An analytical study on progressive interface failure in pullout testing of geosynthetics

Une étude analythical sur l'échec progressif d'interface dans l'essai de dégagement du geosynthetics

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ABSTRACT: Large scale pullout testing of geosynthetic reinforcement was studied analytically. To capture the progressive pullout failure mechanism, material strain softening at the interface between the reinforcement and the soil was modelled in the analyses. Certain known trends in large scale pullout testing were successfully predicted by the analyses. The results showed that the application of pullout force always induced significant non-uniformity in the normal stress acting on the reinforcement, despite the initia stress state within the box being uniform. Therefore interpretation of pullout testing remains problematic even if th e internal distribution of interface shear stress are obtained by strain gauging the embedded length of the reinforcement.

RÉSUMÉ: Le test de dégagement à grande échelle de géosynthétique de renfort a été étudié analytiquement. Pour capturer le mécanisme progressif de panne de dégagement, la contrainte matérielle se ramollissant à l'interface entre le renfort et le sol a été modelée dans les analyses. Certaines tendances bien connes dans le test de dégagement á grande échelle de géosynthétique sont predi t avec succés. Les résultats ont prouvé que l'application de la force de dégagement induit toujours l'irrégularité significative dans l'effort normal agissant sur le renfort, en dépit de l'état initial d'effort dans le cadre étant uniforme. Par conséquent, l'interpretation des restes de test de dégagement est problématique même si la distribution interne de l'effort de cisaillement d'interface étaient mesurés.

1 INTRODUCTION

Adequate soil-reinforcement interaction is essential in a reinforced soil structure. This is achieved by ensuring that the reinforcement pullout capacity is adequate. Large scale pullout testing is considered to be a suitable method for studying the pullout behaviour of geosynthetic reinforcement, and a number o e-searchers have designed and commissioned large scale pullout testing equipment (Palmeira and Milligan, 1989; Lo, 1990, Jura et al., 1991; Fannin and Raju, 1993; and Farrag, et al., 1993, among others).

The pullout capacity and its mobilisation are contributed b the mobilisation of interface shear stress between the reinforcement and the surrounding soil. The mobilisation of interfac shear stress, as a material property, has both a strain hardenin and a strain softening phase. Due to elongation of the geosynthetic reinforcement under applied force, the relative displacement between the reinforcement and surrounding soil decreases with increasing embedment distance. Hence, when the interface shear stress at the front zone is in a strain hardening state, the interface shear stress at the rear zone may be negligibly small. When the interface shear stress at the rear zone reaches a significant value, the interface shear stress at the front zone may be in a strain softening state. This leads to progressive pullout failure, which in turn necessitate large scale pullout testing.

Internal measurements, in the form of strain gauges or telltales mounted on the reinforcement, have been used by researchers in order to gain better interpretation of pullout test results an to examine the influence of box design on the measured progressive failure (e.g., Fannin and Raju 1993). Experimental studies are difficult because of the large number of factors that may influence the results and that large scale pullout testing is e x-tremely resource intensive. Analytical studies have been performed to supplement such research. These studies (e.g., Bergado & Chai 1994) were largely based on t-z curve analysis with strain softening soil springs of constant properties along the embedded length; and do not consider the evolution of stress non-uniformity of the surrounding soil induced by the pullout force (Raju et al 1998). In theory, finite element analysis ca capture the complete stress distribution in a pullout box. But the modelling of strain softening plus the need to have the analysis proceeded to pullout failure, is problematic. Hence a finite difference formulation was adopted in the analytical study reporte in this paper. The broad objective of this study is to examine the evolution of internal stress and strain fields during pullout testin so that pullout test results can be better interpreted.

2 ANALYSIS MODEL AND UMERICAL DETAILS

The layout of the modeled pullout box is shown in Fig. 1. The length of the pullout box was either 2m or 1m. However, the height of the box was 0.6 m irrespective of box length.

