Confining effect of geogrid-reinforced soil: introduction into design method

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ABSTRACT: In current practical problems, the reinforcing effects of geogrid-reinforced soil are generally evaluated by the tensile effect due to the tensile force of a geogrid. However, we have experimentally examined the existence of the confining effect, which is one component of the reinforcing effects and is independent of the tensile force of a geogrid. An evaluation method in which the reinforcing effect can be divided into tensile effect and confining effect is proposed. The validity of the method was verified by the results of a series of new laboratory tests. The confining effect is introduced into the tie-back wedge method of geogrid-reinforced retaining walls in a practical design. A new formula for calculating the maximum tensile force mobilized on the sliding plane on Rankine's active earth pressure theory was derived. Finally, as an example of design of a geogrid-reinforced retaining wall, the results obtained by using the design method with and without consideration of the confining effect are compared.

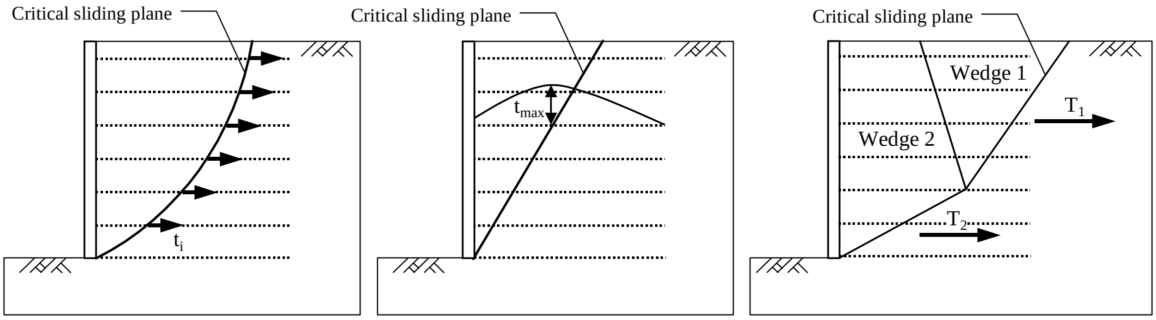
1 INTRODUCTION

In current practical problems, the reinforcing effects, which are applied to the stability analysis of a geogrid-reinforced structure, are generally evaluated based on the tensile force of geogrid. Fukuda et al. (1986) reported, based on in-situ measurements, that the tensile force of a geogrid, which should be mobilized for the stability of a structure, was not mobilized in soil, although the structure maintained sufficient stability. Tatsuoka et al. (1996) reported that a strong earthquake inflicted little damage on a reinforced structure. These studies suggest the existence of an additional reinforcing effect other than the tensile effect due to tensile force of a geogrid. This additional reinforcing effect has not been evaluated quantitatively. In order to establish a design method in which the reinforcing effects are sufficiently evaluated, this additional effect should be evaluated quantitatively.

In a previous study, we experimentally examined the reinforcing effects of geogrid-reinforced soil. We confirmed the existence of an additional reinforcing effect other than the tensile effect in laboratory tests, and we defined this additional effect as the confining effect (Ochiai et al., 1996).

We introduced the confining effect into the Japanese standard design method of geotextiles-reinforced retaining walls published by the Public Works Research Center (1993) (Kawamura et al., 1999). In this design method, the slip circle method is used for internal stability analysis, as shown in Figure 1(a).

In the present study, the confining effect was evaluated quantitatively by laboratory tests and it was introduced into the tie-back wedge method, which is the most widely used method in the world, based on Rankine's earth pressure theory as shown in Figure 1(b). A new formula that takes into account the confining effect is proposed for checking the safety of each layer of a geogrid. Re-



Figures 1. Internal stability analysis of geogrid-reinforced retaining walls in several design method

sults of calculation using the tie-back wedge method with and without consideration of the confining effect are compared.

2 METHOD FOR DISINING A GEOGRID-REINFORCED RETAINING WALL

Several methods have been used for designing and/or checking the stability of a geogrid-reinforced structure. The design methods can be classified into two types (Fukuda et al., 1989): 1) a method using design charts, diagrams and/or graphs; and 2) an original design method applied to each construction method or structure.

