# Behaviour of reinforced earth behind quay walls

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The trend of ocean going deep draft vessels has made it difficult to satisfy equilibrium conditions for quite deep quay walls. This is because the deep gravity walls are subjected to a great deal of external horizontal forces and turning moments. This study focuses on reinforcing the soil behind the wall in order to release a great deal of live load and lateral earth pressures. Finite element technique was employed to investigate the improvement in load-carrying capacity of the wall due to the presence of reinforced earth. A parametric study was conducted to illustrate the behavior of the structure and to study the effect of the reinforcing on the stability of the quay wall. Simplified formulas for design purposes are presented.

يزداد الاتجاه في الآونة إلاخيرة إلي الاعتماد علي السفن الضخمة ذات الغاطس الكبير في نقل البضائع مما ترتب عليه ضرورة تعميق الارصفة القائمة او انشاء أرصفة ذات اعماق كبيرة إلا أن الصعوبة تكمن في تحقيق إتزان هذه الارصفة نتيجة ازدياد القوي الافقية الناتجة سواء كانت من تأثير الاوناش او الشد او الصدمات او نتيجة للضغوط الجانبية للتربة. ويهدف هذا البحث الي درسة استخدام تسليح التربة خلف الحوائط بالشرائح المعدنية بهدف زيادة إتزانها وتقليل الازاحات الأفقية للتربة ومن ثم قوي الضغوط الجانبية. وفي هذه الدرسة تم استخدام نظرية العناصر المحددة واستخدام برنامج حاسب آلي لتوضيح تأثير العوامل المختلفة علي اتزان الحائط. وقد أوضحت الدراسة انه يمكن بتسليح التربة خلف الحائط تقليل القوي الافقية المؤثرة وتحقيق الاتزان وقد تم استنتاج معادلات نظرية توضح ذلك مع تقديم مثال عددي محلول.

**Keywords:** Earth pressure, Load-carrying capacity, Metallic reinforcement, Reinforced earth, Reinforcing elements

## 1. Introduction

Similar to plain concrete, soil is a weak construction material, which has high compressive strength but virtually no tensile strength. To over come this weakness, a high tensile strength material, which puts at certain levels within the soil mass, can be used. When soil and reinforcements are combined, a composite material “reinforced earth” possessing high compressive and tensile strength is produced. Reinforced earth structure is an original composite structure formed by the association of granular soils and linear reinforcement strips which capable of withstanding high tensile forces. Reinforced earth wall has three ingredients: the granular backfill material, the reinforcing elements and the facing elements, as shown in fig. 1. The essential phenomenon in the mechanism of reinforced earth is the soil-reinforcement friction developing along the faces of the reinforcing elements. This reinforcement restrains the lateral deformation of the earth mass by providing an-isotropic cohesion to the soil mass and consequently reduces the lateral pressure.

This study presents the contribution of metallic reinforcements on the stability of multi-layered reinforced vertical walls under both vertical and horizontal strip loadings. An extensive parametric study was carried out to investigate the influence of several parameters on the load response of reinforced soil retaining wall. Finite element method was implemented to study the effect of all the wall parameters on the load-carrying capacity of the reinforced earth wall. Tensile stresses induced in reinforcing elements, settlements and lateral movement of the facing elements are typical output of the analysis. The parameters varied included: the wall height, the vertical spacing between reinforcing elements and the reinforcing elements length. Design formulas for obtaining the maximum tensile stresses induced in the reinforcing elements, including the pertaining parameters are presented and consequently the lateral pressure reduction due to soil reinforcement.

