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Design Theory and Method of Geo-Synthetic Reinforced Soil Retaining Wall Combined with a Gravity Retaining Wall or Full Height Rigid Facing

Xiequn Wang · Rajyaswori Shrestha · Xinping Li · Abhay Kumar Mandal

Abstract Geo-synthetic reinforced soil retaining wall (GRS-RW) combined with a Gravity Retaining wall (GRW) facing or Full High Rigid (FHR) facing is a new type of retaining wall. This type of retaining wall is used to get full advantages of GRW and reinforced soil retaining wall (RS-RW) and to avoid their drawbacks. The design method based on the principle of working strain considers the backfill in the limit state but the reinforcement not in the limit state; while in traditional design method based on the tensile strength of reinforcement, consider both backfill and reinforcements in the limit state and it cannot reflect the influence of reinforcement stiffness. In this paper, numerical analyses were performed to evaluate the stress and strain of both reinforcement and backfill. From the analyses, deformation of the retaining wall, the working performance of GRS-RW with GRW facing, and contribution of geo-grids to GRS-RW with a GRW facing, were evaluated. Analyses are performed for determining the force between GRS-RW with a GRW facing and reinforced soil. Analytical methods, for the calculation of soil pressure acting on the back of GRW, based on the principle of working stress are obtained by comparative analysis between the working performance characteristics of common GRS-RW and GRS-RW with GRW facing. A new analytical method for determining the force between GRS-RW with a GRW facing and reinforced soil *"E"* is proposed. By comparative study between theoretical and numerical analysis results, method 1 and method 2 are recommended for determining the *"E"*. A method for determining the tension in the reinforcement of GRS-RW with a GRW facing based on the principle of working strain is also presented in this paper.

Keywords Geo-synthetic reinforced soil retaining wall (GRS-RW) · Geo-grid · Reinforced soil · Gravity retaining wall (GRW) facing · Working strain · Full height rigid facing (FHR)

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1 Introduction

In the highway, railway, building, mining, port, water conservancy projects, and many other infrastructures,

gravity retaining wall (GRW) has been widely used because of its high rigidity, simple structure, and convenient construction. Slope stability is a common problem to occur in sites of geotechnical engineering related projects. Researchers found that some areas required vegetation for stabilization, some of the roadside slopes required retaining wall and some of the roadside slope required better drainage facilities. GRW mainly relies on its weight to maintain balance and stability. But if GRW is very high, the earth pressure acting on the wall back will be very large, thus the retaining wall will become very thick and uneconomical. Therefore, it is obvious that efforts should be made to reduce the earth pressure and reducing the thickness of the retaining wall. Some researchers have suggested different ways of strengthening soil, (Dahal and Zheng 2018) has said that the reconstitution of soil by adding cement is an effective method for improvement of soil behavior in compression. In this study, geogrid is used as reinforcement material for its obvious technical qualities and being efficient and cost-effective.

In the 1960s, a French engineer, Henri Vidal (Vidal 1969), proposed the modern design theory for reinforced soils. According to his design theory, nickel-plated steel bars were used as reinforcement. And it was successfully applied to a reinforced soil retaining wall (RS-RW) in a highway in 1966. He also predicted that reinforced materials could improve the bearing capacity of the foundation (Zhao 2005). Subsequently, the RS RW technology was widely applied and developed in the U.S.A., Europe, Japan, and China, etc. During this time, geosynthetics were developed to replace metals as reinforcement, thus a new type of geo-synthetic reinforced soil retaining wall (GRS-RW) system was formed(Yang et al. 2009). Geo-grid, a type of geo-synthetics, is an ideal reinforcement material with high strength, low elongation, strong interlocking force with soil, good durability, and not easy to creep. The application of geo-grid in many engineering fields has increased sharply since it emerged in 1982 (Zhao 2005), especially in highway projects (Yu-jing and Ran 2009).

A GRS-RW is much thinner than a traditional gravity retaining wall (GRW) and thus is known as the light retaining wall. GRS-RW is economical especially when the wall is higher, and can save the investment of 30–50% (Zhao 2005). Concrete modular or panel walls are generally used as facings of GRS-RWs and the limit equilibrium method is used as the design method. This method is simple and very practical, but cannot evaluate the stress and strain of both reinforcement material and backfill, as well as the deformation of the retaining wall structure. Therefore, the numerical simulation method is increasingly used for analyzing the working performance of GRS-RW (Rowe and Skinner 2001).

In Japan, researchers (Tatsuoka et al. 2007, 1997) proposed the Reinforced Road with Rigid Facing (denoted as RRR) Construction Method, which became the technical standard for the construction of retaining wall in the Japanese railway engineering. Concisely, RRR Construction Method is an engineering technique in which the reinforced concrete face slab, with the ability to resist bending deformation, is used to construct retaining walls in inclined or vertical slopes. This type of wall is known as GRS-RW with Full Height Rigid (FHR) facing, whose thickness is much less than the GRS-RW with a GRW facing in China.

Due to the lack of specifications, this design is done based on the designer's experience. The bearing capacity of GRS-RW with a GRW is given by:

$$E = \varphi E_1 + E_2 \qquad (1)$$

where; E is the bearing capacity of GRS-RW with a GRW, KN/m; E_1 is the bearing capacity of GRW, KN/m; E_2 is the bearing capacity of GRS-RW, KN/m; φ is the collaborative work coefficient. (Yishan 2003) stated that, when the strength of the wall and bearing capacity of the foundation met the requirements, E_1 was determined by sliding resistance (overturning is almost impossible for GRW); the calculation method of E_2 was the same as that of common RS-RW, and the magnitude depended on the strength, length, and spacing of the reinforcement; and the collaborative work coefficient was taken as 0.7.

