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Dilatancy effects of granular soil on the pullout resistance of strip reinforcement

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ABSTRACT: This paper reports the results of the investigation on the effects of restrained dilatancy to the pullout resistance of geogrid strip reinforcement embedded in dense granular soil. The pullout resistance has been conceptualized to comprise a combined two-dimensional (2-D) and three-dimensional (3-D) interaction resistance. The 2-D interaction resistance, which is the classical soil-reinforcement interface friction, is generated over the middle section while the 3-D interaction resistance is generated at both edges of the strip as a consequence of restrained soil dilatancy. The effect of restrained dilatancy would enhance or reduce the pullout resistance depending on the corresponding potential increase or decrease in dilatancy (i.e., positive or negative dilatancy) during the process of shearing.

1 INTRODUCTION

The prevailing practice of earth reinforcement in retaining walls or steep slopes specifies granular soils for use as backfill materials. In addition, two schemes of earth reinforcement are also employed. One is sheet reinforcement in which reinforcements are laid continuously throughout the reinforced area and the other is strip reinforcement in which reinforcements are laid in intervals. Sheet reinforcement scheme corresponds to the case of free dilatancy while strip reinforcement scheme corresponds to the case of restrained dilatancy (Sobolevsky 1995).

The pullout interaction mechanism of sheet reinforcement is classical soil-reinforcement interface friction which is called here as 2-D interaction mechanism. When strip reinforcement is placed in dense granular soils, another pullout interaction mechanism occurs which is called here as 3-D interaction mechanism. This mechanism develops as a consequence of restrained soil dilatancy effect.

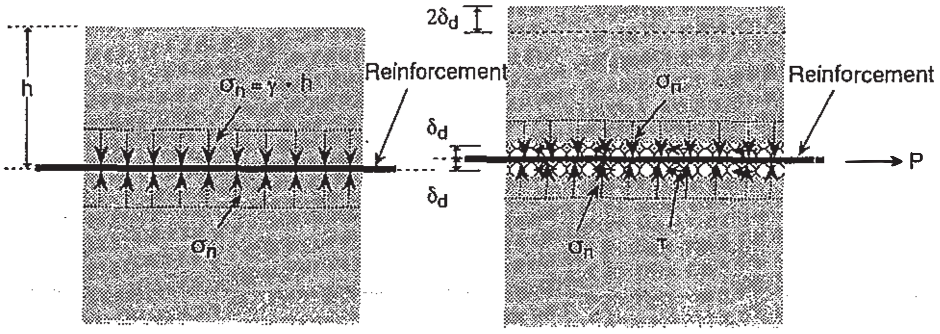
The development of 3-D interaction mechanism was described earlier by Schlosser and Elias.(1978) and is particularly applicable where the early practice of earth reinforcement utilized a very narrow metallic strip reinforcement. However, present earth reinforcement practice includes the use of geosynthetic reinforcement (e.g. geogrid) strips which range in width from few centimeters to a meter. In such a case, the soil-reinforcement interaction can be a combination of 2-D interaction mechanism developing over the middle section and 3-D interaction mechanism developing at both edges of the strip.

2 FREE AND RESTRAINED DILATANCY

Let us first look at the possible consequences of free and restrained dilatancy. The case of free dilatancy occurs for the condition illustrated in Fig. 1a. A reinforcement element placed at a certain depth of dense granular soil is undergoing a normal stress, σ_n. The application of pullout force generates shear along the interface which is accompanied by grain repacking in a layer of certain thickness. It is within this layer that there is volume increase or what is called dilatancy. For sheet reinforcement, dilatancy in the process of shearing does not influence the value of the acting normal stress. The dilatancy would only cause uplifting of the backfill soil lying uppermost.

