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Bearing mechanism of steel grid reinforcement in pullout test

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ABSTRUCT: A series of pullout tests on a composite of welded steel grid reinforcement and granular soil is carried out under different normal pressures to investigate the bearing mechanism of transverse members. This steel grid reinforcement is different from polymer geogrid reinforcement because the longitudinal member of steel grid is less extensible than that of polymer geogrid. Therefore, the bearing resistance mobilized by each transverse member is found to be approximately equal. A general expression representing a relationship between ultimate bearing resistance and normal pressure is developed, which is based on the Prandtl's theory of bearing resistance failure mechanism. This general expression can easily be reduced to the available bearing resistance failure mechanisms. The proposed relationship between bearing resistance and normal pressure can be seen to reasonably represent many available pullout test results.

1. INTRODUCTION

The mechanism and construction technique of reinforced soils have been investigated both in laboratory and field research works. These activities have resulted in developing new reinforcement materials, their geometrical shapes, design and construction methods. As changing the type of reinforcing material and their geometrical shape, the soil - reinforcement interaction and mechanisms in the pullout resistance also change. For instance, as for geogrid or grid type reinforcements, the bearing (transverse) members are mainly responsible for the enhancement of pullout resistance. Further research works, however, are still necessary on the interaction between these members and soil matrix and the mechanism of bearing resistance (Wilson-Fahmy et al., 1994).

In this paper, laboratory pullout tests results of the interaction between granular soil and transverse members of steel grid reinforcement are presented and analyzed. Moreover, a generalized bearing resistance mechanism between granular soil and transverse member of reinforcement is theoretically proposed. The applicability of this proposed equation is discussed through comparison with many available pullout test results.

2. BEARING RESISTANCE THEORY

2.1 Available Equations of Bearing Resistance

Bearing resistance is a major part of pullout resistance mobilized in a composite of granular soil and grid reinforcement. It constitutes more than 90% of the total pullout resistance for steel grid reinforcement embedded in soil (Neilsen and Anderson, 1984) but the bearing mechanism is not very well understood. The two famous equations are used so far to explain the bearing mechanism. These are the general shear failure and punching shear failure mechanisms.

When a grid reinforcement is pulled out from soil subjected to normal pressure, the ultimate bearing resistance per unit width of the reinforcement is given by Eq.(1), which is based on the modified form of Terzaghi-Buisman bearing capacity equation for footing foundation, assuming the small diameter of steel grid member and cohesionless soil (c=0).

$$\frac{F_b}{W} = N \cdot d \cdot \sigma_n \cdot N_q \qquad (1)$$

where F_b is the total ultimate bearing resistance, N, W and d the numbers, width and diameter of the transverse members respectively , σ_n the normal pressure and N_q the bearing resistance factor which is a function of angle of internal friction of soil. For unit ultimate bearing resistance, σ_b, Eq.(1) can be written as Eq.(2).

$$\sigma_b = \frac{F_b}{N \cdot W \cdot d} = \sigma_n \cdot N_q \qquad (2)$$

The expressions for two available mechanisms of ultimate bearing resistance as general shear and punching shear failure mechanisms are given by Eqs.(3) and (4), respectively.

$$\frac{\sigma_b}{\sigma_n} = N_q = \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \cdot e^{\pi \tan\phi} \qquad (3)$$

$$\frac{\sigma_b}{\sigma_n} = N_q = \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \cdot e^{\left(\frac{\pi}{2}+\phi\right)\tan\phi} \qquad (4)$$

Fig.1 shows these two equations as a function of internal friction angle of soil (Jewell et al., 1985). The former seems to represent an upper bound while the latter a lower bound. It can be seen that most of the available data are distributed between these two boundaries.