Although the above design method considered the common characteristics of GRW and GRS-RW, the stiffness of GRW is much greater than that of the concrete face slab of GRS-RW, which may affect the stress and strain of reinforced materials and backfill; On the other hand, the value of collaborative work coefficient, 0.7, is not convincing.

Zou et al. (2011) studied the working properties and design idea on GRS-RW with a GRW facing. But he did not present the specific analytic calculation

method which could be beneficial for GRS-RW with a GRW facing to be applied in engineering practice.

This new retaining wall system has the following features:

- The use of a full-height rigid (FHR) facing that is cast-in-place using staged construction procedures (Fig. 1) (Tatsuoka 1992). The geo-synthetic reinforcement layers are firmly connected to the back of the facing. The importance of this connection for wall stability is illustrated in Fig. 2(Tatsuoka 1992).

- The use of a polymer geogrid reinforcement in cohesionless backfill to ensure good interlocking with the backfill, and the use of a composite of nonwoven and woven geotextiles for nearly saturated cohesive soils to facilitate both drainage and tensile reinforcement of the backfill. This makes possible the use of low-quality on-site soil as the backfill if necessary.

- The use of relatively short reinforcement.

Zou et al. (2013) and Wang et al. (2014) studied the working behavior of GRS-RW having a GRW facing using numerical analysis and suggested its design methods. They found that the required strength of geosynthetic reinforcement is determined according to the working strain of reinforcement. And the soil pressure acting on the back of the rigid wall is calculated with the *Double Wedge Method* (Wang Xie-qun 2014).
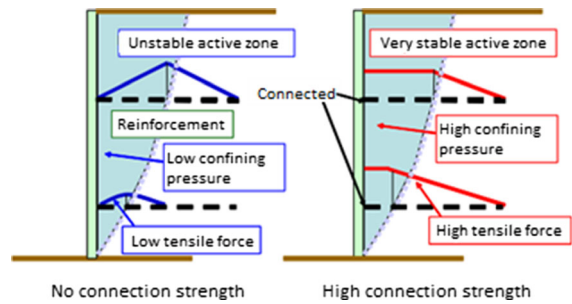
Fig. 2 Effects of firm connection between the reinforcement and the facing (Tatsuoka 1992)

This paper evaluates the working performance of GRS-RW with a GRW facing and the contribution of geo-grids to GRS-RW with a GRW facing, through numerical analytical methods. It considers the stress and strain of both reinforcement and backfill and the deformation of the retaining wall. Through the comparative analysis of the working performance characteristics between common GRS-RW and GRS-RW with a GRW facing, the analytical methods for the calculation of soil pressure acting on the back of GRW are put forward based on the principle of working stress of the reinforcement materials.
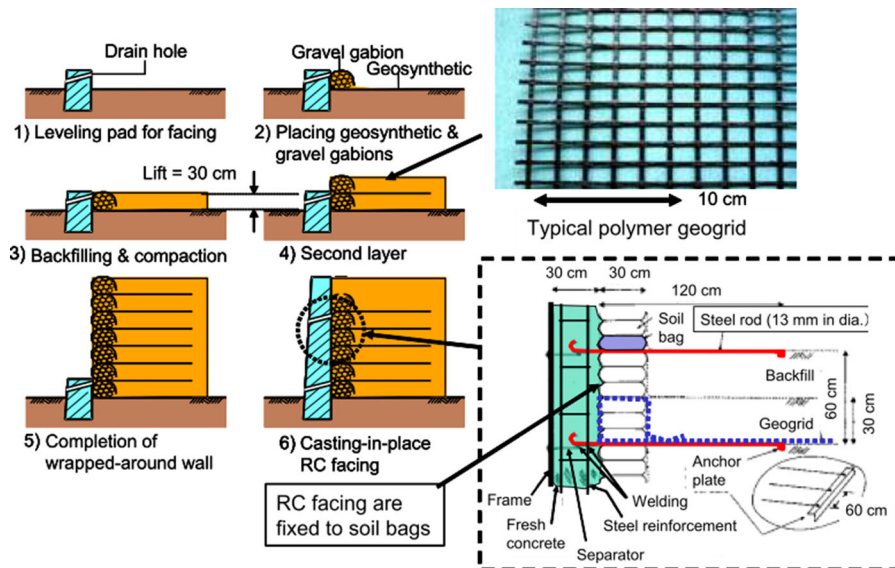
Fig. 1 Staged construction of a GRS-RW with a FHR facing (Tatsuoka 1992)

2 Method and Model for Numerical Analysis on GRS-RW

In the process of calculation, FLAC is suitable for analysis of large deformation problems in geotechnical engineering since it allows material occurrence and rheological yield (Itasca 2005).

Mohr–Coulomb model is used to simulate soil materials. This model of failure envelope corresponds to the shear yield function and tensile stress yield function. Tensile stress is associated with flow rule, while shear stress is not associated with flow rule. Planar failure criteria can be expressed in stress space (σ_1, σ_3) as shown in Fig. 3.

The failure envelop from point A to point B is defined by the Mohr–Coulomb yield function:

$$f^s = \sigma_1 - \sigma_3 N_\phi + 2c\sqrt{N_\phi} \qquad (2)$$

The tensile stress yield function from point B to point C is defined as:

$$f^t = \sigma^t - \sigma_3 \qquad (3)$$

where c—soil's cohesion; σ^t—soil's tensile strength; $N_\phi = \frac{1+\sin\phi}{1-\sin\phi}$; ϕ—soil's angle of internal friction.