In the latter method, internal stability analysis of geogrid-reinforced retaining walls is classified into three types, as shown in Figures 1 (a), (b) and (c) (Bastick et al., 1996; Penman et al., 1998). A critical sliding plane is assumed in these methods. In this paper, the internal stability using the tie-back wedge method is discussed. The formula for checking the safety of each layer of a geogrid is an important point.

3 REINFORCING EFFECTS IN GEOGRID- REINFORCED SOIL

3.1 *A method for evaluating reinforcing effects*

The reinforcing effects of geogrid-reinforced soil are often evaluated by only the tensile effect due to the tensile force of a geogrid. Jewell and Wroth (1987) carried out direct shear tests on reinforced soil, as shown in Figure 2, and they showed that the shear resistance of reinforced soil increased by

$$\tau_{EXT} = \frac{P_R}{A_S}\left(\sin\theta\tan\phi + \cos\theta\right) \tag{1}$$

where τ_{EXT} is the increment of shear resistance, P_R is the mobilized tensile force of the reinforcement, A_S is the area of the sliding plane, ϕ is the internal friction angle of soil and θ is the angle between the reinforcement and the sliding plane.

Equation (1) can be considered as the tensile effect due to the tensile force of a geogrid. As shown in Equation (1), τ_{EXT} does not depend on the normal stress on the sliding plane and it is equal to the increment of apparent cohesion of soil, c_T, in Figure 3. Considering this tensile effect, the relationship between the shear strength of reinforced soil, s_R, and the normal stress, σ_n, can be expressed

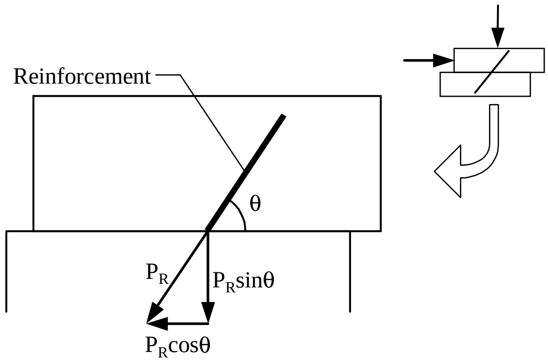


Figure 2. Direct shear test on reinforced soil

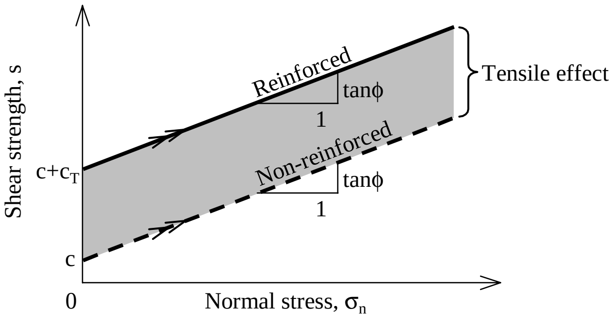


Figure 3. Relationship between shear strength, s, and normal stress on sliding plane, σ_n, considering only tensile effect

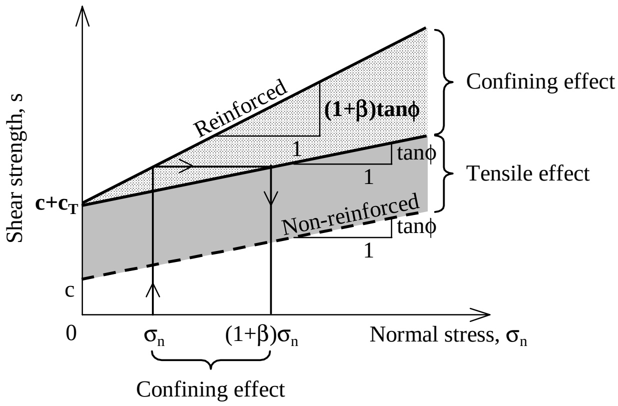


Figure 4. Relationship between s and σ_n, considering both of tensile effect and confining effect

$$
\begin{aligned}
s_R &= c + c_T + \sigma_n \tan\phi \\
&= c + \frac{P_R}{A_S}(\sin\theta \tan\phi + \cos\theta) + \sigma_n \tan\phi
\end{aligned} \tag{2}
$$

Fukushima et al. (1988) carried out large-scale triaxial compression tests using geogrid-reinforced sand, and their results clearly showed the internal friction angle increases.

