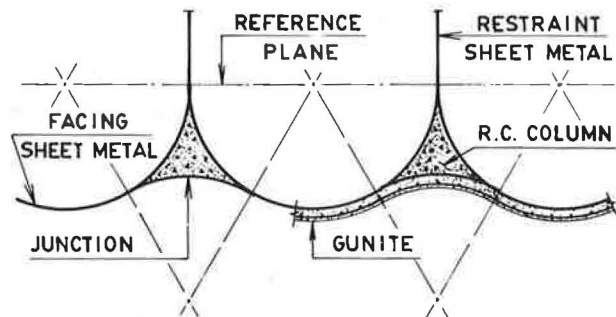

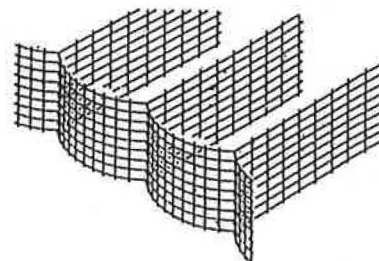FIGURE 16   Gunited junction-type structure: plan view.

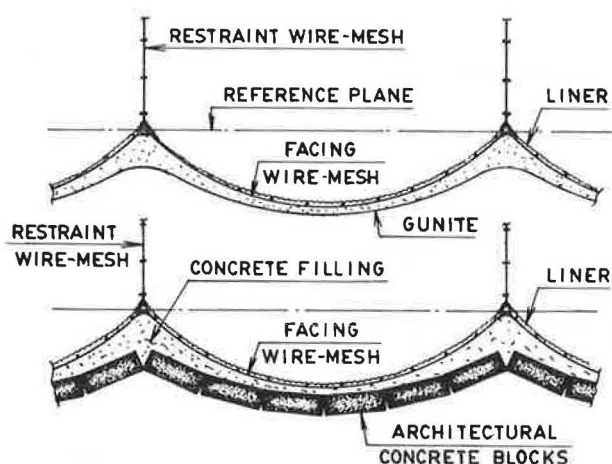FIGURE 17   Wire-mesh structure: overall view.

FIGURE 18 Coated wire-mesh structures.

Figure 18 shows this covering first with gunite and secondly with architectural concrete blocks.

CONCLUSIONS

It is hoped that the TER-VOILE concept will take its place among retaining wall designs that foster interdependence between structure and backfill.

The existence of such types of structure may be traced back to the dawn of civilization. Several writers have described armored earth structures and armored earth structural components used in ancient times or even by animals (7).

The old principles have recently been revitalized and optimized. Soil friction has been known from time immemorial; however, with the wide acceptance of armored earth, it has never been studied and tested with such persistence as nowadays.

From this standpoint, REINFORCED EARTH has succeeded in greatly advancing the knowledge of soil friction with masterly use of this ancient principle. REINFORCED EARTH has been a great revelation in its time.

Cribs used for retaining walls are also very ancient. In antiquity wood was used; steel and concrete have appeared too in modern-day construction. Several types of crib walls using corrugated galvanized steel or aluminum alloys have been developed, particularly those built from complete pipe sections or small bore pipes slit along a diameter.

TER-VOILE uses the age-old principle of cribs and optimizes to the utmost. The basic TER-VOILE cell described in this article is a structure subject to tension only; the author takes the liberty of claiming this to be a novelty.

Arching in backfill has also been known since time immemorial and has been studied in great detail in silos, but much less attention has been given to its use in retaining walls. TER-VOILE cells, with their reliance on soil friction, highlight the formation of arches in the horizontal plane.

Though not revolutionary, TER-VOILE is a step forward in optimizing retaining structures and has novel features. It is a new principle, then, and not to be confused with its established peers.

GLOSSARY

ox, oy, oz	=	axes of coordinates
H	=	overall length of structure
H_C	=	height for computation
h_c	=	equivalent height of extra loads (live and dead)
B	=	width of cell
b	=	camber of facing
L	=	overall length of restraints
L_z	=	length of plane of restraints at depth z
L_m	=	average length of plane of restraints
l	=	length of restraints for computation
G_o	=	center of gravity of the surface enclosed by facing and reference plane
W	=	weight of entire retaining structure
P	=	earth pressure
F_r	=	factor of safety against overturning
F_g	=	factor of safety against sliding
M_s	=	stability moment
M_r	=	overturning moment
g	=	live load
p	=	dead load
T_z	=	reaction from facing due to thrust from backfill at depth z
ϕ	=	internal friction angle of the backfill
ϕ_1	=	internal friction angle of foundation soil
ϕ_m	=	internal friction angle of backfill
ϕ_r	=	internal friction angle of fill in rear of structure
ψ	=	soil–structure friction angle
f	=	soil–structure friction coefficient
K_o	=	coefficient of pressure at rest
K_{om}	=	coefficient of pressure at rest of backfill
K_{ar}	=	coefficient of active pressure of fill in rear of structure
γ_m	=	specific weight of backfill
γ_r	=	specific weight of fill in rear of structure
Φ	=	function of variable z
G_z	=	stress in vertical direction
G_x	=	stress in horizontal direction
G_y	=	stress in horizontal direction
τ	=	friction stress between soil and restraint
τ_z	=	friction stress between soil and restraint at depth z
$dr = \Delta H$	=	infinitely small element of height

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