Selection of parameters for MSE retaining walls

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Abstract. The paper deals with the results of design analyses to evaluate the behavior of soil and reinforcement in mechanically stabilized earth (MSE) retaining walls. Using the Plaxis 2D software package, the influence of various parameters of the MSE wall on its behavior under load was evaluated. The paper presents some recommendations on the use of MSE retaining walls in the design of highways, including connection sections between bridges and approach embankments in conditions of Vietnam.

1. Introduction
Nowadays, in the practice of transport construction, including in Vietnam, MSE retaining walls are frequently used due to their advantages such as low own weight, simplicity of construction, high rates of erection and low cost as compared to conventional reinforced concrete retaining walls. Even at high embankments, a MSE retaining wall can have a vertical outer slope [1].

Due to the indicated advantages of MSE walls, they were used for construction of Nga Tu Vong and Cau Giay overpasses in Hanoi. However, the design of these retaining walls did not take into account many factors affecting the reliability and durability of both retaining walls and overpasses in general.

This paper presents the results of the study that help to explain the behavior of the MSE retaining walls built at the overpasses in Vietnam.

2. Mechanism of interaction between reinforcing elements and soil in MSE retaining walls
The combination of reinforcing elements and compacted soil particles should form an internally stable composite structure that is able to resist shear. The way the soil load is transferred to reinforcing elements depends on the design of the MSE wall. Soil has good mechanical properties in compression, and the material of reinforcing elements has the ability to resist tensioning. The composition of soil and reinforcing elements can create a system that is resistant to compression and tension, and reduces the horizontal displacement of the soil mass and increases its load resistance.

The reinforcement is intended to take up lateral stress \( \sigma_3 \) inside the reinforced soil element, which is in a triaxial stress state. The lateral stress \( \sigma_3 \) is determined through the vertical stress \( \sigma_1 \) with the following equation:

\[
\sigma_3 = K \sigma_1.
\]  

(1)

Where \( K \) is the coefficient of horizontal soil pressure, which is determined as per the theory of Jaky, and can be taken equal to at-rest lateral earth pressure, represented as \( K_0 = 1 - \sin \phi \).

Under the action of \( \sigma_1 \), the soil sample without reinforcing elements will be deformed in the vertical direction and will undergo displacements \( \Delta_1 \), and in the transverse direction, respectively, \( \Delta_2 \).
The soil sample with reinforcement will be deformed in the vertical direction with displacement $\Delta'_y$, and in the transverse direction with transverse displacement $\Delta'_z$ (Figure 1).

The above displacements shall be determined with the following equations [2]:

$$\Delta_y = \frac{\sigma_1}{E} d_y; \hspace{0.5cm} \Delta_z = \frac{\nu \sigma_1}{E} d_z$$

$$\Delta'_y = \frac{\sigma_1}{E} d_y - \frac{\nu \sigma_3}{E} d_y; \hspace{0.5cm} \Delta'_z = \frac{\sigma_3}{E} d_z - \frac{\nu \sigma_1}{E} d_z$$

(2)

Where $E$ is the deformation modulus of the soil behind the retaining wall, and $\nu$ is Poisson's ratio.

Thus, due to the presence of reinforcement, soil deformation in the transverse direction decreases and, correspondingly, displacement in the vertical direction ($\Delta'_y < \Delta_y$ and $\Delta'_z < \Delta_z$). The lateral pressure $\sigma_3$ is determined by the reinforcement action on the soil due to friction forces between the soil and the reinforcement. The soil block is stable if $\sigma_1$ does not exceed the tensile strength of the reinforcement, or the friction force between the soil layers and reinforcement, or the passive soil pressure. This is the main principle of the reinforcement performance in a reinforced soil element.

(a) (b)

Figure 1. Soil element deformation pattern: (a) without reinforcement; (b) with reinforcement.

3. Force in reinforcement of a reinforced soil element

The results of theoretical and experimental studies [4–9] show that stresses in the reinforcement at the contact with the wall are relatively low, but increase gradually to a maximum at a distance of about $0.3H$ and then decrease gradually to almost zero (Figure 2).