We have defined the confining effect as an effect that is independent of the tensile effect, and we have proposed an evaluation method that takes into account both the tensile effect and the confining effect, as shown in Figure 4. "$\beta \cdot \tan\phi$" in Figure 4 is the increment of the slope of the rein-

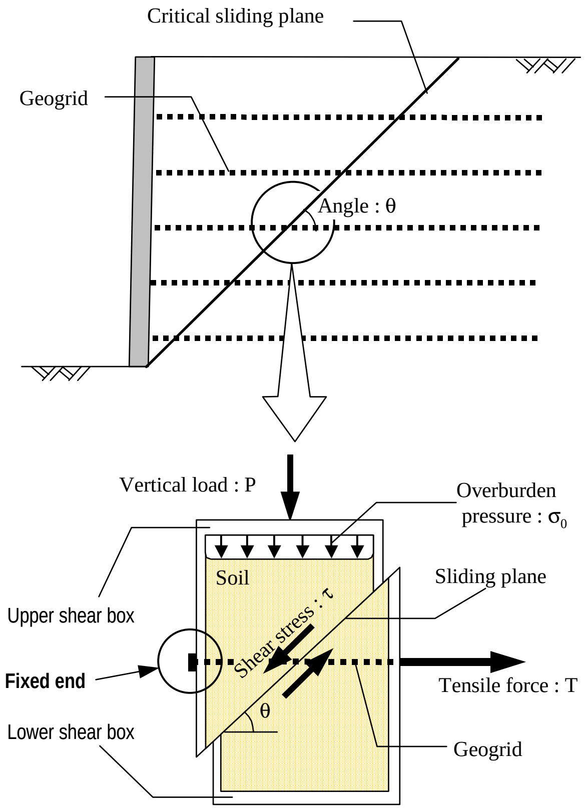


Figure 5. Sketch of shear box in the test apparatus

Table 1. Test conditions

Soil materials	Toyoura sand, Masado
Sliding angle, θ	30, 40, 50 (degree)
Tensile force of geogrid, T	0.373, 0.981, 1.961 (kN)
Shape index, R	0.19, 0.42, 0.57
Relative density of Toyoura sand, D_r	45, 75, 85%
Dry unit weight of Masado, γ_d	15.68, 16.76, 18.33 (kN/m^3)

forced line of the s-σ_n relation. However, in order to simply introduce the confining effect into a design method, the shear strength of reinforced soil should be evaluated not as the increment of the internal friction angle, $\beta\tan\phi$, but as the increment of the normal stress, $\beta\sigma_n$, as follows:

$$s = c + \frac{P_R}{A_S}(\sin\theta\tan\phi + \cos\theta) + (1+\beta)\sigma_n \tan\phi \tag{3}$$

The confining effect is the effect of restriction of soil around the geogrid by the geogrid, and the confining stress around the geogrid apparently increases. If the confining effect can be also evaluated quantitatively, it will become possible to establish a design method that sufficiently evaluates the reinforcing effects.

3.2 *Experimental verification of reinforcing effects*

3.2.1 *Test apparatus and test procedure*

A new shear test apparatus was developed to investigate the reinforcing effects on the sliding plane of geogrid-reinforced soil mass, as shown in Figure 5 (Ochiai et al., 1996). The shear box is rectangular in shape and is 200 mm wide, 200 mm long and 380 mm high. The shear box is divided into two equally sized upper and lower parts by sliding plane inclined by an angle of θ. One end of the geogrid is fixed to the upper part of the shear box, so that the sliding soil mass with geogrids moves as a rigid block. This is the central feature. A constant tensile force of the geogrid is provided so that the confining effect can be estimated separately from the tensile effect.