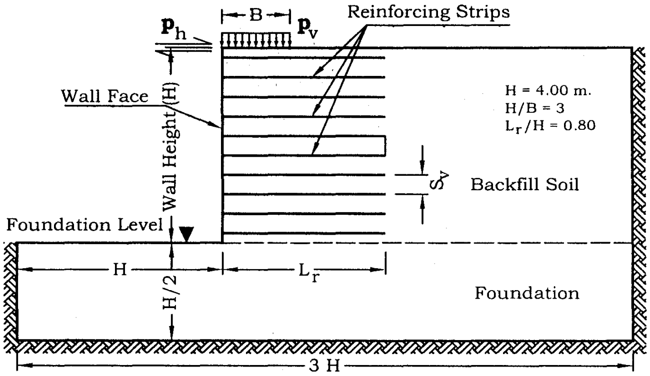


Fig. 1.Geometry of reinforced soil wall.

## 2. Geometry of the structure

Fig. 1 illustrates the geometry of the cross-section of reinforced earth vertical wall used in the analysis. It was found from a preliminary study that the extension of the backfill beyond the wall face should be ≥ twice the height of the wall, *H*, and the bedding thickness under the wall should be ≥ half the height of wall [1]. The effective bed layer should extend to a distance of the wall height, *H*, in front of the wall.

The parameters considered in the analysis are: (i) the loading strip width, *B*, in terms of $H/B$ where *H* is the wall height (four values of $H/B$ were adopted, $H/B$ = 2, 3, 4 and 5); (ii) the length of the reinforcing elements, $L_r$, in terms of $L_r/H$ (four values of $L_r/H$ were considered, $L_r/H$ = 0.8, 1.0, 1.20 and 1.40); (iii) the spacing between the reinforcing layers in the vertical direction, $S_v$, in terms of $H/S_v$ ($H/S_v$ = 5, 10, 15 and 20 were conducted); and, (iv) cases of loading in the vertical and horizontal directions.

### *2.1. Behavior of reinforced earth structure*

Fig. 2. shows that in a reinforcing earth structure, the line of the maximum tensile forces separates two zones: (i) an active zone behind the face where the shear stresses are directed outwards giving rise to an increase of the tensile forces in the reinforcements and (ii) a resistant zone where the shear stresses mobilized to prevent the sliding of the reinforcements is directed inwards, towards the free end of the reinforcements. By holding these two zones together, the reinforced earth mass processes overall cohesion.

The behavior and failure mechanisms of reinforced earth structure are quite different from those of classical retaining structures. This basic difference is mainly due to the effect of the presence of reinforcements, which restrain the lateral deformation of the structure and thus modify the stresses and strains patterns [2-5]. Considering the internal stability of reinforced earth structure, the failure can be caused either by a progressive breakage of the reinforcements along the line of maximum tensile forces or by a slippage of the reinforcements when the available length of reinforcements in the resistant zone is not sufficient to resist the maximum tensile forces. The slippage of the reinforcements occurred when the pullout resistance was insufficient. The pullout resistance of the reinforcements depends on the friction mobilized on the soil-strip interfaces. This friction is a complex three-dimensional phenomenon, which depends on different parameters: friction characteristics of soil, density of the soil

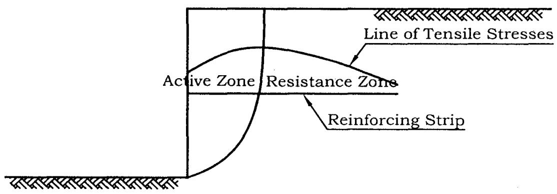


Fig. 2. Failure mechanism of reinforced earth wall.

and roughness of soil-strip interfaces, and is particularly governed by the dilatancy behavior of dense granular soil [5].

Reinforced earth has been used efficiently to improve the properties of weak soils, the stability of vertical cuts, in the construction and repair of embankments and side slopes, roads, erosion control and so on. Vidal [6,7] showed that reinforcing the soil material increases the load-carrying of a composite material formed from a stable granular soil mass and thus increasing the stability of the structure as well as resisting the tensile forces in the soil mass.

Most investigators worked in the field of reinforced earth retaining walls have concentrated on the behavior of the structure under vertical loads, [8-13] yet a little [14] can be found about the behavior of the reinforced retaining wall under both vertical and horizontal loadings. Therefore, the present work focuses on the analysis of multi-layered reinforced earth behind quay walls under both vertical and horizontal loadings.