The interaction between soil and structure or between two soils has two kinds of situations: one is that there is no relative displacement (e.g. dislocation or open) between soil and structure, only the transmission of force, thus they can be viewed as a continuum composed of two kinds of materials; another is that there is the relative displacement between soil and structure or between two soils, here it is needed to set up the contact surface element. The contact element provided by FLAC is used to simulate the sliding contact surface or open. Mohr–Coulomb
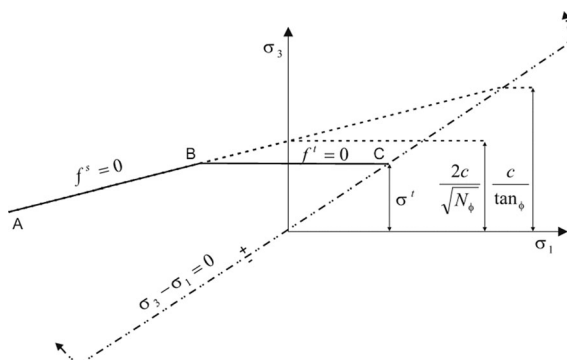
criterion can be used to express interface shear strength.

$$F_{\max} = c_{in}L + \tan\phi_{in}F_n \qquad (4)$$

where; c_{in} = interface cohesion between contact surfaces; L = effective contact length; ϕin = interface friction angle between contact surfaces; Fn = normal force acting on the contact surface.

2.1 Geogrid simulation using cable element

Cable element can be used to simulate the geo-grid in FLAC which is a one-dimensional axial unit, can be fixed in particular grid points, yields force is along its length when the grid deforms. Cable elements can be used to simulate the structure having the tensile ability, such as anchor and geogrid. Figure 4 shows the mechanical model for a cable used to simulate the reinforcement and the reinforcement-soil contact surface.

The interface shear strength criterion in the cable element is shown in Fig. 5. The maximum shear stress $F_s^{\max}$ changes with confining pressure.

If $\sigma_c' < 0$

$$\frac{F_s^{\max}}{L} = S_{bond} \qquad (5)$$

If $\sigma_c' \geq 0$

$$\frac{F_s^{\max}}{L} = S_{bond} + \sigma_c' \times \tan(S_{friction}) \times perimeter \qquad (6)$$

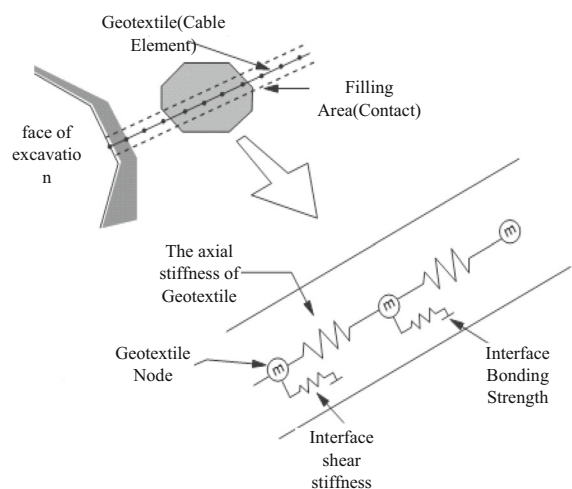**Fig. 3** Mohr—coulomb failure criteria used in FLAC software

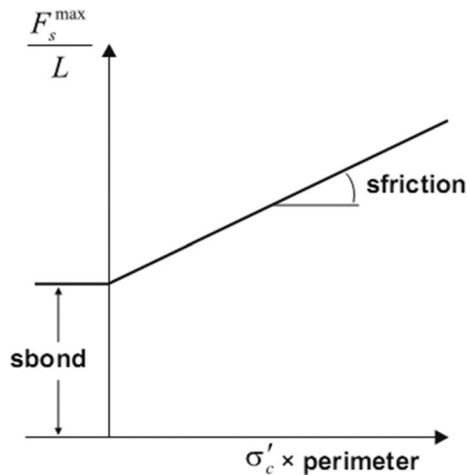**Fig. 4** Mechanical model of reinforced soil showing the cable element and contact surface

Fig. 5 shear strength criterion for the contact surface

where: L is the unit length of cable; S_{bond} is interface cohesion between soil and the cable surface; σ_c' is the effective confining stress perpendicular to the line unit; $S_{friction}$ is interface friction angle between soil and the cable surface; *perimeter* is the outside perimeter of the cable element.

2.2 Analytical Methods for Action Force between Reinforced Soil and GRW

The action force between reinforced soil and GRW can be calculated by the following three analytical methods:

2.3 Method 1

It is assumed that the reinforcement has no effect on the critical slip surface of reinforced soil, and the earth pressure of GRS-RW with a GRW facing is shared by the GRW and reinforcement. Thus the horizontal forces between GRW with a vertical back of the wall and reinforced filling (E) can be expressed as:

$$E = E_{ax} - T_r \tag{7}$$

where : E_{ax}—horizontal component of the active earth pressure (kN), which can be obtained as per the coulomb active earth pressure coefficient recommended by the Chinese Design and Construction of GRS-RW in Highway.

T_r— total tension of reinforcement in the corresponding working condition (kN).

2.4 Method 2

Assuming the slip surface of reinforced soil behind the GRW is the Rankine's active slip plane, taking the active zone as a sliding body to find the solution of horizontal forces between the GRW and the reinforced soil, E (see Fig. 6).

Also assuming the back of the wall is vertical, and no load is applied on the reinforced soil body. The forces on the sliding body include: (1) the gravity of active zone (W); (2) the normal stress (N) and the friction force (F) on the slip plane; (3) the total tension of reinforcement materials (Tr); (4) the horizontal forces (E) between the GRW and the reinforced soil; (5) and the friction between the back of the wall and the reinforced soil ($E \tan \delta$).