Two kinds of soil, dry Toyoura Sand, which is Japanese standard sand, and Masado, which is a decomposed granite soil with optimum water content (w_{opt}=12.6%), were used in a series of tests. After applying a constant value of tensile force of the geogrid, T, and an overburden pressure, σ_0, tests were carried out by vertical loading at a constant speed of 0.35 mm/min. The test conditions are summarized in Table 1. The shape index, R, for evaluating the contact area between the soil and the geogrid was previously proposed by the authors (Ochiai et al., 1996).

3.2.2 *Test results*

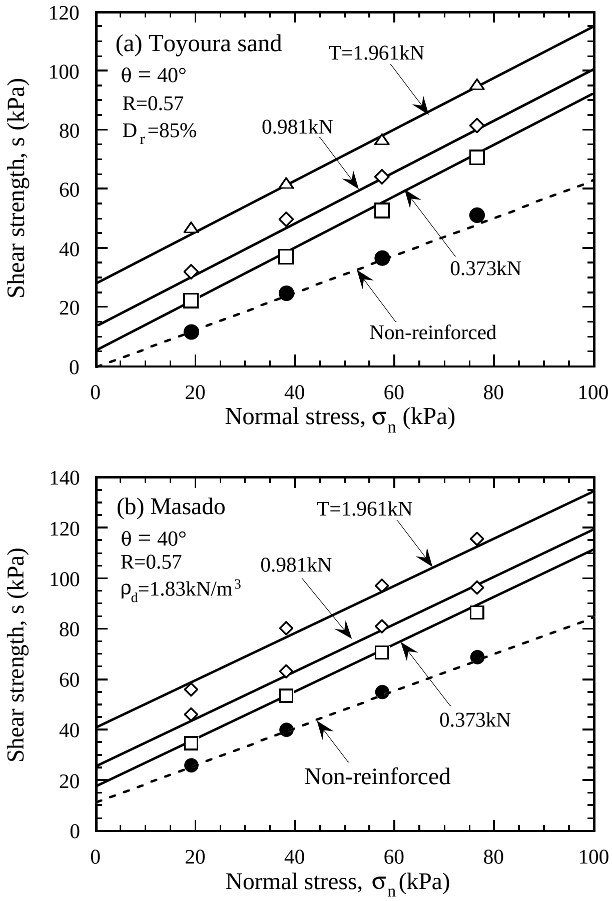
Figures 6 (a) and (b) shows the typical relationships between shear strength, s, and normal stress, σ_n, obtained from the results of a series of tests conducted under the condition of various tensile forces of the geogrid. The shear strength, s, is defined as the maximum value of shear stress, $\tau=(P/A)\sin\theta$, until the shear displacement reaches 10 mm. P is the vertical load, A is the area of the sliding plane and θ is the sliding angle. The normal stress, σ_n, is the normal component of the overburden pressure, σ_0, against the sliding plane and is expressed as $\sigma_n=\sigma_0\cos\theta$. The relationships between s and σ_n for both non-reinforced and reinforced soils are expressed by straight lines. Similar relationships were obtained under different conditions of the sliding angle, θ, shape index, R, relative density of Toyoura sand, D_r, and dry unit weight of Masado, γ_d.

The relationships can therefore be modeled as shown in Figure 7. For Toyoura sand, the intercept of the relationship of non-reinforced sand is zero. The evaluation method that takes into account both the tensile effect and the confining effect was verified (see Figure 7) by laboratory tests in which the sliding plane in the geogrid-reinforced soil mass was simulated.

Considering the stress condition near the sliding plane of a reinforced retaining walls as shown in Figure 5, Equation (3) can be rewritten as Equation (4).

$$s_R = c + \frac{T}{A}(\sin\theta\tan\phi + \cos\theta) + \sigma_n \tan\phi + \beta \cdot \sigma_n \tan\phi \tag{4}$$

The fourth term in Equation (4), $\beta \cdot \sigma_n\tan\phi$, is the confining effect independent of the tensile force of the geogrid. The term means that the normal stress on the sliding plane, σ_n, increases due to the confining effect, as illustrated in Figure 8. The coefficient β is a parameter of the confining effect, results of a series of tests showed that the confining effect parameter, β, depends on the internal friction angle, ϕ, and the shape index of the geogrid, R, as shown in Figure 9. The range of confining effect parameter, β, is from 0.2 to 0.4 in these tests. However, in order to use the confining effect in a practical design method, further investigation of accurate methods for estimating the confining effect parameter, β, is needed.