A flexible sleeve with a length equal to 10% of the box length was incorporated in the model. A flexible sleeve is defined as one with nil shear stress transfer between the reinforcement and the surrounding soil, but allows the reinforcement to deflec freely (and compatibly) with the soil in the vertical direction. The design details of a flexible sleeve is reported in Lo (1998) It is different from a rigid sleeve which constrained the vertica displacement of the reinforcement to zero by a rigid device. As discussed in Raju et al (1998), a flexible sleeve arrangement gives a more uniform stress field. The front wall of the pullou box (i.e., the wall near exit sleeve) was taken either as a frictionless boundary or as a frictional boundary with an interface friction angle equal to 75% of the peak friction angle of the soil. The latter condition is considered as the limitin roughness that may be realised in an actual pullout box. The rear wall was considered as a roller boundary. The bottom boundary was fixe whereas the top boundary was subject to a prescribed uniform

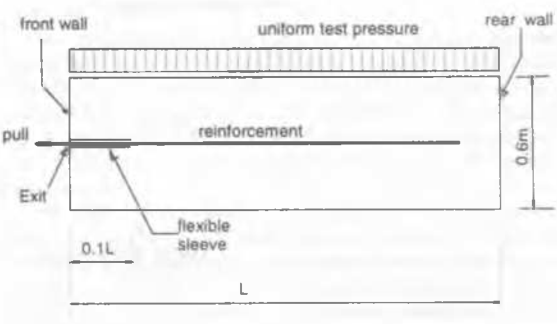

Figure 1. Details of pull out box

test pressure. In this paper, only the results corresponding to test pressure of 50 kPa is presented. The soil was modelled as Mohr-Coulomb elastic-plastic material with a no -associated flow rule. The soil parameters used in the analyses were: unit weight, $\gamma = 20$ kN/ ^{3}, Young's modulus, E = 25 MPa, Poisson's ratio, $\nu = 0.3$, friction angle, $\phi = 40°$, and dilation angle, $\psi = 10°$.

The reinforcement was modelled as a linear elastic one - dimensional element. Three sets of reinforcement axial stiffness, J, of 300 kN/m, 500 kN/m and 800 kN/m, were considered i n this study. Shear springs at the reinforcement nodal points wer used to model the interaction between the reinforcement and the surrounding soil. These shear springs had stiffness-strength characteristics described by a family of piecewise linear shear stress transfer functions as shown in Fig. 2. The maximum shear stress was defined by the peak interface friction angle, δ_{peak}, which was assigned to be 30°. The fully strain softened shear stress was defined by the residual interface friction angle, δ_{resid}, which was assigned to be 21°. It is important to emphasise that δ_{peak} and δ_{resid} were element material properties, n ot average properties and scale dependent as assumed in some design equa-tion for pullout resistance. The algorithm will select the appro-priate piecewise linear function depending on the local interfac normal stress, σ_n. Normal coupling springs of adequately high stiffness were also included in the numerical model.

The horizontal stress, σ_h, of a normally consolidated sandy deposit is commonly assessed by the equation $\sigma_h = (1-\sin\phi)\sigma_v$, where σ_v is the vertical stress. In a retaining wall, the effect of compaction at shallow depth leads to a horizontal stress consid-erably higher than that given by the above equation, and may even approach the passive pressure value (Ingold, 1979). Lo (1998) conducted pullout tests with a pre-loading pressure ap-plied prior to the application of test pressure so that the effects of vertical compaction stress could be at least partly simulated. I this study, the initial earth pressure coefficient was taken as 1.0.

The finite difference stress analysis program known as FLAC, Fast Lagrangian Analysis of Continua (FLAC 1996), was used for this research. In FLAC, the equations of equilibriu and stress strain behaviour are expressed in finite differenc form and are solved by an explicit iterative scheme. The analy-sis is inherently incremental and can model material strain sof-tening without causing particular numerical difficulties. The nu-merical principles of FLAC-analysis are detailed in Cundall & Board (1988). The program includes looping control commands and an internal programming language for implementing use - defined procedures. This feature is used in the present study t incorporate interface strain softening.

The pullout box was divided into 80 x 30 elements in the analyses. The analysis modelled a constant rate of pullout dis-placement at the front end of the reinforcement in each case. The pullout displacements were applied to the front end of the rei n-forcement as a prescribed pseudo velocity.

It is important to emphasise that the material models and p a-rameters adopted in this study were not specific to any particular soil or reinforcement. It is not the intention of this paper t quantitatively predict the response in a pullout testing. Thes were reasonable assumptions so that the complicated behaviou pattern, in particular the influence of test conditions, can be bet-ter understood.