An extensive parametric study was carried out to investigate the influence of several parameters on the load response of reinforced soil quay walls. Finite element modeling adopted in the parametric study was verified and substantiated by the results on the tested models.

## 3. Material properties

The soils used in this study are Well-graded coarse-grained soils compacted to a minimum of 95% standard Proctor density. It is, also, assumed to be homogenous, at least over the reinforcing elements length, $L_r$. The dry unit weight, $\phi_d$, of these soils is taken to be equal 18.0 $kN/m^3$, and the angle of internal friction, $\phi$, is taken to be $30^o$.

The cross-sectional area, the modulus of elasticity and the allowable and yield stresses, define the mechanical properties of the galvanized metallic strips used in this work. The cross-sectional area of galvanized strips, $A_o$, is 1.50 $mm^2$ length of the wall. The allowable and yield stresses, $f_a$, $f_y$ of these strips are 140 MPa and 280 MPa, respectively, and their modulus of elasticity is $2.0x10^5$ MPa. The reinforcing strip layers are arranged within the backfill in even spaces.

## 4. Theoretical model

Fig. 3 illustrates the two-dimensional finite element mesh adopted throughout this analysis. Plane-strain eight-nodes bilinear element was used to represent the backfill soils. Three-nodes truss element was adopted to model the reinforcing strips. Three-node pers side interface element was introduced to treat the connection between the soil and the reinforcing elements. The boundary conditions imposed were: the base nodes were restrained in the horizontal and vertical directions and the left-hand and right-hand side nodes were prevented to move in the horizontal direction.

## 5. Results

### 5.1. Tensile stresses

Fig. 4 illustrates the distribution of tensile stresses, $f_s$, along the reinforcing strip, which the maximum tensile stresses occurred, under different values of $H/S_v$ ratio. The plot shows that the tensile stresses vary from one end to the other of the reinforcement. At the free ends, the tensile stresses are very small, very close to be zero, and at the attachment point to the face elements, tensile stresses depend on the density of reinforcements. Thus, if the reinforcements were very close, the tensile stresses at the facing element would be zero. Also, the results showed that an increase of the $H/S_v$ ratio results in a significant decrease in the maximum tensile stresses induced in the reinforcing strips. For example, the reduction in the maximum tensile stresses induced in the structure due to different values of $H/S_v$ was about 195% (from 190.67 MPa to 64.67 MPa) and about 100% (from 129.33 MPa to 64.67 MPa) and about 29% (from 83.40 MPa to 64.67 MPa) as the ratio of $H/S_v$ changed from 5, 10, 15 to 20 under the same loading strip width ratio, $H/B$. Also, from this figure, we can see that the position of the maximum tensile stress is, approximately, at the same distance from the face of the wall. This means that an increase of $H/S_v$ leads to a decrease of the vertical spacing between the

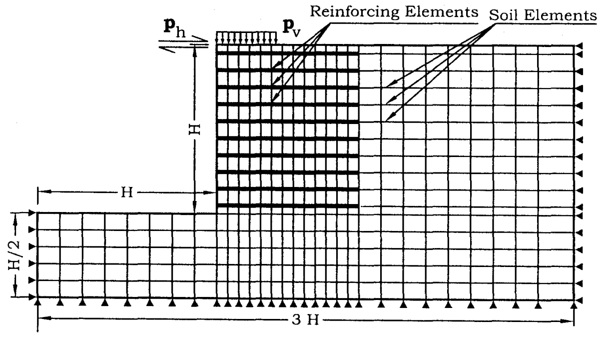


Fig. 3. Finite element mesh.