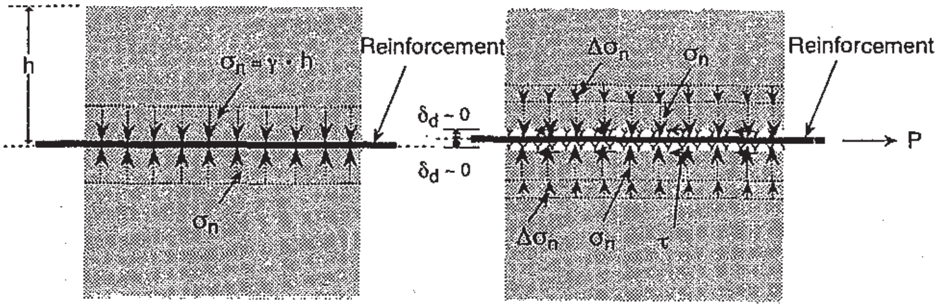
Turning now to the case of restrained dilatancy (Fig. 1b), a reinforcement element is placed under the same condition as before. The application of pullout force leads to the mobilization of shear along the interface which could develop dilatancy. But for strip reinforcement, dilatancy will be restrained by the surrounding non-dilating soil inducing an increase in normal stress, $\Delta\sigma_n$ on the soil-reinforcement interface. This increase in normal stress results to an increase in the interface shear stress and eventually to an enhancement of pullout resistance.

Measured vertical displacement associated with pullout displacement is shown in Fig. 2 deduced from pullout tests on specimens having width that were slightly smaller than the width of the pullout testing box. It is generally understood that volume increase (positive dilatancy) in the process of shearing decreases with increasing applied normal stress. Conse-



initial condition stress condition during shear

(a) free dilatancy



initial condition stress condition during shear

(b) restrained dilatancy

Fig. 1 Stress condition for free and restrained dilatancy

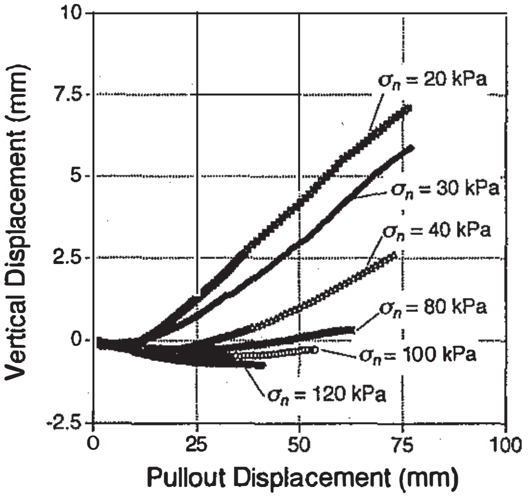


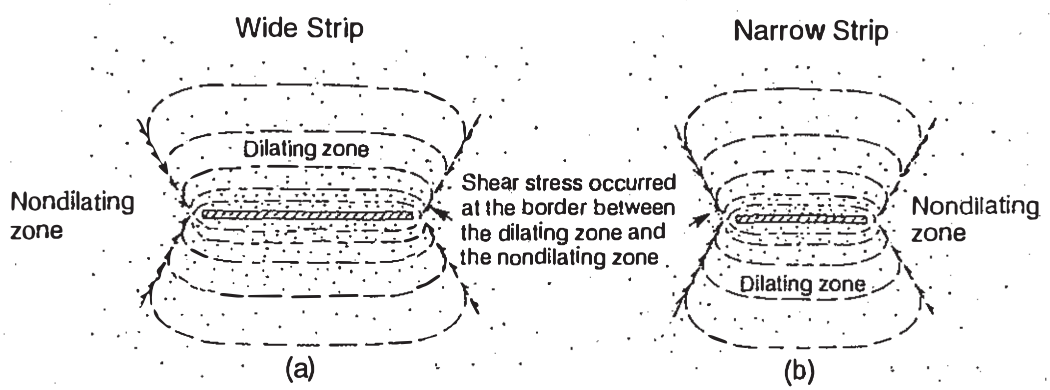
Fig. 2 Measured dilatancy during reinforcement pullout (the case of free dilatancy)

quently, the increase in acting normal stress due to restrained dilatancy is expected to diminish with increasing applied normal stress. Further increase in applied normal stress resulted in volume decrease (negative dilatancy) during the process of shearing which can reduce the acting normal stress when dilatancy is restrained.