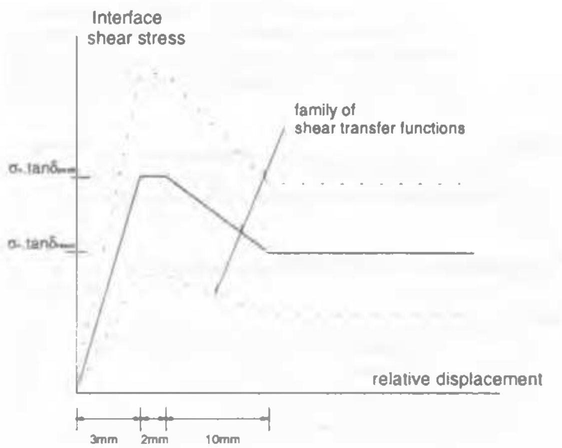

Figure 2. Shear stress transfer function

3 RESULTS OF REFERENCE CASE

3.1 *Reference case*

The reference case is defined as a pullout box of length 2m with a smooth front wall, under 50 kPa test pressure and the pulled re-inforcement is of 500 kN/m stiffness. These conditions wer considered as reasonable and probably induce slightly higher progressive failure relative to high strength/stiffness reinforce-ment used in reinforced soil structures. Hence the analysis re-sults of the reference case were examined in detail.

3.2 *Force displacement behaviour*

The reinforcement pullout force is plotted against the displace-ment in Fig. 3. To eliminate the elongation of the reinforcemen within the sleeve, the displacement at the end of the sleeve (i.e., 0.2m from the exit) is plotted in this figure. A maximum pullout force of 71 kN was mobilized at 150 mm pullout displacement. The corresponding displacement at exit was 177 mm due to the extra elongation of the reinforcement in the sleeve.

The peak pullout force was lower than that given by the peak interface strength, as expected, but higher than that given by the fully softened interface strength. Once the peak pullout forc was achieved, further application of displacement at the rei n-forcement front end led to a rapid reduction of pullout force to 64 kN. which corresponds to that given by a fully softened inter-face strength. It is important to note that even at 50% of th maximum pullout force, a significant region of the interface was at a strain softening state. Hence the relevance of modelling the interface strain softening was demonstrated.

This rapid drop in pullout force from peak alue to fully sof-tened value appears to be related to the decrease in the rei n-forcement elongation after the peak. When the reinforcemen was pulled beyond the maximum pullout force, the reduction i reinforcement tension led to a reduction in the elongation of the reinforcement. Since the displacement at the reinforcement fron end was prescribed as increasing, other points along the rein-forcement had to move forward further and thus inducing further strain softening of the interface shear stress. This became a self-perpetuating process as illustrated in Fig. 4.

The displacements at three different locations (i.e., at 0.75 m, 1.05 m and 1.35 m respectively from the sleeve) alo g the rein-forcement are plotted against horizontal reinforcement displace-ment at sleeve exit in Fig. 5. The rapid increases of these loca displacements after the pullout force reaching the peak demon-strate the above process.

The force displacement curve so predicted conformed to known trend obtained from large scale pullout testing, with the exception of the rapid reduction of the peak pullout force to a e-sidual value. However, most pullout tests were terminated a less than 150mm pullout displacement. Hence the rapid reduc-tion of peak force to a residual value may not have been experi-mentally captured.