Figures 6. Typical test results – relationships between shear strength, s, and normal stress, σ_n, under the condition of various tensile forces of geogrid

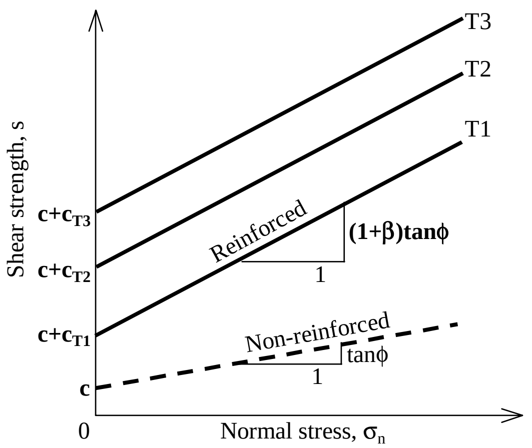


Figure 7. Method for evaluating shear strength of reinforced soil

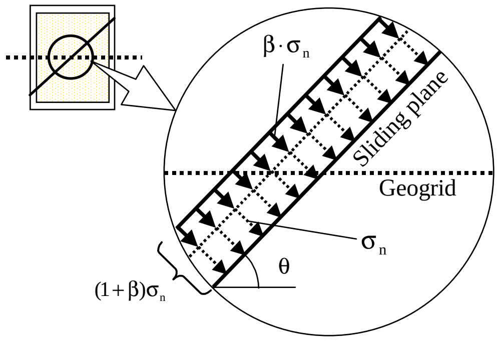


Figure 8. Condition of normal stress on the sliding plane in geogrid-reinforced soil mass

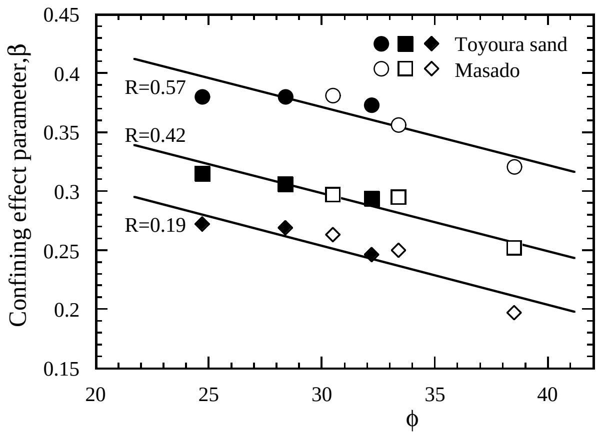


Figure 9. Confining effect parameter, β

4 INTRODUCTION OF THE CONFINIG EFFECT INTO A DESIGN METHOD

The confining effect should be considered in the internal stability analysis of a geogrid-reinforced retaining wall. In this paper the confining effect is introduced into the tie-back wedge method recommended in the Canadian Foundation Engineering Manual (1992), as shown in Figure 1(b). Internal stability includes the following failure mechanisms:

1) Rupture of the geogrid due to tensile over-stressing
2) Pullout of the geogrid within the reinforced soil mass
3) Failure of the facing connection

The confining effect mobilized in the reinforced soil mass is introduced into the first of the above mechanisms. In the case of the external stability in which the reinforced soil mass is regarded as a rigid block, the confining effect is not mobilized.