Figure 2. Distribution of tensile forces along the reinforcement

Depending on the strength of the reinforcement, the soil failure surface is different: with high strength reinforcement, the failure takes place along a plane, and with low strength reinforcement, the failure takes place along a plane in the upper part of the embankment, and along a parabola in the embankment lower part (see Figure 2).
To determine the tensile force in the reinforcement, it is necessary to define the horizontal stress that occurs in the zone of active deformation at a depth \( z \) from the wall top. This horizontal stress can be determined as follows:

\[
\sigma_h = K \cdot \sigma_v; \quad \sigma_v = \gamma \cdot z \tag{3}
\]

Where \( \sigma_h \) is the tensile stress in the reinforcement, which corresponds to stress \( \sigma_3 \) in equation (1); \( \sigma_v \) is the vertical stress at the depth \( z \), corresponding to \( \sigma_1 \) in equation (1); and \( \gamma \) is the specific gravity of soil in the reinforced soil element.

The tests show that the horizontal soil pressure coefficient \( K \) at the top of the wall is slightly higher than the at-rest pressure coefficient \( K_0 = 1 - \sin \phi \), and the \( K \) value tends to the value of the active soil pressure coefficient \( K_a = \tan^2(45^\circ - \phi/2) \), which is characteristic of the fill lower part [12].

In case the reinforcement is a material with high tensile strength, the horizontal soil pressure coefficient \( K \) almost does not change along the wall and is about 0.65.

Then the force \( T_i \) for each layer \( i \) per 1 m of the wall length is determined by the equation:

- Reinforcement in the form of plates:
  \[
  T_i = \sigma_h \cdot S_v \tag{4}
  \]
- Reinforcement in the form of rods and meshes:
  \[
  T_i = \sigma_h \cdot S_v \cdot S_h \tag{5}
  \]

Where \( S_v \) and \( S_h \) are spacing in the vertical direction between plate layers and in the horizontal direction between rods or frames.

4. Factors influencing the behavior of MSE retaining walls

The authors used the Plaxis 2D version 8.2 finite element software [3] to evaluate parameters that influence the behavior of reinforced soil retaining walls at the section where the embankment connects to the bridge.

4.1. Initial parameters

The foundation soils are assumed as alternate soil layers that are most characteristic of the conditions of Hanoi. Soil properties are given in Table 1.

| Parameter                              | Designation                  | Soil layers | Units       |
|----------------------------------------|------------------------------|-------------|-------------|
| Model of material behaviour           | Mohr- Coulomb                | 1           | 2           | 3           | -            |
| Type of soil                           | Draining                     |             |             |             | -            |
| Specific weight in dry condition       | \( \gamma_{unsat} \)           | 19.5        | 18.2        | 17.6        | kN/m\(^3\)  |
| Specific weight in water saturated condition | \( \gamma_{sat} \)            | 20.2        | 19.7        | 20.9        | kN/m\(^3\)  |
| Young’s modulus                       | \( E_{ref} \)                 | 25000       | 23500       | 31500       | kN/m\(^2\)  |
| Poisson’s ratio                        | \( \nu \)                     | 0.3         | 0.3         | 0.3         | -            |
| Cohesion of soil                      | \( c_{ref} \)                 | 0.05        | 0.05        | 100         | kN/m\(^2\)  |
| Angle of internal friction            | \( \phi \)                    | 34.5        | 32.6        | 30          | degree      |
| Dilatancy angle                       | \( \psi \)                    | 4.5         | 2.6         | 0           | degree      |
| Strength reduction factor at interface | \( R_{inter} \)               | 0.75        | 0.75        | 0.85        | -            |

In Table 1, the following notation is used: 1 is for compacted medium sand; 2 – medium sand; 3 - coarse sand.

The height of the assumed wall is \( H = 5 \) m; thickness: \( d = 10 \) cm; reinforcement with tensile strength \( T_s = 20 \) kN/m (with a relative deformation of 5%); reinforcement length \( L \) and vertical spacing between reinforcement layers \( S_v \). The initial design parameters are given in Table 2.
Table 2. The initial design parameters.

| Parameter                      | Designation | Element of construction | Units          |
|--------------------------------|-------------|--------------------------|----------------|
| Model of material behaviour    |             |                          |                |
| Normal (axial) stiffness       | EA          | Linear elastic           | 2.92E+6 kN/m²  |
| Flexural stiffness             | EI          | Elastoplastic            | 2.43E+4 kN/m²/m|
| Replaceable parameters         | w           |                          | 0.5925 kN/m²/m |
| Poisson’s ratio                | v           |                          | 0.2 kN/m²/m    |

In accordance with [10], the intensity of uniform distributed load due to the embankment weight and live load is assumed as \( q = 15 \) kN/m.