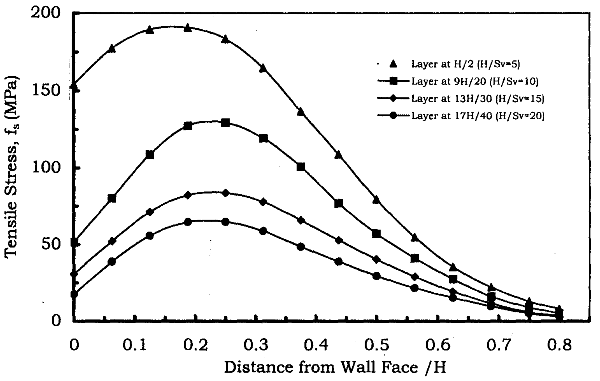


Fig. 4. Tensile stress distribution along strip of maximum tensile stress. ($H/B$ =3, $L_r/H$=0.80, $p_v$=75.0 kN/ m$^2$).

reinforcing elements, $S_v$ and thus an increase in the frictional and shear resistance of the reinforcing structure, which leads to an increase the horizontal stiffness of the structure. Thus, the increase of the horizontal stiffness of the structure means the improvement of the mechanical properties of the soil, which leads the soil to sustain higher confining stresses under the same value of vertical loads.

Fig. 5 illustrates the value of the tensile stresses ratio $f_s/f_{s(max)}$ at different levels within the structure. From this figure, the locus of the maximum tensile stresses is very close to be at 0.45 of the wall height measured from the foundation level of the wall.

### *5.2. Lateral movement*

The lateral movement ratio, $\delta_h/H$ of the wall face elements at different levels ratio, $h/H$ under different values of $H/S_v$ ratio is illustrated in fig. 6. The results showed a significant reduction of the lateral movement ratio, $\delta_h/H$ of the wall face due to the contribution of reinforcements. For instance, the reduction was about 112% and about 49% as the ratio of $H/S_v$ changed from 10, 15 to 20 under the same loading strip width ratio, $H/B$. As mentioned before, this reduction occurred due to the contribution of reinforcements to increase the horizontal stiffness of the structure, which develops a confining stress within the soil mass and thus, decreases the lateral movements induced in the face elements.

### *5.3. Vertical displacement*

The relation between the vertical displacement ratio, $\delta_v/H$ and the reinforcing element length ratio, $L_r/H$ at the upper reinforcing layer of the reinforcement under different values of $H/S_v$ ratio, is represented in fig. 7. As expected, the vertical displacement ratio, $\delta_v/H$ decreases with the increase of $H/S_v$ ratios. For example, the maximum vertical displacement ratio, $\delta_v/H$ was found to be 1.97 for $H/S_v$ equal 5, 0.68 for $H/S_v$ equal 10, 0.55 for $H/S_v$ equal 15 and 0.46 for $H/S_v$ equal 20.

## 6. Parametric study

The parametric study conducted herein involves the following design parameters: (i) the vertical spacing between the reinforcing layers, $S_v$, in terms of $H/S_v$; (ii) the loading strip width, $B$, in terms of $H/B$; (iii) the length of the reinforcing elements, $L_r$, in terms of $L_r/H$; and (iv) cases of horizontal load, toward and outward the wall.

### *6.1. Vertical spacing ratio, $H/S_v$ as a variable*

Fig. 8 illustrates the variation of the maximum tensile stress ratio, $F_{ms}$, due to different vertical spacing ratios, $H/S_v$, for a reinforcing elements length ratio, $L_r/H$ = 0.80, the width ratio of loading strip, $H/B$ = 3 and the vertical applied pressure, $p_v$ = 75.00 kN/m$^2$. For these conditions, the results obtained show a linear trend when $ln(F_{ms})$ is plotted versus the vertical spacing ratio, $H/S_v$.