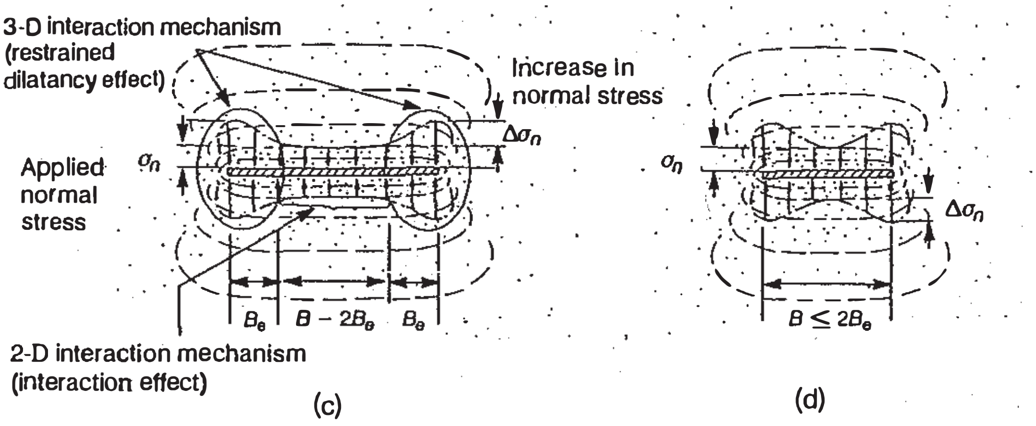
3 PULLOUT INTERACTION MECHANISM

As shown in Figs. 3 a and b, the non-dilating zone in the backfill soil surrounding the strip reinforcement functions as a restraint against soil dilatancy in the dilating zone. This generates shear stresses at the border between the dilating and the non-dilating zones and results in an increase in normal stresses at both edges of the strip reinforcement. A 3-D interaction mechanism develops at both edges of the strip reinforcement while its middle section experiences a 2-D interaction behavior (Fig. 3c). As the width of reinforcement becomes narrower, the influence of restrained dilatancy results in the development of what is considered a purely 3-D interaction mechanism (Fig. 3d). Based on this combined interaction mechanism, the distribution of normal stresses imposed on the strip reinforcement is idealized as shown in Fig. 4. Note that the above discussion has so far considered only the effect of restrained positive dilatancy. The effect of restrained negative dilatancy that occur under high applied normal stresses is envisaged as to reduce the acting normal stress at both edges of the strip, such that on the extent of B_e in Fig. 4.

Another aspect of this interaction mechanism that requires due consideration is that only part of the reinforcement length will be mobilized when an extensible reinforcement such as geogrid is pulled out from the



Shear stress and strain mobilized around a strip reinforcement



Distribution of normal stress on the strip reinforcement

Fig. 3 Conceptualized pullout interaction mechanism of strip reinforcement with positive dilatancy

backfill soil. This effect is particularly prevalent under high normal stresses whereby nodal displacements tend to localize near the pullout load application which results in shorter mobilized length. Thus, the evaluation of maximum pullout resistance should take into account only the effective/mobilized length.

Following the Japanese standard (Hayashi et al. 1994), which basically corresponds to the 2-D interaction mechanism, the pullout force from 2-D interaction resistance can be expressed as follows:

$$P_{2\text{-}D} = 2 \cdot B \cdot L_e \cdot (c_p + \sigma_n \cdot \tan \delta_p) \qquad (1)$$

where $P_{2\text{-}D}$ = pullout force from 2-D interaction resistance; B = width of strip reinforcement; σ_n = applied normal stress; c_p = interface adhesion; and δ_p = interface friction angle. The pullout force from 3-D interaction resistance can be taken as:

$$P_{3\text{-}D} = P_{TE} - P_{2\text{-}D} \qquad (2)$$

where $P_{3\text{-}D}$ = pullout force from 3-D interaction resistance; and P_{TE} = maximum effective pullout resistance.