Figure 3. Loading diagram and its representation in Plaxis

4.2. Spacing \( S_v \) between the reinforcement layers and its influence on the behavior of the MSE retaining wall

Let us assume the initial length of the reinforcement as \( L = 5 \) m and the value of \( S_v \) varying from 0.2 m to 0.7 m.
The presented results show that with an increase of spacing between reinforcing elements, the failure area extends beyond the reinforcement zone. Thus, some reinforcement is excluded from the work, which reduces the effectiveness of reinforcement.

It is important to evaluate the stability of the MSE retaining wall, which is characterized by the tilt stability factor

\[ M_{sf} = \frac{M_k}{M_t} \]

Where \( M_k \) is the restraining force moment; and \( M_t \) is the moment of tilting force [11].

**Figure 5. Plot of system stability factor M_{sf} as a function of S_v**

The plots in Figure 5 show that with a significant increase in the spacing \( S_v \) between the layers of reinforcement, the stability factor of the structural system decreases. When the spacing between the
layers of reinforcement increases to 0.6 m ÷ 0.7 m, the system stability factor decreases sharply. For the given initial data, the optimal spacing $S_v$ between the layers of reinforcement is 0.3 m ÷ 0.5 m.

4.3. Length of reinforcement in the MSE retaining wall

Figure 6 shows the effect of the reinforcement length $L$ on propagation of the failure surface in the MSE retaining wall at the spacing between the reinforcement layers $S_v = 0.5$ m and the length of reinforcement $L$ varying in the range of 3 m ÷ 10 m (respectively, at $L = (0.6 ÷ 2.0)$ H).

![Figure 6](image)

**Figure 6.** Propagation of the failure surface

The results show that with an increase in the length of reinforcing elements the volume of the failure zone also increases, which is in line with Rankine’s theory.
Figure 7. Plot of system stability factor $M_{sf}$ as a function of the reinforcing elements length

The plot in Figure 7 shows that with an increase in the length of reinforcement $L$, the change of the system stability factor is almost linearly dependent.

Figure 8. Maximum horizontal displacement of the MSE retaining wall top

The change of the reinforcement length from 5 to 10 m results in a decrease of 10% only in the maximum horizontal displacement of the retaining wall top (Figure 8). The obtained results show that an increase in the length of reinforcement does not have a significant effect on the horizontal displacement of the MSE retaining wall top. It can be concluded that the optimal length of reinforcement is $L = (0.7 \div 1.0) H$, where $H$ is the design height of the retaining wall.

4.4. Influence of reinforcement strength $T_a$

The choice of reinforcement tensile strength $T_a$ depends on many parameters (the height of the retaining soil wall, properties of the fill soil behind the wall, vertical load behind the wall, etc.) and is the basis for the design analyses and design of MSE retaining walls.

As before, let us assume the spacing between the reinforcement layers is $S_v = 0.5$ m, the length of reinforcing elements $L = 5$ m, and $T_a$ will vary in the range of 10-80 kN/m (with a relative deformation of 5%). Based on the above assumption, we will assess the influence of reinforcement tensile strength $T_a$ on the performance of the MSE retaining wall. The initial parameters of reinforcement are given in Table 3.
Table 3. The initial parameters of reinforcement

| Parameter                      | Designation | Reinforcing elements | Units |
|-------------------------------|-------------|----------------------|-------|
| Model of material behavior    | Model       | Elastoplastic        | -     |
| Ultimate tensile strength     | $T_a$       | 10 20 40 60 80       | kN/m  |
| Normal (axial) stiffness      | $E_A$       | 200 400 800 1200 1600| kN/m  |

Figure 9. Change of the failure surface at various $T_a$

The reinforcement strength $T_a$ has a significant impact on the shape of the failure surface behind the retaining wall. At small value of $T_a$, the critical failure plane passes through the reinforcement layers (Figure 9, a-b) and moves gradually down to the bottom of the reinforced zone. With an increase of $T_a$, it does not intersect the reinforcement layers (Figure 9, c-d) and, thus, the effectiveness of reinforcement is reduced.
The plot of the system stability factor $M_{sf}$ as a function of reinforcement strength $T_a$ shows that with an increase of $T_a$ from 10 to 20 kN/m, the system stability factor increases, but with a further change of $T_a$ from 20 kN/m to 80 kN/m, the factor does not change significantly.