The gravity of active zone,

$$W = 0.5H^2\gamma / \tan \alpha \tag{8}$$

According to the force equilibrium condition:
In the Y direction,

$$W = N \cos \alpha + N \sin \alpha \tan \phi + E \tan \delta \tag{9}$$

So,

$$N = \frac{W - E \tan \delta}{\cos \alpha + \sin \alpha \tan \phi} \tag{10}$$

In the X direction,

$$E + T_r + N \cos \alpha \tan \phi = N \sin \alpha \tag{11}$$

Then,

$$E = \frac{\frac{\sin \alpha - \cos \alpha \tan \phi}{\cos \alpha + \sin \alpha \tan \phi} W - T_r}{1 + \frac{\sin \alpha - \cos \alpha \tan \phi}{\cos \alpha + \sin \alpha \tan \phi} \tan \delta} \tag{12}$$
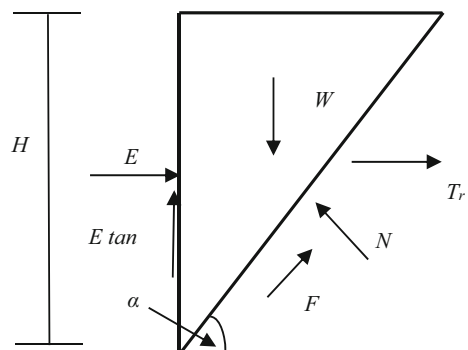

Fig. 6 Force Diagram of slip body Method (2)

2.5 Method 3

Assuming that the potential slip plane of the backfill behind the wall is determined with 0.3H method owing to the application of reinforcement. The sliding body in the active zone is used to determine the force between GRW and reinforced soil, E.

When the back of the wall is vertical, and the reinforced soil doesn't have any external load, the forces acting on the slip body are shown in Fig. 7, which includes: (1) the gravity of active zone (W); (2) the normal force (N_1) and the friction force (F_1) on the bottom of slip plane; (3) the normal force (N_2) and the friction force (F_2)in the vertical slip plane; (4) the total tension of reinforcements (T_r); (5)the horizontal forces (E) between the GRW and the reinforced soil; and (6) the friction between the back of the wall and the reinforced soil ($F_2 = E \tan \delta$).

The normal force, N_2 in the vertical sliding plane is taken as the active earth pressure:

$$N_2 = 0.5K_a\gamma h^2$$
$$= 0.5 \tan^2(45° - \phi/2)\gamma H^2(1 - 0.3\tan\alpha)^2 \quad (13)$$

where, $h = H - 0.3H \tan \alpha$.

The gravity of the active zone:

$$W = 0.15H(h + H)\gamma = 0.15H^2(2 - 0.3\tan\alpha)\gamma \quad (14)$$

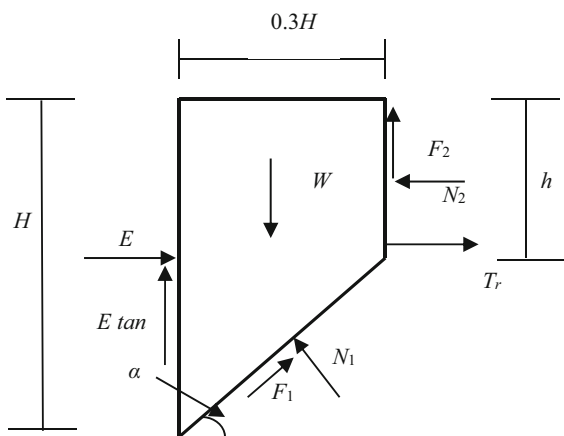According to the equilibrium conditions,
In the Y direction,

$$W = N_1 \cos \alpha + N_1 \sin \alpha \tan \phi + N_2 \tan \phi + E \tan \delta \quad (15)$$

So,

$$N_1 = \frac{W - N_2 \tan \phi - E \tan \delta}{\cos \alpha + \sin \alpha \tan \phi} \quad (16)$$

In the X direction,

$$E + T_r + N_1 \cos \alpha \tan \phi = N_1 \sin \alpha + N_2 \quad (17)$$

Then,

$$E = \frac{\frac{\sin\alpha - \cos\alpha\tan\phi}{\cos\alpha + \sin\alpha\tan\phi}(W - N_2\tan\phi) + N_2 - T_r}{1 + \frac{\sin\alpha - \cos\alpha\tan\phi}{\cos\alpha + \sin\alpha\tan\phi}\tan\delta} \quad (18)$$

3 Illustration of the Methods for Calculating the Force between GRW and Reinforced Soil based on an Example

3.1 Numerical Analysis of GRS-RW

This study adopts a typical GRS-RW configuration used for embankment slope, as shown in Fig. 8, for numerical and theoretical analyses. The height of the GRW is 10 m, the wall widths at the top and bottom of the wall are 1.0 m and 3.0 m respectively. The buried depth of GRW is 1.0 m. There is an embankment of 8 m above the top of the wall with a gradient of 1.5(Horizontal): 1(Vertical), which is replaced using the overload acting on the top of the wall to simulate its effect. A total of 19 layers of 9 m long geo-grid are laid in the backfill at a vertical interval of 0.5 m. Two
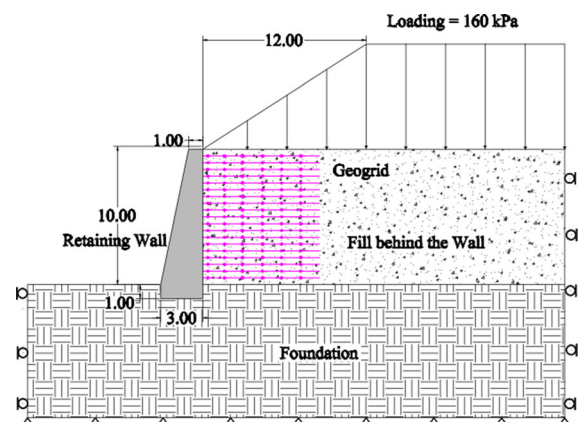