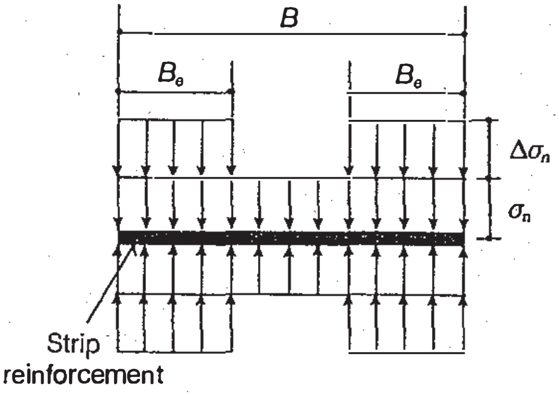


Fig. 4 Idealized distribution of normal stress on the interface with positive dilatancy

4 TESTING DETAILS AND RESULTS

The test apparatus and instrumentations used in this investigation have been described elsewhere (Alfaro et al. 1995). A well-graded sandy gravel was used as backfill soil with the following particle size properties:

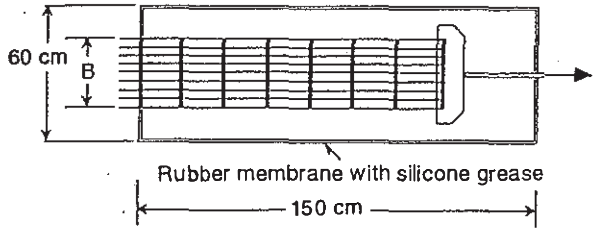


Fig. 5 Typical test arrangement of strip reinforcement

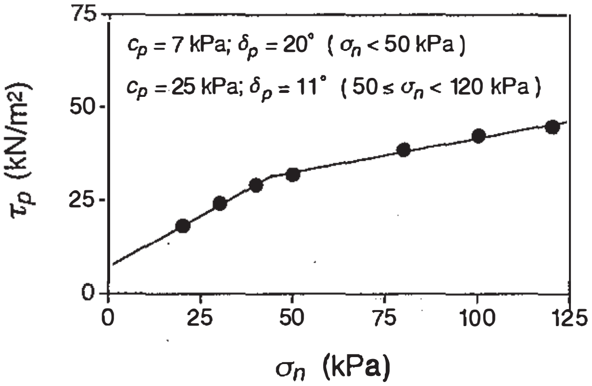


Fig. 6 Interaction parameters for 2-D interaction mechanism (case of free dilatancy)

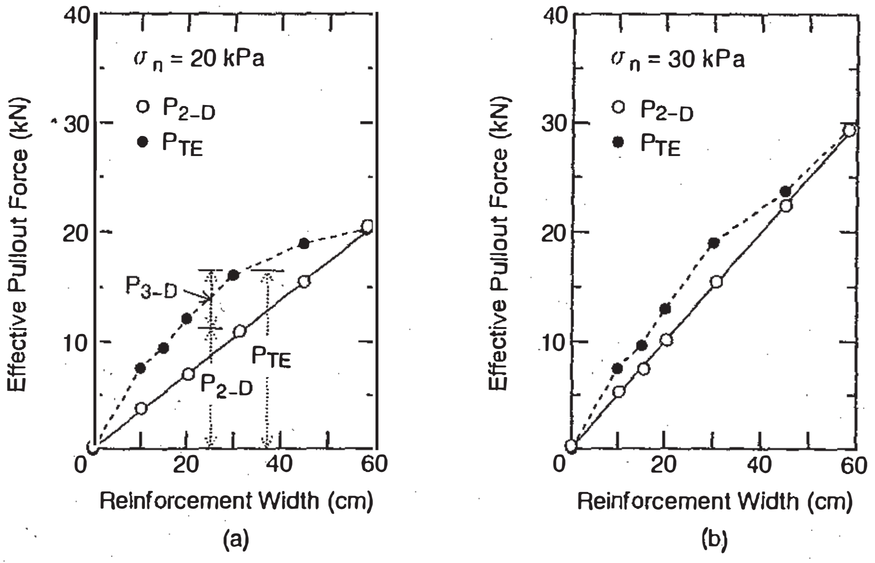
average particle size d_{50} = 4.74 mm; uniformity coefficient C_u = 15; and coefficient of curvature of the gradation curve C_c = 1.67. The maximum and minimum dry unit weights were 19.10 kN/m^3 and 14.32 kN/m^3, respectively. The internal friction angle of the compacted soil was 45° at a relative density of 95%. Tensar SR-80 geogrid was employed as reinforcement specimen.