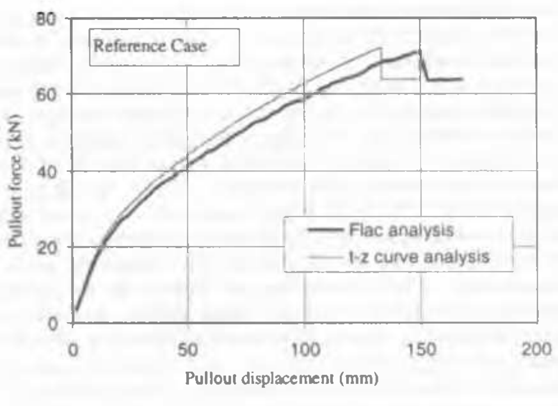

Figure 3. Pullout forc -displacement response

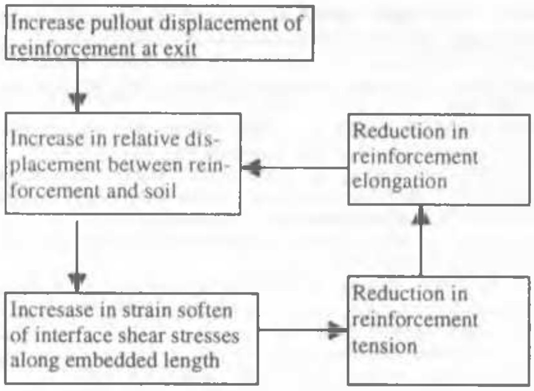

Figure. 4. Mechanism of pullout force softening

A t-z curve analysis was performed to check whether the force displacement response obtained from the FLAC analysis could be captured by such a simpler model. The same shear stress transfer function indicated in Fig.2 was used in the t -z curve analysis also. The vertical stress acting on the reinforcement was assumed to be constant in the t -z curve analysis. The result of the t-z curve analysis is compared with that obtained from the FLAC analysis in Fig. 3 and reasonable agreement is observed. The sharp reduction in pullout force from peak value to fully softened value was also indicated in the t -z curve analysis. The overall reinforcement load-extension stiffness obtaine from the t -z curve analysis was somewhat higher than that obtained from the FLAC analysis. This is partly because the horizontal displacement of the soil in a pullout box was not modelle in a t-z curve analysis.

3.3 *Stress Distribution*

The FLAC analysis gave an essentially uniform distribution of vertical stress, as expected, prior to the application of pullou force. However, the distribution of vertical stress changed with application of pullout force as illustrated in Fig. 6. For a pullout force equal to 50% of the peak value, the vertical stresses actin on the reinforcement (σ_n) were smaller than the average overburden stres (56 kPa) within the front region defined by a distance of less than 0.6 m of the pullout box. In the mid region, defined by a distance of about 0.5 m to 1.4 m from the front o the pullout box, σ_n was higher than the average overburden stress and had a maximum value of 61 kPa. In the rear region, defined by a distance greater than 1.4 m behind the front wall, σ_n was essentially equal to the average overburden stress.

At maximum pullout force, σ_n within the front region of the pullout box remained practically the same as above. In the mid region, σ_n was close to the average value. σ_n in the rear zon was highly non-uniform. σ_n increased rapidly between the distance of 1.4 m to 1.6 . It reduced sharply to 30 kPa at the rear end of the reinforcement. σ_n jumped back to 72 kPa slightly behind the rear end of the reinforcement. When the pullout forc was at the residual value, the σ_n distribution along the reinforcement was similar to that at the peak pullout force.

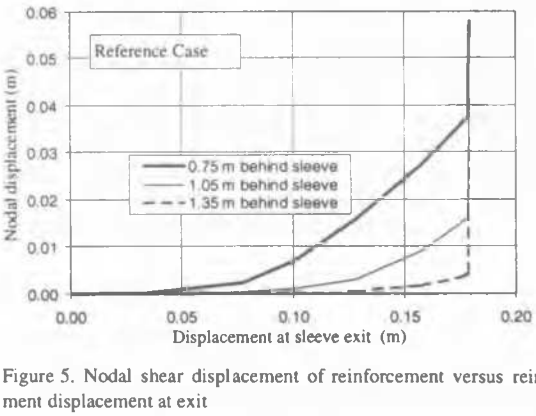

Figure 5. Nodal shear displacement of reinforcement versus reinforcement displacement at exit

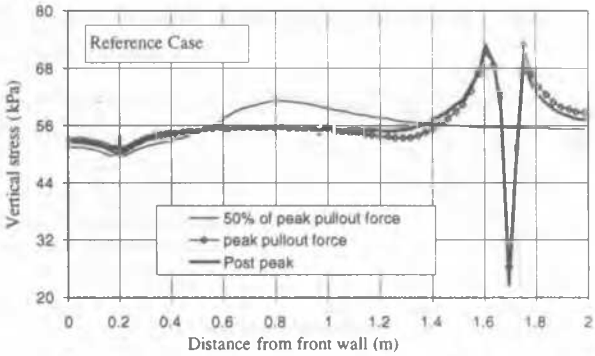

Figure 6. Distribution of vertical stress at mid height of 2m box

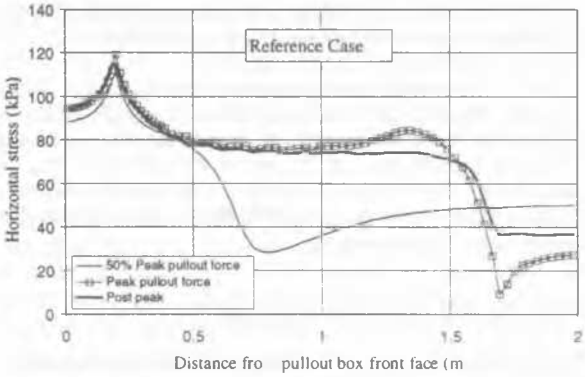

Figure 7. Distribution of horizontal stress of soil along mid height of box

The rapid reduction of σ_n in the rear zone of the reinforcement can be explained by looking at the distribution of horizontal stress as presented in Fig. 7. The pullout force led to reduction in horizontal stress in the rear zone of the reinforcement. At maximum pullout force, the horizontal stress was reduced t such a low value that the soil elements approached failure, whic in turn limited the value of vertical stress.