Fig. 7 Force Diagram of slip body for Method (3)

Fig. 8 Calculation Model

types of geogrid (denoted as G1 and G2) are adopted for comparison. Typical parameters of the foundation soil, backfill soil, and GRW materials and their interfaces are used, which are summarized in Table 1–3. The foundation soil simulates typical over-consolidated surficial soils. The backfill, on the other hand, simulates normal consolidated cohesionless soils that are typically used as backfill. The dilation angle is assumed to be zero for both backfill and foundation soils to be conservative (i.e. soils have lower strength upon shear failure). It is noted that the current numerical simulation aims at evaluating the analytical approaches for the GRS-RW (i.e. Methods 1, 2, and 3). A more detailed parametric study for evaluating the effects of soil parameters on the performance of GRS-RW is beyond the scope of the current study.

Figures 9, 10 and 11 respectively shows the horizontal displacement, horizontal stress distribution between the back of the wall and reinforced soil, and the maximum tensile strain in each layer of geogrid where " − 1" refers to the state of filling up to the top of the wall and " − 2" refers to the state of completion of the overload on top of the wall. Table 4 summarizes the numerical analysis results, maximum horizontal displacement, horizontal forces between wall and reinforcements and mean value of the maximum strain of geo-grid in GRS-RW.

3.2 Analytical Calculation of the Force between the GRW and the Reinforced Soil, E

The methods proposed in Sect. 2.2 are respectively used to calculate force, E between the GRW and reinforced soil. (Fig. 11)

Table 2 Shear strength parameters of the contact surfaces

Interface	Cohesion (kPa)	Angle of friction (°)
Foundation—Backfill	2	33
Retaining wall—Backfill	0	18
Retaining wall— Foundation soil	0	20

3.3 Calculation with Method 1

On the example for the numerical analysis of GRS-RW with a GRW facing, the horizontal component of the active earth pressure as the filling is up to the top of the wall, E_{ax}, can be calculated according to the coulomb active earth pressure coefficient recommended by the Chinese Specifications of the Design and Construction Technology of Retaining Wall at Highway Engineering:

$$E_{ax} = 0.5 K_{ax} \gamma H^2$$
$$K_{ax} = K_a \sin(90^o - \varepsilon - \delta)$$
$$K_a = \frac{\cos^2(\phi - \varepsilon)}{\cos^2 \delta \cdot \cos(\delta + \varepsilon)\left[1 + \sqrt{\frac{\sin(\delta+\phi)\cdot\sin(\phi-\beta)}{\cos(\delta+\varepsilon)\cdot\cos(\varepsilon-\beta)}}\right]}$$

(19)

where, H—height of retaining wall.

ϕ— backfill's internal friction angle;

γ— unit weight of the backfill;

ε—angle between the back of the wall and the vertical line, which is positive as the back of the wall inclines forward while the opposite is negative;

δ— interface friction angle between the wall and the backfill;

β—angle of inclination of the filling on the top of the wall.

In the example in Sect. 3.1, assuming:

Table 1 Material model and parameters of foundation soil, backfill and retaining wall

Materials	Model	Modulus of Elasticity (MPa)	Cohesion (kPa)	Internal frictional angle (°)	Angle of dilatancy (°)	Poisson's ratio	Unitweight (kN/m³)
Foundation soil	M-C	60	20	36	0	0.3	22
Backfill	M-C	30	0	33	0	0.3	19
Retaining wall	Elastic	40,000	-	-	-	0.3	25

Table 3 Interface parameters between geogrid and backfill

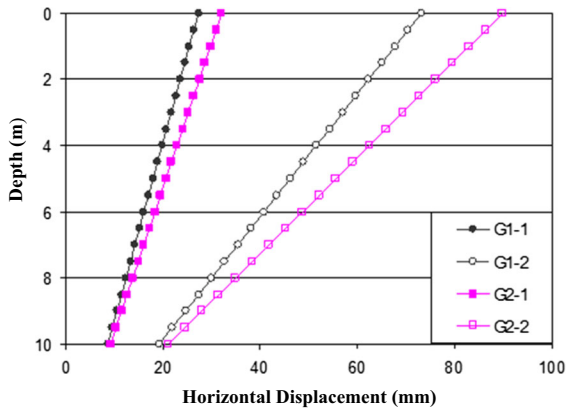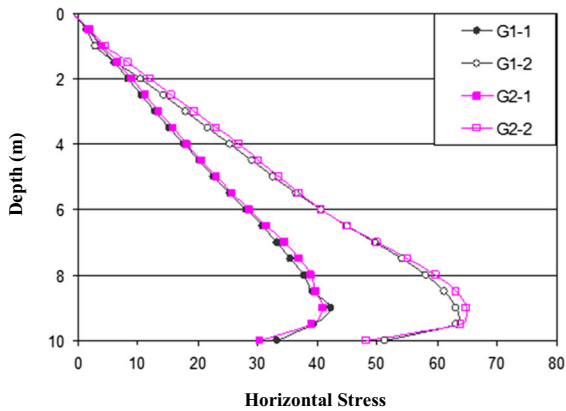| Type of geogrid	Tensile strength (kN/m)	Tensile stiffness (kN/m)	Interface friction angle (°)	Interface cohesive force (kPa)
G1	50	500	30	10
G2	25	250	30	10

Fig. 9 Horizontal Displacement of the GRW

Fig .10 Horizontal Stress between GRW and Reinforced Soil

The unit weight of backfill, $\gamma=19kN/m^3$, the internal frictional angle, $\phi=33°$, the angle between the back of the wall and the vertical line, $\varepsilon=0$ the angle of friction between wall and backfill, $\delta=18°$, angle of inclination of the filling on the top of the wall, $\beta=0$, and the filling is up to top of the wall (Case 1).

when loading is completed (Case 2), the horizontal component of active earth pressure, E_{ax} is still calculated with the method recommended by the Chinese Specifications of the Design and Construction Technology of Retaining Wall at Highway

Engineering: first, the maximum load 160 kPa is converted into the equivalent filling with a height of 8.42 m, and then the active earth pressure and its horizontal component is calculated step by step.