Based on the plotted results in fig. 8, the maximum tensile stresses ratio, $F_{ms}$ can be approximately expressed as:

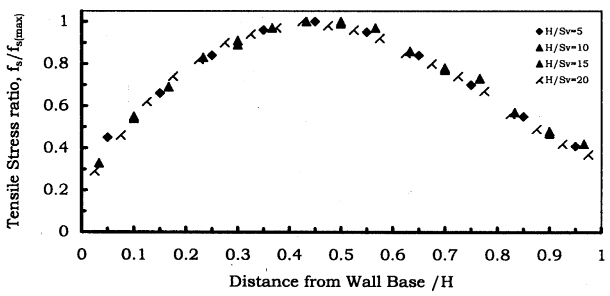


Fig. 5. Maximum tensile stress distribution at different levels within the structure. ($H/B$=3, $L_r/H$=0.80, $p_v$=75.0 kN m[2]).

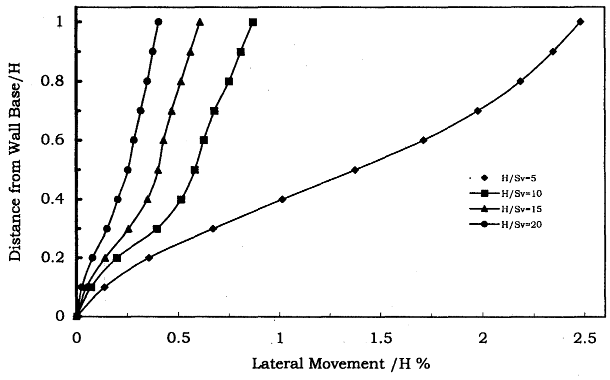


Fig. 6. Lateral movement of wall face ($H/B$=3, $L_r/H$=0.80, $p_v$=75.0 kN m[2]).

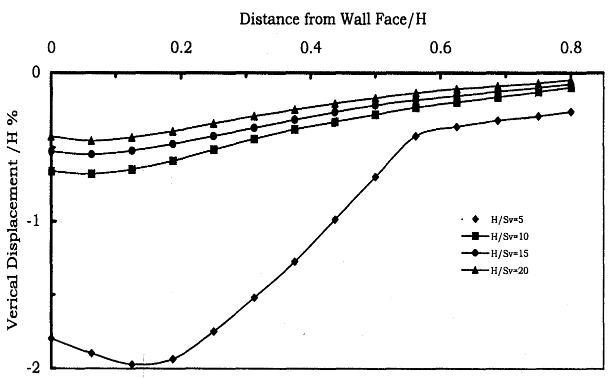


Fig. 7. Distribution of vertical displacement at the upper layer reinforcement ($H/B$=3, $L_r/H$=0.80, $p_v$=75.00 kN m[2]).

$$F_{ms} = 3.60/e^{[a*(H/Sv)]} \quad (1)$$

Where: a is the slope of the best-fit line in fig. 8, which estimated to be 0.075.

*6.2. Loading strip ratio, H/B as a variable*

Fig. 9 represents the relation between the maximum tensile stresses ratio, $F_{mB}$, due to different loading strip ratios, $H/B$, for a reinforcing elements length ratio, $L_r/H$ = 0.80, vertical spacing ratio, $H/S_v$ = 10 and vertical applied load, $P_v$ = 100.00 kN.

From the best fit of the plot in fig. 9, the maximum tensile stresses ratio, $F_{mB}$ may be approximately given as the following:

$$F_{mB} = 8.40/[e^{[a*(H/Sv)]+[b*(H/B)]}]. \quad (2)$$

In which: *b* is the slope of the best-fit line in fig. 9, which estimated to be 0.28.

*6.3. Reinforcing elements length ratio, $L_r/H$ as a variable*

Fig. 10 demonstrates the relationship between the maximum tensile stresses ratio, $F_{mL}$, and the reinforcing elements length ratio, $L_r/H$ under the following conditions: *a*) the loading strip width ratio, $H/B$=3, b) the vertical spacing ratio, $H/S_v$.= 10, and c) the vertical applied pressure, $p_v$=75.00 kN/m[2]. The results showed a linear relationship on semi-logarithmic scale.

Based on the plotted results in fig. 10, the maximum tensile stresses ratio, $F_{mL}$ can be approximately expressed as:

$$F_{mL} = 8.52/[e^{[a*(H/Sv)]+[b*(H/B)]+[c*(L_r/H)]}]. \quad (3)$$

In which c is the rate of variation of the slope of the fitted straight line in fig. 10, which found to be equal 0.033.