4.1 *A design method considering the confining effect*

4.1.1 *Design method without consideration of the confining*

In the tie-back wedge method, the safety of each layer of the geogrid is referenced to an internal Rankine active plane propagating from the toe of the wall at an angle of 45 + ϕ/2 degrees to horizontal. The essential features are summarized in Figure 10. The maximum tensile force of the geogrid, T_{max}, is mobilized at the sliding plane in the reinforced soil mass. Rankine's earth pressure theory considers horizontal earth pressure as a triangular distribution. Horizontal active earth pressure, $\sigma_h(z)$, at the depth of z from the top of wall can be expressed as

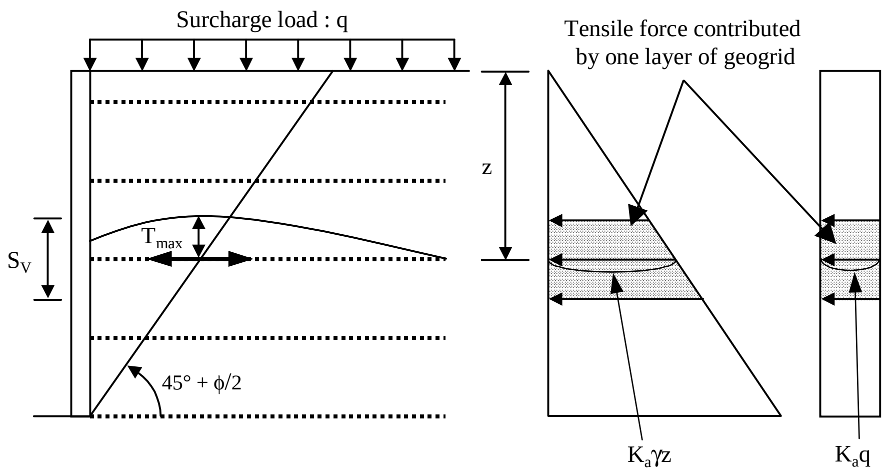


Figure 10. Tie-back wedge method for internal stability analysis (Canadian Foundation Engineering Manual, 1992)

$$\sigma_h(z) = K_a\gamma z + K_a q \tag{5}$$

where K_a is the coefficient of Rankine's active earth pressure, γ is unit weight of soil and q is the surcharge load.

The tensile force of the geogrid is thought to resist the horizontal earth pressure directly, and the sum of tensile forces of each layer of the geogrid must be larger than that of the horizontal earth pressure.

The maximum tensile force, T_{max}, of the geogrid at the depth of z from the top of wall is expressed as the area of the gray zone in Figure 10 and it is computed as follows:

$$T_{max} = \sigma_h(z) \times S_v = (K_a\gamma z + K_a p) \times S_v \tag{6}$$

where S_v is the contributory area about each geogrid layer. The allowable design tensile force of the geogrid, T_A, must exceed the maximum tensile force, T_{max}, as follows:

$$T_A \geq T_{max} = (K_a\gamma z + K_a p) \times S_V \tag{7}$$

Equation (7) is used to check the safety of each layer of the geogrid, and the vertical spacing of each layer of geogrid is determined. The length of each layer of the geogrid is determined by considering the pullout resistance of the geogrid. However, the determination of length is not discussed in this paper.

4.1.2 *A design method with consideration of the confining effect*

The confining effect can be expressed as "$\beta \cdot \sigma_n \tan\phi$", as shown in Equation (4), and it is the effect of an additional normal stress, $\beta\sigma_n$, apparently induced on the sliding plane. Thus, the overburden pressure on the horizontal surface of the geogrid, σ_0, which can be computed as $\sigma_o=\sigma_n/\cos\theta$, apparently increases by the amount of $\beta\sigma_0$ due to the confining effect. It is assumed that the ultimate earth pressure of the reinforced retaining wall under plastic equilibrium conditions increases by the amount of $K_a\beta\sigma_0=K_a\beta\gamma z$ due to the confining effect. This assumption is based on follows. The sliding angle of the ultimate slip failure, 45+ϕ/2 degrees, and the coefficient of Rankine's active earth pressure, K_a, is regarded as a constant, because the confining effect is evaluated independently the internal friction angle, ϕ, as shown in Figure 4. Therefore, the maximum tensile force that directly resists to the horizontal earth pressure can be reduced by the amount of $K_a\beta\gamma z$.