Geogrid tension (Tr) can be estimated using the average value of the maximum tension strains at all layers of geogrids, which are obtained by the numerical analysis, multiplying the tensile stiffness of reinforcement corresponding to the average value.

The calculation results obtained by using method 1 are shown in Table 5. Comparing the results in Tables 4 and 5, the calculated value of horizontal force, E between GRW and the reinforced soil is consistent with the results from the numerical analysis in this study. Among them, when the filling is up to the top of the wall, the calculated results of the E is a little bit smaller than that from the numerical simulation due to the small displacements of both the GRW and the reinforced soil, which does not fully achieve the limit state yet.

3.4 Calculation by Method 2

Method 2 is based on the assumption that the critical slip plane of reinforced soil is Rankine's active slip plane, and the principle and calculation procedure are the same as in method 1. The calculation results are summarized in Table 6, and the calculation values of the horizontal force between GRW and the reinforced soil are consistent with the results from numerical analysis.

3.5 Calculation by Method 3

Method 3 assumes that the slip plane of the backfill is determined with the 0.3H method. Table 7 shows the calculated results which are significantly lower than those from the numerical analysis, especially in the phase of completion of overload. The potential slip plane obtained with the 0.3H method can roughly reflect the position of the maximum tensile strain in

Table 4 Summarized results from numerical analysis in this study

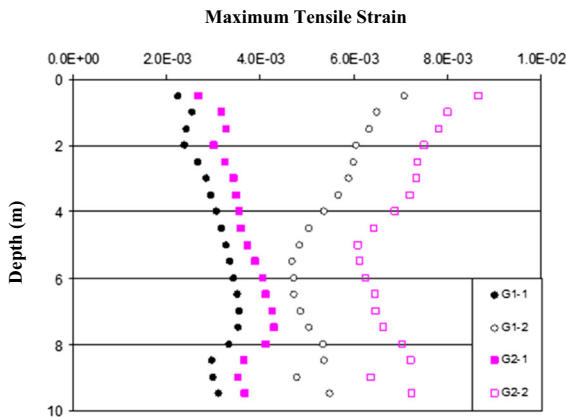| Number	Geogrid type	Working condition	Maximum horizontal displacement (mm)	Horizontal stress (kN/m)	Average value of maximum strain of geogiid (%)
G1-1	G1	1-filling up to wall top	27.3	232.0	0.30
G1-2	G1	2-completing overload	73.1	342.6	0.55
G2-1	G2	1-filling up to wall top	32.1	234.9	0.36
G2-2	G2	2-completing overload	89.9	351.6	0.70

Fig. 11 Maximum tensile strain in each layer of geogrid

each layer of geogrid, which is the measured data or the results from numerical analysis and has certain positive significance for selecting the desired length of reinforcements in the design of GRS-RW. But it is still to be verified whether the 0.3H method can be used for both the stability analysis of reinforced soil structure and soil pressure calculation or not.

4 Design Method for GRS-RW having a Full Rigid Facing

The numerical analysis results from Wang et al. (2014) show that the lateral earth pressure acting on GRS-RW with GRW facings is lower than that on the gabion, and presents a distinct nonlinear distribution along with the height of the wall so it is difficult to capture its mathematical laws. Thus, for determination of earth pressure on the back of the wall, it can be referred to "Japanese Specification for RRR—B: Design and Construction" in which the Double Wedge method is used for the analysis of internal stability of GRS-RW having a full-high rigid facing.

The Double Wedge Method (Fig. 12) given in the Japanese Specification resembles the specification provided by the German Architectural Institute (DIBT) for the calculation of internal stability of an ordinary GRS-RW, only that the former merely takes into account the case of sliding plane passing through the heel of the wall owing to the high stiffness of FHR facing. In this method, the lower end a on the earth

Table 5 Calculation results using method 1

Number	Geogrid type	working condition	E_{ax} (kN/m)	T_r (kN/m)	$E = E_{ax}—T_r$ (kN/m)
G1-1	G1	1-filling up to the top of wall	245.3	28.6	216.6
G1-2	G1	2-after completing overload	395.1	51.9	343.3
G2-1	G2	1-filling up to the top of wall	245.3	17.2	228.1
G2-2	G2	2- after completing overload	395.1	33.3	361.9

Table 6 Calculation results using method 2

Number	Geogrid type	Working condition	T_r (kN/m)	E (kN/m)
G1-1	G1	1-filling up to the top of wall	28.6	213.7
G1-2	G1	2-after completing overload	51.9	340.5
G2-1	G2	1-filling up to the top of wall	17.2	223.5
G2-2	G2	2-after completing overload	33.3	356.3

Table 7 Calculation results using method 3	Number	Geogrid type	Working condition	Tr (kN/m)	E (kN/m)
	G1-1	G1	1-filling up to the top of wall	28.6	196.9
	G1-2	G1	2-after completing overload	51.9	240.7
	G2-1	G2	1-filling up to the top of wall	17.2	206.7
	G2-2	G2	2-after completing overload	33.3	256.5

wedge F in Fig. 12 is fixed on the heel of the rigid facing, the minimum safety factor is found by changing the position of b, which can be realized by changing θ_f and θ_b (simple programming can help simplify the calculation procedure).