Eq. (3) is a general formula to evaluate the maximum tensile stresses ratio, Fm, where $F_{mL}$ equals $(T_{s(max)})/(A \times p_v)$, within the wall under vertical loading with different parameters, in which $T_{s(max)}$ is the maximum tensile force in the reinforcing element within the embankment and A is the cross-sectional area of the reinforcing strips, which equal 1.5 mm[2] per meter length of the wall.

*6.3. Effect of horizontal loads*

Fig. 11 presents the relationship between the effect of horizontal load and the maximum tensile stresses, $F_m$, for a reinforcing element length ratio, $L_r/H$ = 0.80, loading strip width ratio, $H/B$ = 3, vertical spacing ratio, $H/S_v$ = 10, and vertical applied pressure, $p_v$ = 75.00 kN/m$^2$. Horizontal load was taken as a ratio from the vertical load. Based on the plotted results in fig. 11, the maximum tensile stresses ratio can be approximately expressed as follows:

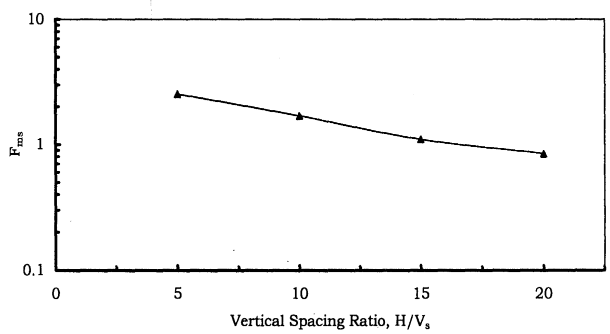


Fig. 8. Maximum tensil stress ratio, $F_{ms}$ versus vertical spacing ratio, $H/S_v$ (($H/B$=3, $L_r/H$=0.80, $p_v$=75.00 kN m$^2$).

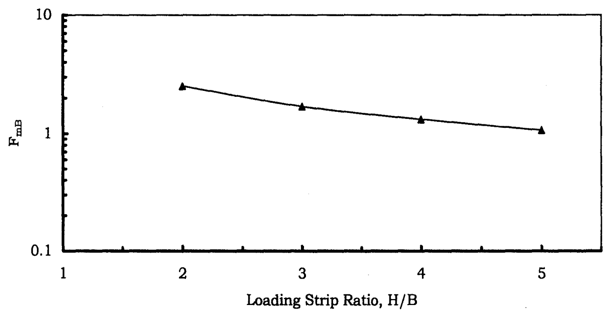


Fig. 9. Maximum tensil stress ratio, $F_{mB}$ versus loading strip ratio, $H/B$ ($H/S_v$ =10, $L_r/H$=0.80, $p_v$=100.00 kN m$^2$).

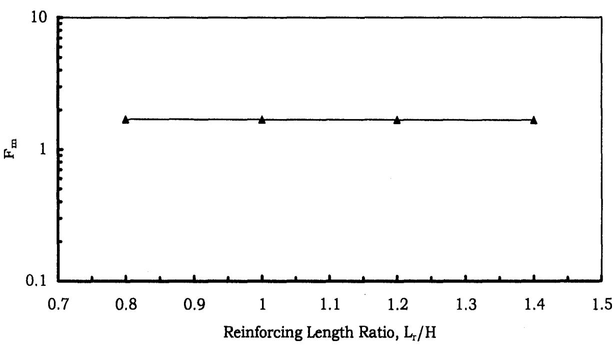


Fig. 10. Maxium tensile stress ratio, $F_m$ versus reinforcing length ratio, Lr/H (H/Sv=10, H/B=3, Pv = 75.00kN/m$^2$)

In case of horizontal load, $p_h$, applied outward the wall:

$$F_O = 1.685*[e^{d*(p_h/p_v)}]. \quad (4)$$

In which: $d$ is the slope of the fitted straight line in fig. 11, which equals 1.35.