Finally, considering the confining effect, Equation (7) of the design method recommended in the Canadian Foundation Engineering Manual (1992) can be rewritten as

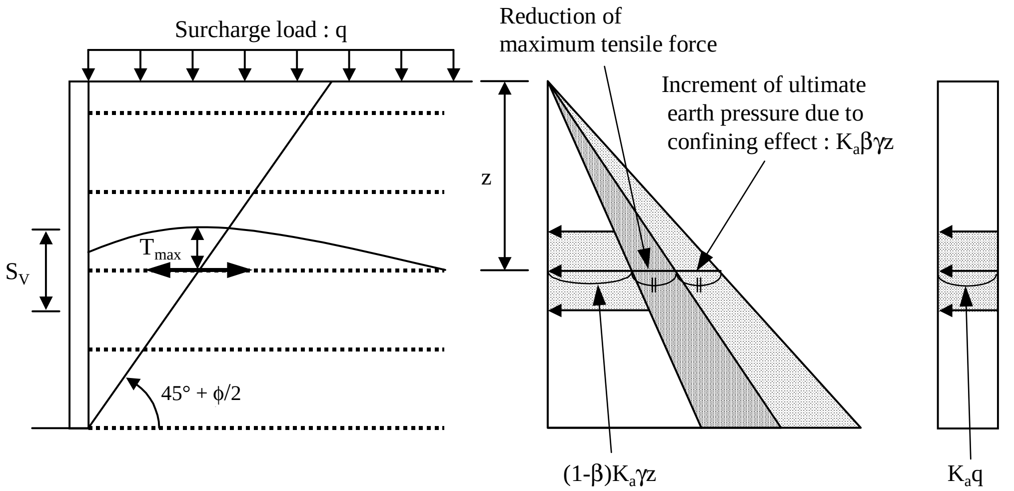


Figure 11. Tie-back wedge method for internal stability analysis considering the confining effect (proposed method)

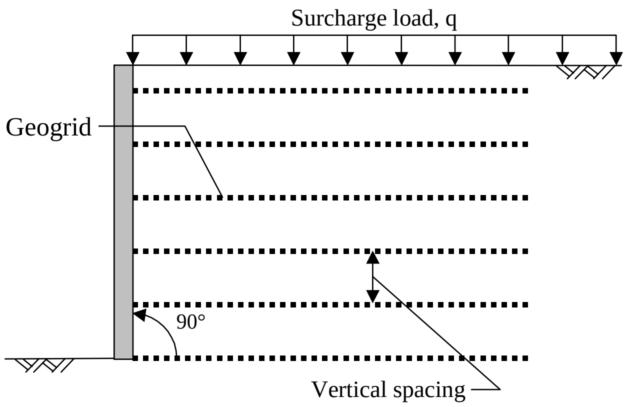


Figure 12. Cross-sectional diagram for design

Table 2. Design conditions

Unit weight of soil, γ_t	17.7kN/m^3
Internal friction angle, ϕ	30 degree
Cohesion, c	0kN/m^2
Allowable tensile strength of geogrid, T_A	39.8kN/m^2
Surcharge load, q	9.8kN/m^2
Confining effect parameter, β	0, 0.1, 0.2, 0.3, 0.4

$$T_A \geq T_{max} = [(1-\beta)K_a\gamma z + K_a p] \times S_V \quad (8)$$

This equation is used to check the safety of each layer of the geogrid in the reinforced retaining wall.