The specific steps of the Double Wedge Method are as following:

(1) Assuming that a potential slip plane is obtained through the values of θf and θb and neglect the pulling force in reinforcement. Earth pressure acting on the rigid facing, P_f can be calculated according to the limit equilibrium equation of forces acting on the two earth wedges (i.e., F and B in Fig. 12 (b), where H_f and H_b are the horizontal seismic loads on earth wedge F and

B, respectively), i.e., employing the geometric relations of the force polygons (Fig. 12 c);

(2) Selecting an isolated body which includes the rigid facing and earth wedges F and B (Fig. 12 (a), where W_{gh} is the horizontal seismic force acting on the rigid facing; $W_{gv}tan\varphi_d$ is the friction resistance between the bottom surface of the rigid facing and the foundation soil, which is not considered in most cases due to its in-deterministic nature (therefore the result is safer). The tension in reinforcement acting on the potential slip planes ab and bc should be counted in (tension T_i in each layer of reinforcement is calculated according to Eq. (20)).

(a) The mechanism of rigid retaining wall   (b) Double wedge theory
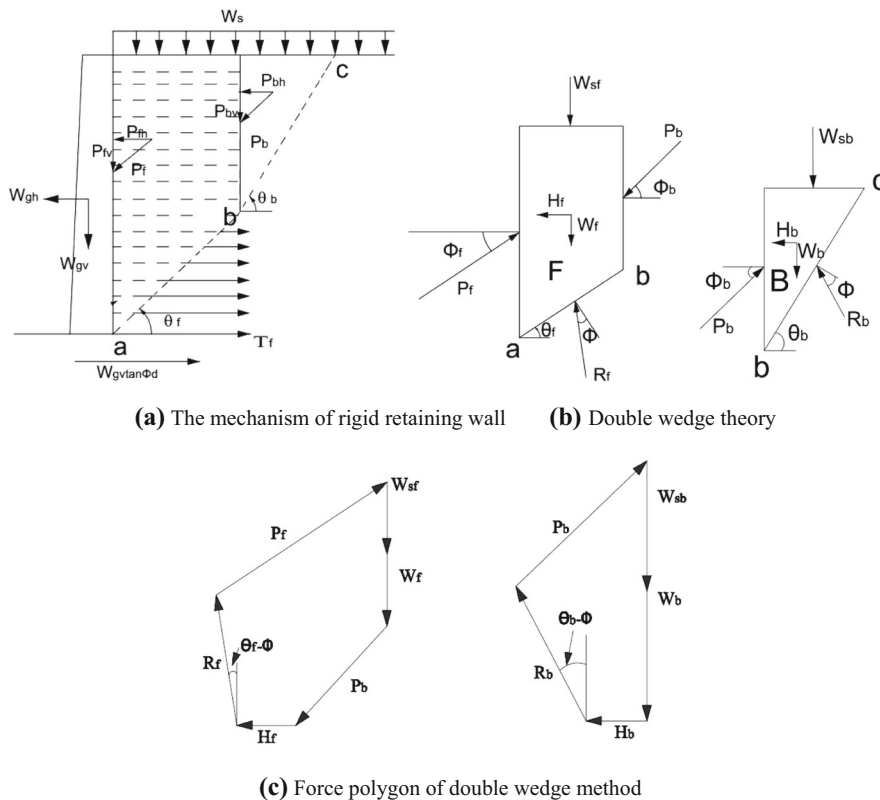
(c) Force polygon of double wedge method

Fig.12 Schematic diagram for determination of soil pressure with double Wedge Method in Japanese

$$T_i = 2\sigma_v L_e f \frac{1}{F_s} \tag{20}$$

Compute the stability safety coefficients against sliding and against overturning of the rigid facing, F_s and F_o, until the minimum safety factors of all potential failure planes, $(F_s)_{min}$ and $(F_o)_{min}$ meet the requirements, and the corresponding earth pressure acting on the back of rigid facing is the one we are searching for. If any of both $(F_s)_{min}$ and $(F_o)_{min}$ fails to meet the specified requirements, one should alter the layout of the reinforcement (spacing and/or length), and/or employ reinforcement with higher tensile strength, and repeat the above computation procedure in the same way until the specified safety coefficient is satisfied.

Visibly, the Japanese Double Wedge Method still employs AASHTO simplified method to calculate the tension in reinforcement (Aashto 1998).

According to the above analyses, it is recommended that the method based on the working strain in reinforcement, which is given in Sects. 2.1 and 2.2, should be adopted to determine the tensile force in each layer of reinforcement.

5 Discussion

The calculation of earth pressure and the correct evaluation of the contribution of reinforcements are the keys to the design of the GRS-RW. The ultimate tensile strain of geo-synthetic reinforcement is significantly greater than the ultimate strain of filling material; and generally, the deformation of geo-synthetic reinforcement in the limit state is not be allowed in engineering projects. In the traditional design method for GRS-RW, it considers the tensile strength of reinforcements as the design index but doesn't consider the deformation control, so the design calculation results are vastly different from the practically measured data.

The design idea for an ordinary GRS-RW or a GRS-RW with a GRW facing can be based on the Working Strain Principle, which means the filling material, is in the ultimate state while the reinforcement is in a working state (not entering the limit state). In this study, based on the field measured data of the GRS-RWs from the literature, the numerical analysis results on both GRS-RW with an FHR facing and GRS-RW

with a GRW facing and the recommendations from the foreign codes, a design idea based on the working stress and strain of reinforcements as design control indices is proposed.