In case of horizontal load, $p_h$, applied toward the wall:

$$F_T = 1.725/[e^{e*(p_h/p_v)}]. \quad (5)$$

In which: $e$ is the slope of the fitted straight line in fig. 11, which equals 0.80.

To take the effect of horizontal load into account, eq. (3) is rewritten as:

$$F_{mo} = 8.535/[e^{a*(H/Sv)+b*(H/B)+c*(L_r/H)-d*(p_h/p_v)}]. \quad (6)$$

In case of horizontal load, $p_h$, applied outward the wall.

And;

$$F_{mt} = 8.495/[e^{a*(H/Sv)+b*(H/B)+c*(L_r/H)+e*(p_h/p_v)}]. \quad (7)$$

In case of horizontal load, $p_h$, applied toward the wall.

Eqs. (6) and (7) are general formulas to evaluate the maximum tensile stresses ratio within the wall under vertical and horizontal loads due to different design parameters of the reinforcing quay walls.

## 7. Example

For a reinforced-soil wall of height, $H$ equals 4.00 m. It is required to estimate the maximum tensile forces in the reinforcing flat bars, due to a vertical applied strip load, q=100.0 kN/m$^2$ which distributed over a distance of 2.0 m, as well as due to a horizontal load of 10.0 kN/m affects outward the wall. Consider the vertical spacing ratio, $H/s_v$ equals 5, 10, and 15 and the reinforcing strip length ratio, equals 0.80. The properties of backfill soil are: $\gamma$=18.0 kN/m$^2$ and $\gamma$=30.0$^o$. The reinforcing strips have a cross section of 0.02 m$^2$/m and their allowable and yield stresses are 140 MPa and 280 MPa, respectively, and their modulus of elasticity is 2.0x10$^5$ MPa.

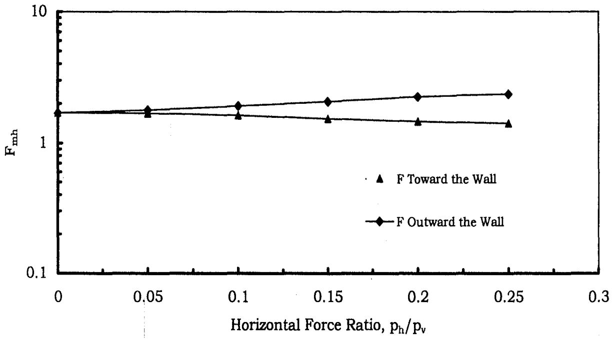


Fig. 11. Maximum tensile stress ratio, Fmh versus horizontal load ratio, $F/p$ ($H/S_v$=10, H/B=3, Lr/H=080, $p_v$=75.00kN/m$^2$).

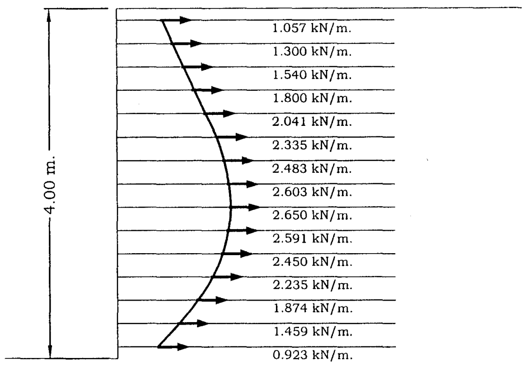


Fig. Distribution of tensile forces within the reinforcing layers.

## 8. Solution

From eqs. (1) to (4), the constants *a*, *b*, *c* and *d* are estimated as: 0.075, 0.28, 0.033 and 1.35, respectively.