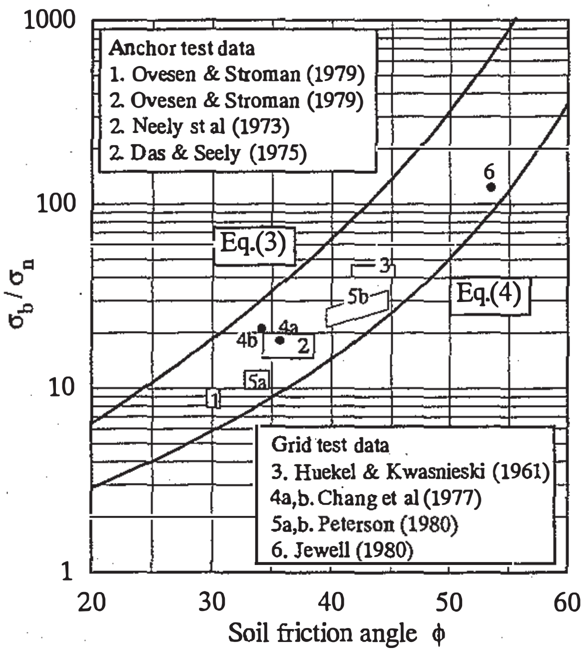

Fig.1 Comparison of anchor and grid reinforcements pullout test data and two failure mechanisms (after Jewell et al., 1985)

2.2 Proposed Equation Besed on Prandtl's Theory

Following the Prandtl's mechanism as shown in Fig.2, moment equilibrium of forces on planes AO and AP about point A may give Eq.(5).

$$\left.\begin{aligned} q_\omega &= \sigma_b e^{-2\omega \cdot \tan\phi} \tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \\ &\text{or} \\ \sigma_b &= q_\omega e^{2\omega \cdot \tan\phi} \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \end{aligned}\right| \qquad (5)$$

in which q_ω is the maximum stress on a plane displaced by ω from plane OA, σ_b the ultimate unit bearing resistance, ω the radial angle of any plane from plane OA and ϕ the angle of internal friction of sands.

It relates the ultimate unit bearing resistance, σ_b, to the maximum stress, q_ω, on any plane at a radial displacement of ω. The relationship between the maximum stress, q_ω, and the normal pressure, σ_n, can be obtained by using Fig.2 representing the stress conditions at point P and superposition of different stresses. The relationship between normal pressure, σ_n, and maximum stress, q_ω, is shown by Eq.(6), assuming that K_o stress condition exists at point P.

$$\left.\begin{aligned} q_\omega &= \sigma_n \{\cos\delta + (1 - \sin\phi)\sin\delta\} \\ &\text{or} \\ q_\omega &= \sigma_n \left[\cos\left\{\omega - \left(\frac{\pi}{4} + \frac{\phi}{2}\right)\right\}\right. \\ &\quad \left. + (1 - \sin\phi)\sin\left\{\omega - \left(\frac{\pi}{4} + \frac{\phi}{2}\right)\right\}\right] \end{aligned}\right| \qquad (6)$$

where δ is the angle between normal pressure, σ_n, and maximum stress, q_ω, being equal to $\{\omega - (\pi/4+\phi/2)\}$.

Fig.3 shows a relationship in Eq.(6) for an angle of internal friction $\phi = 37.3°$ of the soil used in the present study. It is seen in this figure that full development of the plastic zone occurs at $\omega = \pi/2$, where the ratio, q_ω/σ_n, becomes the maximum.

Combination of Eqs.(5) and (6) gives a general expression of Eq.(7) relating the ultimate unit bearing resistance, σ_b to the normal pressure, σ_n.

$$\left.\begin{aligned} \sigma_b = \sigma_n e^{2\omega\tan\phi} \tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) &\left[\cos\left\{\omega - \left(\frac{\pi}{4} + \frac{\phi}{2}\right)\right\}\right. \\ &\left. + (1 - \sin\phi)\sin\left\{\omega - \left(\frac{\pi}{4} + \frac{\phi}{2}\right)\right\}\right] \end{aligned}\right\} (7)$$

Eq.(7) is general equation based on Prandtl's theory, which can be used for any extent of plastic