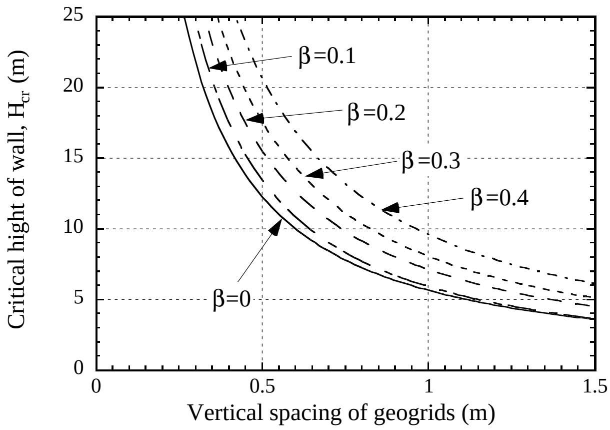
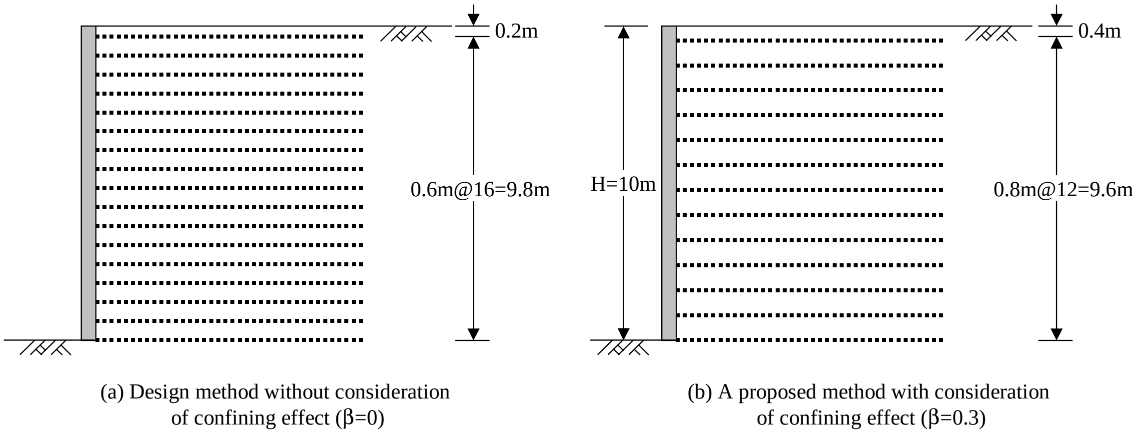


Figure 13. Critical height of geogrid-reinforced retaining wall, H_{cr}, at various values of β



Figures 14. Comparison of results obtained by using the design method with and without consideration of confining effect

4.2 *Examples of calculations using the proposed design method*

A cross-sectional diagram of a geogrid-reinforced retaining wall and the parameters for design are shown in Figure 12 and Table 2, respectively. The values of the confining effect parameters, β, used for the computation are 0-0.4. These values are obtained from a series of tests, as shown in Figure 9.

Figure 13 shows comparisons of calculated values of the critical height of the retaining wall, H_{cr}, under the condition of various confining effect parameters and the various vertical spacings of geogrids. In the case of β=0, the confining effect is not considered in the design method. The critical height, H_{cr}, increases with decreases in the vertical spacing of geogrids and increases in the confining effect parameter, β. In the proposed design method, the critical height of wall, H_{cr}, increases by 10-60%, depending on the value of the confining effect parameter, β.

Figures 14 (a) and (b) show examples of the arrangement of geogrids determined in the cases of β=0 and β=0.3, respectively. The design conditions are the same as those in Figure 12 and Table 2, and the height of the retaining wall is H_{cr}=10m. The length of geogrids is not discussed in these examples, and the confining effect is not considered in pullout failure analysis. However, we are continuously investigating to introduce to the confining effect parameter into the pullout failure mechanism. In a case in which the confining effect is not considered, the vertical spacing of geogrid is 0.6m and 17 layers of geogrid are needed, while in a case in which the confining effect is considered, the vertical spacing is 0.8m and 13 layers are needed. The layers of geogrid can be reduced by about 20% in these design conditions.

5 CONCLUSIONS

An evaluation method in which the reinforcing effects can be divided into tensile effect and confining effect is proposed in order to introduce the confining effect into design methods. Laboratory shear tests were carried out to investigate the reinforcing effects on the sliding plane of a geogrid-reinforced soil mass. The confining effect is introduced into the tie-back wedge method of geogrid-reinforced retaining walls based on Rankine's active earth pressure theory. The main conclusions are:

1) The utility of the proposed evaluation method that considers both the tensile effect and the confining effect was verified by the results of laboratory tests.
2) The confining effect is independent of the tensile force of the geogrid but dependent on the internal friction angle, ϕ, and the shape index, R.
3) The range of the confining effect parameter, β, which expresses the amount of the mobilized confining effects, was 0.2-0.4 in these tests.
4) A new formula for calculating the maximum tensile force of a geogrid on the sliding plane is proposed.
5) For examples of calculation using the proposed design method, the critical height of walls increases by 10-60% and the layers of geogrid reduce by 20%.

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