In the case of study, the ratios $L_r/H$ and $H/B$ are 0.80 and 2.00, respectively.
Using these constants in eq. (6), yields $F_{mL}$ = 3.74, 2.57 and 1.76, for $H/s_v$ = 5, 10 and 15, respectively.
Since: $F_{mL}= T_{s(max)}/(A_o\ x\ p_v)$,
Then: the maximum tensile force in strips is 5.61, 3.85 and 2.65 kN/m, for $H/s_v$ = 5, 10 and 15, respectively.
*Check the reinforcing element area:* the reinforcing area must be strong enough to prevent failure in tension, where the resisting tensile force is:

$$A\ x\ f_a\ ]\ T_{s(max)}. \tag{8}$$

With A= 0.02 m$^2$/m and $f_a$ = 140.0 MPa, $A$ x $f_a$ = 2.80 kN/m, So to prevent the failure in the reinforcing elements, the vertical spacing between the reinforcing layer must be at least 15.

## 9. Conclusions

Reinforced earth wall is a construction material consisting of a frictional backfill material and linear reinforcing strips, usually placed horizontally. The reinforcement is usually capable of withstanding high tensile forces and restraining the lateral deformation of the reinforced mass. The mechanism of soil-to-reinforcement stress transfer is friction between the soil and reinforcement surfaces. The frictional resistance is the most critical part of a reinforced earth system.

It may be concluded that the load-carrying capacity of the wall increases and both the settlement and lateral movement decrease with the increase of the vertical spacing ratio of the reinforcement. Results showed, also that no significant reduction of the maximum tensile stress in the reinforcing elements due to the increase of the reinforcement length ratio. The resistance of the wall improves when the horizontal load applied towards the wall since this load helps to reduce the tensile loads within the reinforcing elements. The location of the maximum tensile stresses is almost at 0.45 of the wall height measured from the bottom level of the wall. Formulas to evaluate the maximum tensile stress within the reinforcing elements under vertical and horizontal loads due to different design parameters of the reinforcing quay walls are estimated and presented.

## Notations

| | |
|---|---|
| *a, b, c, d, e* | are the constants denoted in eqs. (1,2,3,4 and 5), |
| A | is the cross-sectional area of the reinforcing element, |
| *B* | is the width of loading, |
| *H* | is the wall height, |
| $f_a$ | is the allowable stress of the galvanized metallic strips, |
| $f_s$ | is the tensile stresses in the reinforcing strips, |
| $f_y$ | is the yield stress of the galvanized metallic strips, |

| | |
|---|---|
| $f_{s(max)}$ | is the maximum tensile stresses in the reinforcing strips, |
| $p_h$ | is the horizontal applied load, |
| $p_v$ | is the vertical applied pressure, |
| $E_s$ | is the modulus of elasticity of the galvanized metallic strips, |
| $F_m$, | is the maximum tensile stresses ratio, |
| $F_o$ | is the maximum tensile stresses ratio when the horizontal load is applied outward the wall, |
| $F_T$ | is the maximum tensile stresses ratio when the horizontal load is applied toward the wall, |
| $L_r$ | is the length of the reinforcing elements, |
| $P_v$ | is the vertical applied load, |
| $S_v$ | is the spacing between reinforcing layers, |
| $F_{mB}$, | is the maximum tensile stresses ratio due to Loading strip ratio, |
| $F_{ms}$, | is the maximum tensile stresses ratio due to vertical spacing ratio, |
| $F_{maxo}$ | is the maximum tensile stresses ratio when all the parameters are taken into account including outward effect of the horizontal load, |
| $F_{maxo}$ | is the maximum tensile stresses ratio when all the parameters are taken into account including toward effect of the horizontal load, |
| $H/B$ | is the loading strip width ratio, |
| $H/S_v$ | is the vertical spacing ratio, |
| $L_r/H$ | is the reinforcing elements length ratio, |
| $\phi$ | is the angle of internal friction of soil, |
| $\gamma$ | is the soil unit weight, |
| $\delta_h$ | is the lateral movement of the wall face elements, and |
| $\delta_v$ | is the vertical displacement of the reinforcing elements. |

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