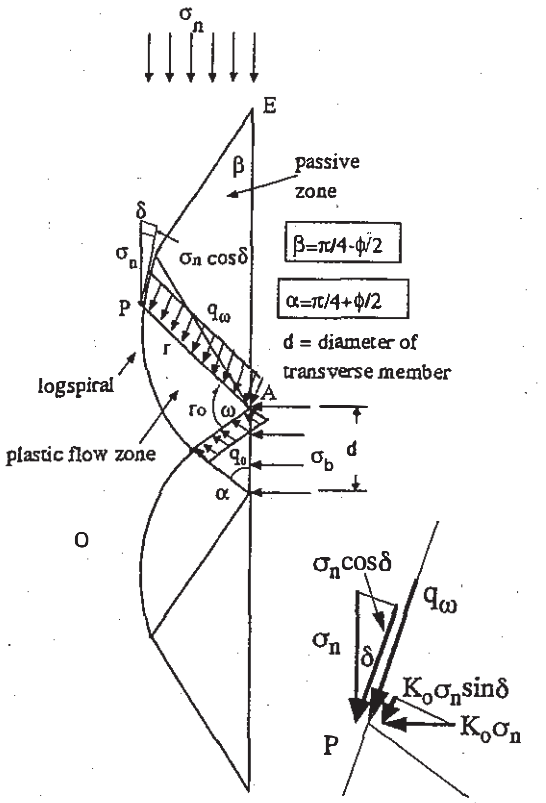

Fig.2 Rupture surface in Prandtl's failure mechanism

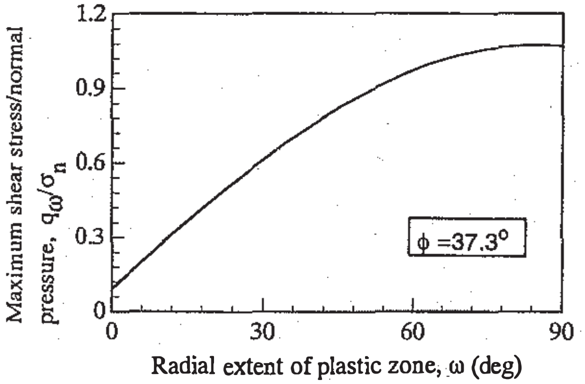

Fig.3 Relationship between normalized maximum stress and angle of displacement of plane

zone. As an illustration, Fig.4 shows the relationship between normalized ultimate unit bearing resistance, σ_b/σ_n and the radial angle, ω for soil with φ=37.3°. It can be seen that the plastic wedge extended to ω=π/2=90° provides about 2 times ultimate bearing resistance of the plastic wedge extended to π/4+φ/2=63.65°.

According to Prandtl's theory, full development of plastic zone takes place at ω=π/2, therefore, putting this value into Eq.(7) produces Eq.(8), which is proposed for this study.

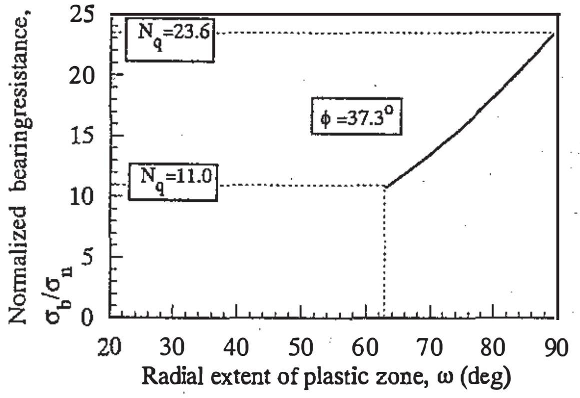

Fig.4 Normalized bearing resistance versus radial extent of plane in plastic zone

$$\sigma_b = \sigma_n e^{\pi \tan\phi} \tan(\frac{\pi}{4}+\frac{\phi}{2}) \left[\cos\left\{(\frac{\pi}{4}-\frac{\phi}{2})\right\} + (1-\sin\phi)\sin\left\{(\frac{\pi}{4}-\frac{\phi}{2})\right\} \right] \tag{8}$$

Further, Eq.(7) can easily be reduced to Eq.(4) which represents the punching shear failure mechanism proposed by Jewell et al. (1985).