4 INFLUENCE OF REINFORCEMENT STIFFNESS, T ST CONDITIONS AND BOX DESIGN

For the purpose of comparing the pullout force displacement relationship for different box designs and test conditions, a mobilization factor (MF) is introduced:

$$MF = P / (2\, \sigma_{vo}\, L_b \tan \delta_{peak}) \quad (1)$$

where P = pullout force (at exit location), σ_{vo} = pressure applie at the top boundary plus vertical stress due to the self weight of 0.3m height of soil, L_b = initial bonded length of reinforcement. For a relatively high axial stiffness reinforcement, the maximum MF value should approach unity. For a reinforcement with a relatively low axial stiffness, maximum MF should approac $\tan(\delta_{resid})/\tan(\delta_{peak}) = 0.64$.

The influence of reinforcement stiffness was examined b conducting the analysis for different J values of 800 kN/m an 300 kN/m. The mobilisation curves so obtained were compare to that of the reference case (J= 500 kN/m). As evident from Fig. 8, the reinforcement stiffness has a slight influence on the peak mobilised value but a significant influence on the rate of mobilisation.

The effect of box length was studied by repeating the analyses for a 1m box. All three cases of different reinforcement stiffnesses were analysed. As evident from Fig. 8, the shorter box gave a higher peak mobilised value and a significantl higher rate of mobilisation. This is in agreement with know trend deduced experimentally (Fannin and Raju 1993).

The influence of the front wall roughness and the provision of

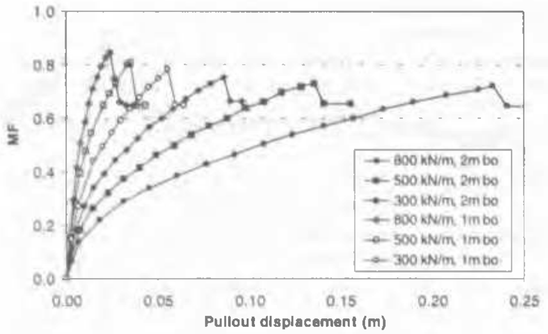

Figure 8. Influence of reinforcement stiffness o n mobilisati factor for 1m & 2m boxes

sleeve for the design of pullout boxes were also examined b conducting the following additional analyses for a 2m box.

- Box design with no sleeve,
- Box design with a rough front wall, and
- Box design with a rough front wall and no sleeve

The mobilisation curves obtained from these analyses wer close, although different, to that of the reference case (Fig. 3) and hence were not plotted for clarity. This finding conforme to that obtained by Raju et al (1998) based on a synthesis of a limited range of test results.

5 SUMMARY AND CONCLUSIONS

The preliminary results of an analytical study on progressive pullout failure in large scale pullout testing of geosynthetics were reported. The force displacement curves so obtained conformed to known trends deduced experimentally (Fannin and Raju 1993)

Although a uniform boundary stress was applied at the upper boundary, the normal stress on the reinforcement became non-uniform due to the application of the pullout force. Hence, even if the reinforcement forces and displacements along the embedded length of the geosynthetic were measured, their interpretation would be difficult unless internal distribution of norma stresses is also measured.

A preliminary parametric study was conducted to study the effects of different factors that influence the design of a pullou box. The analysis results showed that front wall roughness an the elimination of the flexible sleeve had only a slight influence on the pullout mobilisation curve. The effects of reinforcement stiffness and box length on the mobilisation of pullout forc along the reinforcement were also studied. Increasing reinforcement axial stiffness and/or decreasing pullout box length reduced the reinforcement elongation and hence resulted in more uniform shear displacement distributions along the reinforcement. This led to the mobilisation of a higher average shea stress along the interface. The net effects were a higher pea MF value, a considerably higher rate of mobilisation before th peak, and an apparently slower rate of strain softening of the pullout force after the peak.

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