Pullout tests were conducted using specimen widths (B = 10, 15, 20, 30, 45, and 58 cm) under four applied normal stresses that range from σ_n = 20 kPa to 120 kPa. The series of tests with specimen widths of B = 58 cm, which is slightly smaller than the width of the testing box of 60 cm, corresponds to a 2-D interaction mechanism or the case of free dilatancy. This inter-action mechanism was envisaged to be appropriate to this series of tests because the lubricated side walls would not induce a restraining effect which could be caused by the presence of dilating and non-dilating zones within the backfill soil. Thus, the assumed 2-D interaction behavior across the width of the reinforce-ment is appropriate. On the other hand, the narrower specimens with respect to the box width (Fig. 5) are assumed to experience a combination of the 2-D and 3-D interaction mechanism or includes the case of restrained dilatancy. The pullout testing procedures and the evaluation of pullout resistance followed the Japanese standard method as reported by Hayashi et al. (1994).

Results of the series of tests which corresponds to the 2-D interaction mechanism are shown in Fig. 6 together with the interface parameters. The contribution of 2-D interaction resistance for narrower specimen was derived from test results on specimen width, B = 58 cm based on specimen width proportion. The difference between the maximum effective pullout force measured for narrower widths and their corresponding 2-D interaction resistance is considered as the contribution of the 3-D interaction resistance as expressed in Equation (2) and illustrated in Fig. 7. As can be seen in this figure, the specimen width has influence on the pullout resistance particularly on the development of 3-D interaction resistance.

A test specimen which has a width approaching the width of the pullout testing box (e.g., B = 45 cm) develops minimal 3-D interaction resistance. This is attributed to the minimal restraint provided by the dilating soil which is partly due to the lubricated membrane on the side walls and by a smaller non-dilating zone of soil at both edges of the specimen (Fig. 8). Minimal 3-D interaction resistance is also observed in specimens smaller than 20 cm which was considered to occur because the extent of B_e at both edges of the specimen overlapped each other (Fig. 9) which could have reduced the magnitude of the 3-D interaction resistance. For the same geogrid and soil used in this investigation, it was found in previous study (Alfaro et al. 1995b) that the 3-D interaction resistance could be generated within 10 cm at both edges of the strip. This implies that for these particular reinforcement and backfill materials, the combined 2-D and 3-D interaction mechanism is applicable for strip width, B, greater than 20 cm. As the strip width becomes narrow, such that B ≤ 20 cm, the 3-D interaction mechanism develops across the strip width.

Figure 10 shows the variation of 3-D interaction resistance with applied normal stress. It can be seen that the 3-D interaction resistance diminishes with increasing applied normal stress which becomes negative in magnitude when the applied normal stress is greater than 100 kPa. This seems to be consistent with the results in Fig. 2 indicating negative dilatancy under the applied normal stress greater than 100 kPa. The implication of this finding is that the effect of restrained positive dilatancy which occurred under low applied normal stress (i.e., σ_n < 100 kPa) would enhance the pullout resistance while the restrained negative dilatancy which occurred under high applied normal stress (σ_n ≥ 100 kPa) would reduce the pullout resistance. The latter phenomenon might have been one of the causes for some pullout failure of strip reinforcement at lower levels of constructed reinforced soil structures even with the expected high overburden normal stresses.