3. PULLOUT TEST RESULTS AND DISCUSSION

Laboratory tests were performed using a pullout test apparatus. The inside dimensions of this apparatus were 1050mm long, 754mm wide, 475mm high. The steel grid reinforcement used in this study is shown in Fig.5. The grid size of the steel grid reinforcement is 225mm long, 150mm wide. The diameter of each reinforcement member is 6mm. To investigate the relationship between bearing resistance and number of transverse member, number of transverse member was changed from one to three. The relative density and other physical properties of granular soil are shown in Table 1. The reinforcements were pulled out at constant displacement rate of 1 mm/min. For further details

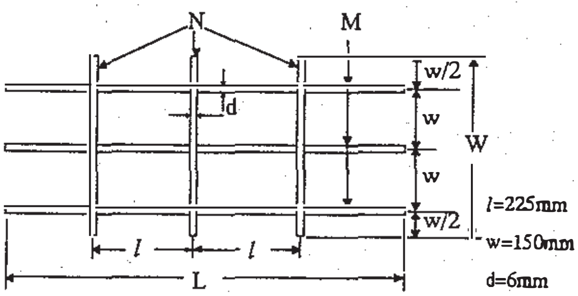

Fig.5 Dimensions of steel grid reinforcement

Table 1. Relative density and physical properties of granular soil.

Mean particle size, D_{50} (mm)	0.46
Uniformity coefficient, U_c	3.71
Curvature coefficient, U_c'	0.84
Relative density, D_r (%)	80.2
Frictional angle, ϕ (degree)	37.3

on apparatus and test procedure, the reader should refer to Matsui et al. (1996).

Fig.6 shows the relationship between bearing resistance and pullout displacement under overburden pressure of 98.1 kPa. The bearing resistance increases as increasing number of transverse members. Fig.7 shows the relationship between ultimate bearing resistance and number of transverse members under different normal pressures. The ultimate bearing resistance increases as increasing normal pressure and number of transverse members until tensile failure of longitudinal member will occur. Fig.8 shows the relationship between ultimate bearing resistance and normal pressure, in which the bearing resistance is normalized by number of transverse members. The relationship is almost similar regardless of number of transverse members. This behavior is attributed by that the longitudinal member hardly extends. Therefore, there is no interaction between transverse member reinforcements used in the present study (Matsui et al., 1996). Fig.8 also shows a comparison between theoretical result by the proposed equation and pullout test data. It can be seen that the slope of the proposed equation is almost parallel to that of the data points, although they are located around slightly upward off the proposed equation. Therefore, this proposed equation might represent the mechanism of bearing resistance.

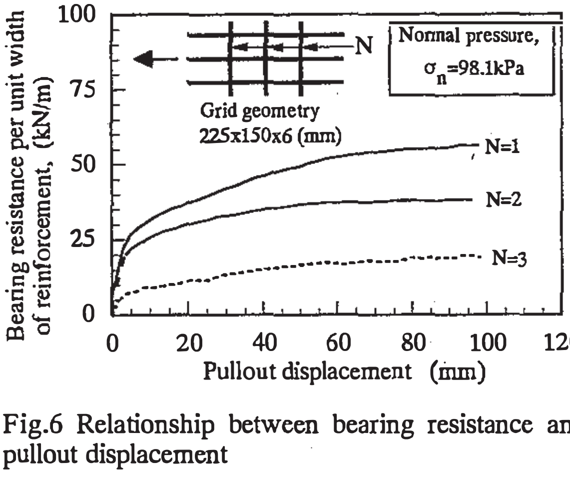

Fig.6 Relationship between bearing resistance and pullout displacement

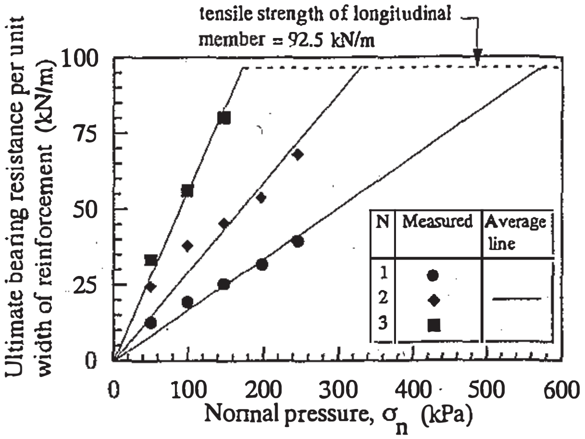

Fig.7 Relationship between number of transverse member and ultimate bearing resistance under different normal pressures