Based on the above studies, an analytical method for determining the force between GRS-RW with a GRW facing and reinforced soil, 'E' is proposed for the first time. By comparison between the theoretical calculation results and the numerical analysis results, method 1 and 2 is recommended for determining the E. In these two calculation methods, Tr is the total tension of reinforcements and takes the value corresponding to the certain working condition. Namely, Tr is the design control index which is the product of value between 0.5% ~ 2% of the strain of reinforcement and the corresponding stiffness of reinforcement. Among them, the design working strain of reinforcement is determined according to the specific engineering project. For a GRS-RW with a GRW facing, if firstly pouring the GRW facing before the filling reinforced soil, then the deformation of reinforced soil and reinforcement are subjected to the restraint from the GRW, so the limits for the working strain of reinforcement approximately taken as 0.5% ~ 1%; while for a GRS-RW with FHR facing, if firstly filling reinforced soil before pouring the rigid facing, the working strain of the reinforcement approximately taken as 1% ~ 2%. For example, for some engineering projects (such as the abutment and retaining walls at high-speed railways), whose deformations are strictly controlled, the working strains of reinforcement take the lower limit; while for the engineering projects where the deformations are not strictly controlled, the working strain of reinforcement takes the upper limit.

6 Conclusions

GRS-RW with a GRW facing and GRS-RW with FHR facing are two types of new GRS-RW system and have been widely used in engineering projects in recent years. Due to the shortage of systematical research on the working properties of the new retaining wall system, the design theory and method of GRS-RW with a GRW facing are not explicit yet. The design method based on the principle of working strain is more suitable. In the current study, the design theories and analytical methods are presented based on the

existing research results in China and abroad, and the design method for GRS-RW having an FHR facing is introduced.

A design idea based on the working stress and strain of reinforcements as design control indices is proposed. An analytical method for determining the force between GRS-RW with a GRW facing and reinforced soil, 'E' is proposed for the first time. By comparison between the theoretical calculation results and the numerical analysis results, methods 1 and 2 are recommended for determining E. In these two calculation methods, T_r is the total tension of reinforcements and takes the value corresponding to the certain working condition. Namely, T_r is the design control index and takes as the product between the $0.5\% \sim 2\%$ strain of reinforcement and the corresponding stiffness of reinforcement. Among them, the design working strain of reinforcement is determined according to the specific engineering project. For a GRS-RW with a GRW facing, if firstly pouring the GRW facing before the filling reinforced soil, then the deformation of reinforced soil and reinforcement are obviously subjected to the restraint from the GRW, so the limits for the working strain of reinforcement approximately takes as $0.5\% \sim 1\%$; while for a GRS-RW with FHR facing, if firstly filling reinforced soil before pouring the rigid facing, the working strain of the reinforcement approximately takes as $1\% \sim 2\%$. For examples, for some engineering projects (such as the abutment and retaining walls at high-speed railways), whose deformations are strictly controlled, the working strains of reinforcement take the lower limit; while for the engineering projects where the deformations are not strictly controlled, the working strain of reinforcement take the upper limit.

Compliance with ethical standards

References

Aashto LRFD (1998) Bridge design specifications. American association of state highway and transportation officials. 5–138

Dahal BK, Dahal RK (2017) Landslide hazard map: tool for optimization of low-cost mitigation. Geoenvironmental Disasters 4:8

Dahal BK, Zheng J-J (2018) Compression behavior of reconstituted clay: a study on black clay. J Nepal Geol Soc 55:55–60

ITASCA (2005) FLAC fast Lagrangian analysis of continua v.5·0. User's manual. ITASCA Consulting Group Minneapolis. MN, USA, pp 3–2, 3–24

Rowe RK, Skinner GD (2001) Numerical analysis of geosynthetic reinforced retaining wall constructed on a layered soil foundation. Geotext Geomembr 19:387–412

Tatsuoka F (1992) Roles of facing rigidity in soil reinforcing, keynote lecture. Proc Int Symp Earth Reinf Pract (IS Kyushu'91) 146:831–870

Tatsuoka F, Tateyama M, Mohri Y, Matsushima K (2007) Remedial treatment of soil structures using geosynthetic-reinforcing technology. Geotext Geomembr 25:204–220

Tatsuoka F, Tateyama M, Uchimura T, Koseki J (1997) Geosynthetic-reinforced soil retaining walls as important permanent structures 1996–1997 mercer lecture. Geosynth Int 4:81–136

Vidal H (1969) The principle of reinforced earth. Highway research record

Wang X-Q, Zhang W L, Leng JJ, Liu JG, Deng WD (2014) Working behaviour and design method of geosynthetic reinforced soil retaining wall with rigid facing. Yangtze River Scientific Research Institute. https://doi.org/10.3969/j.issn.1001-5485.2014.03.006

Yang G-Q, Zhou Y-T, Zhou Q-Y, Xue X-H (2009) Experimental research on geogrid reinforced earth retaining wall. Rock Soil Mech 1:047

Yishan G (2003) The application of reinforced technique in gravel retaining wall design. Optim Cap Constr

Yu-Jing M, Ran W (2009) An analysis of the performance parameters of geogrids-reinforced earth retaining walls with the finite element method. Traffic Eng Technol Natl Def 1:25–28

Zhao W (2005) Geosynthetics. China Machine Press, Beijing

Zou W-L, Leng J-J, Wang X-Q (2011) Numerical analysis of working properties and soil pressure calculation of geosynthetic-reinforced soil gravity retaining wall. Rock Soil Mech 32:70–75

Zou WL, Wx Q, Xie N, Zhuang YF (2013) Numerical analysis of working properties and inquiry of design method on Geosynthetic-Reinforced Soil Retaining Walls (GRS-RWs) with rigid facings. Design and Practice of Geosynthetic-Reinforced Soil Structure. DEStech Publications, Inc, Lancaster, Pennsylvania

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