(a)

(b)

Fig. 7 Pullout resistances for various specimen widths

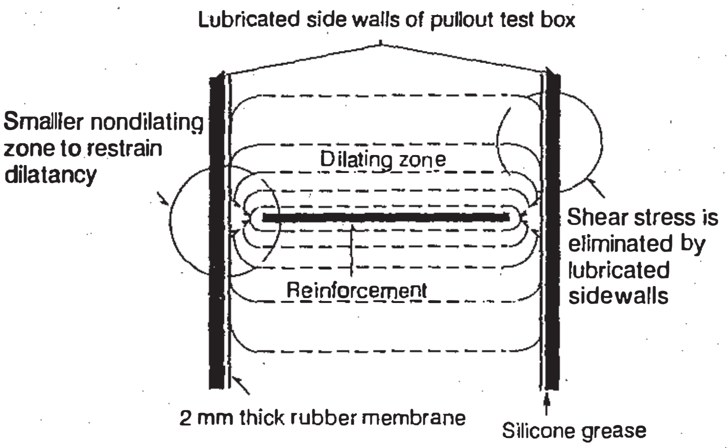


Fig. 8 Soil-reinforcement interaction for specimen width smaller than the box width

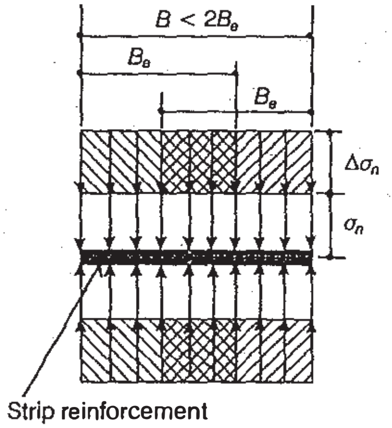


Fig. 9 Soil-reinforcement interaction for narrow specimen width

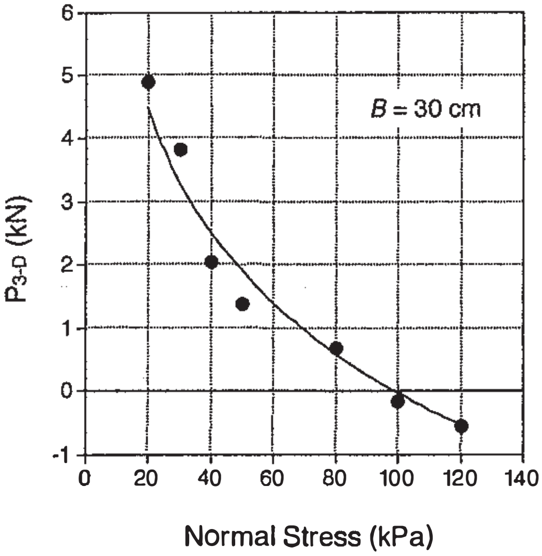


Fig. 10 Variation of 3-D interaction resistance with applied normal stress

5 CONCLUSIONS

When strip reinforcement is placed in dense granular soil, its pullout resistance can be a combination of 2-D interaction resistance generated over the middle section and 3-D interaction resistance generated at both edges. The 2-D interaction resistance is the classical soil-reinforcement interface friction while the 3-D interaction resistance is a consequence of restrained dilatancy.

For this particular investigation, the effect of restrained dilatancy would be to enhance the pullout resistance under the applied normal stresses lower than 100 kPa. On the other hand, the effect of restrained dilatancy would reduce the pullout resistance under the applied normal stress that is equal to or greater than 100 kPa. These effects should therefore be taken into account in the evaluation of pullout resistance and in the design methodology for reinforced soil structures using strip reinforcements.

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