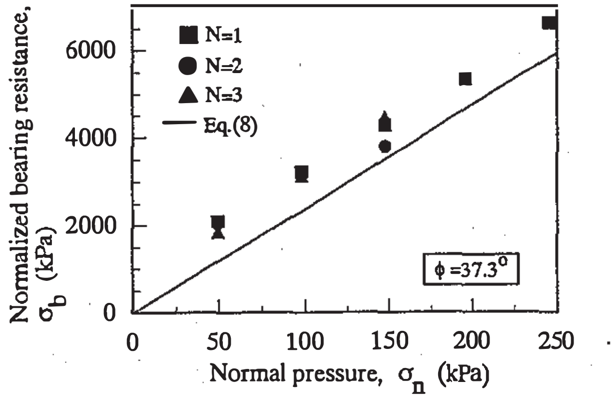

Fig.8 Relationship between normalized ultimate bearing resistance and normal pressure

4. APPLICABILITY OF THE PROPOSED EQUATION

The authors tried to check the applicability of the proposed equation through the comparison between the theoretical values and available pullout test data. Wiseman et al. (1995) performed pullout tests in laboratory and field using welded wire mesh-geotextile composite with granular soils. The welded wire mesh reinforcements were almost same dimensions and materials used in the present study. Fig.9 shows the relationship between ultimate bearing resistance and normal or overburden pressure with the proposed equation, in which internal friction angle of ϕ=34° is used. It can be seen from Fig.9 that the proposed equation estimates pullout test data very well.

Palmeira et al. (1989) collected many pullout test data of grid reinforcement and anchor. Fig. 10 shows the relationship between bearing factor Nq and friction angle of granular soils. It is evident from Fig.10 that the proposed equation can reasonably represent many pullout test data . Therefore, the proposed equation can approximately estimate bearing factor in the range of friction angle around from 30° to 50°, while the available two failure mechanisms give upper and lower bounds of almost all data.

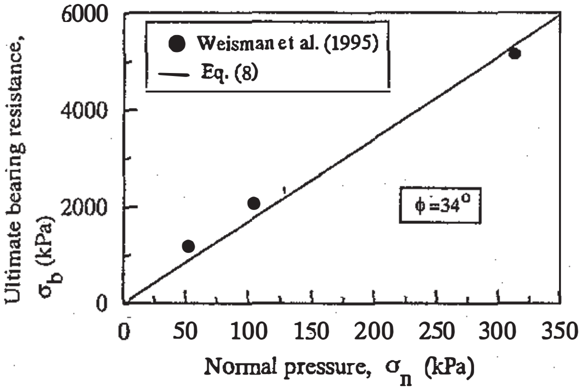

Fig.9 Comparison between proposed equation and available pullout test data of grid reinforcement

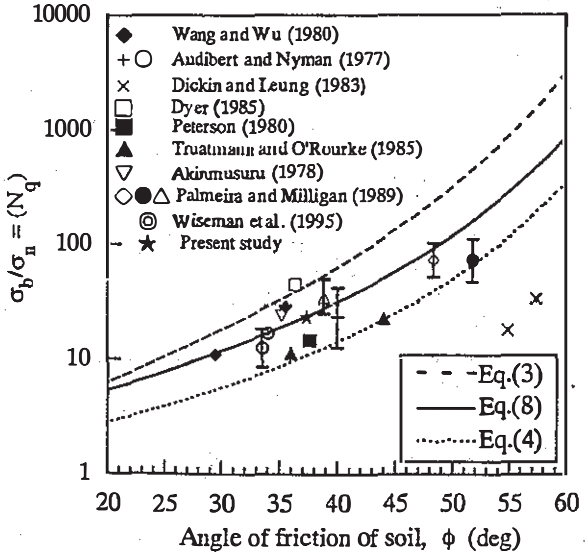

Fig.10 Comparison between proposed equation and available pullout test data of anchor and grid reinforcements

5. CONCLUSIONS

1. Because the longitudinal member hardly extends, there is no interaction between transverse members of steel grid reinforcement used in the present study. Therefore, each transverse member mobilizes approximately equal bearing resistance.
2. The bearing resistance increases as increasing the number of transverse members and normal pressure until the tensile failure of longitudinal member will occur.
3. The proposed equation based on the Prandtl's theory can reasonably represent pullout test data in the present study and available ones of grid reinforcement and anchor.

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