Obviously, the choice of reinforcement is very important. The optimal tensile strength of the reinforcement should ensure that the critical failure plane passes through the reinforced zone, and system stability factor $M_{sf}$ meets the requirements of standards and regulations, and the reinforcement does not break. The use of reinforcement with high strength characteristics is not a determining factor for ensuring the reliability and efficiency of MSE retaining walls.

5. Conclusions

1. The shape of critical failure surface behind the MSE retaining wall depends on the spacing between the reinforcement layers $S_v$, the length of reinforcement $L$ and reinforcement tensile strength $T_a$. The failure surface may be located completely within the reinforced zone, or partially, or may occur outside the reinforced zone.

2. The MSE wall works effectively if the assigned optimal spacing between the reinforcement layers is $S_v = (0.3 \div 0.5)$ m, and the length of the reinforcement is $L = (0.7 \div 1.0)$ H, but more than 3m. The choice of shorter or longer reinforcement proved to be ineffective both in terms of reliability and cost efficiency.

3. Selecting the appropriate strength of reinforcement for each project is the most important task. The choice of high-strength reinforcement is not significant for increasing the system stability factor, or for reducing horizontal displacement of the retaining wall top. The reinforced soil element performs well with low-strength reinforcement and a small spacing between the layers of reinforcement (while ensuring the requirements of overall stability).

4. Owing to the advantages of MSE walls, their use in the design of connection sections between bridges and approaches seems to be practical, including in the conditions of Vietnam.

References

[1] Dương Hạc Hải. Thiết kế và thi công tường chắn đê có cột. Nhà xuất bản Xây dựng – Hà nội, 2012. - 121 tr.

[2] А.Д. Соколов – Армогрунтовые системы автодорожных мостов и транспортных развязок. Монография.- СПб.: ООО Отраслевая медиа корпорация «Держава», 2013 г. – 504 с.
[3] R.B.J. Brimkgreve & W. Broere. *Plaxis 2D version 8.2. Plaxis b.v, the Netherlands – 2006. p. 179.

[4] Yan Jiang et al., *Field Monitoring of Mechanically Stabilized Earth Walls to Investigate Secondary Reinforcement Effects*, The University of Kansas Department of Civil, Environmental and Architectural Engineering 1530 West 15th St Lawrence, Kansas 66045-7609, 2015. – 90 p.

[5] Prime AE Group, Inc. Harrisburg, Pennsylvania, *Spreadsheet Design of Mechanically Stabilized Earth Walls*, for The Pennsylvania Department of Transportation Central Office, 55 p.

[6] Ioannis Zevgolis, Philippe Bourdeau, *Mechanically Stabilized Earth Wall Abutments for Bridge Support*, TRB Subject Code: 62-6 Soil Compaction and Stabilization, April 2007, 161 p.

[7] U.S. Department of Transportation Federal Highway Administration. *Mechanically Stabilized Earth Wall And Reinforced Soil Slopes Design & Contraction Guidelines*. NHI Course No.132042, 2011, 418 p.

[8] Mathew J. Rahmeyer, *Developing More Efficient Mechanically Stabilized Earth (MSE) Wall Reinforcements*, Utah State University, 2016, 171 p.

[9] Elias, V., Christopher, B.R., Berg, R.R.: *Mechanically stabilized earth walls and reinforced soil slopes, design & construction guidelines*. Report No. FHWA-NHI-00-043. Federal Highway Administration, p. 394, March 2001.

[10] Tiêu chuẩn thiết kế cầu 22TCN272-05. Hà Nội, 2005. - 672 tr.

[11] Гольштейн М.Н., Царьков А.А., Черкасов И.И. Механика грунтов. Основания и фундаменты. М.: Транспорт,1981. - 320 с.

[12] Nguyễn Đình Dũng. Hướng dẫn thiết kế và thi công tường chắn đất có cốt theo phương pháp RRR. Nhà xuất bản: Xây dựng, 2005. -124 tr.