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Finite element modelling of inclined pullout behaviour of geosynthetic sheet

Modélisation par éléments finis du comportement d'arrachement incliné d'une feuille géosynthétique

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ABSTRACT: Three-dimensional, elasto-plastic, finite element analyses (FEA) have been conducted using PLAXIS 3D to model the inclined pullout behaviour of sheet geosynthetic embedded in landfill cover system. The geosynthetic behaviour was modelled with bending/'plate' elements instead of conventionally used axial/'geogrid' elements. The behaviour of the sand was modelled using the elasto-plastic Mohr-Coulomb constitutive relationship. The results obtained from the numerical analyses were compared with the corresponding model test results reported by Bhowmik et al. (2019, 2020a) and Bhowmik (2019). The results showed that the conventional approach of modelling geosynthetics using axial elements is ineffective in simulating their inclined pullout behaviour. When the sheet geosynthetics were modelled using bending elements, the peak pullout force values at different inclinations were predicted with reasonable accuracy. However, the post-peak response was not satisfactorily modelled due to the inability of Mohr-Coulomb constitutive relationship in modelling the strain-softening response once the peak value is reached. Both model tests and FEA showed that the values of peak pullout force increased by nearly 20-25% with an increase in pullout inclination from 0° to 30°. This enhancement in the pullout force values with increasing pull inclinations may be attributed to the resistance imparted by the vertical component of the inclined pullout force, in addition to the frictional resistance mobilized by the horizontal component of the pullout force at the soil-geosynthetic interface

RÉSUMÉ : Des analyses tridimensionnelles, élasto-plastiques, par éléments finis (FEA) ont été menées à l'aide de PLAXIS 3D pour modéliser le comportement d'arrachement incliné des géosynthétiques en feuille intégrés dans le système de couverture de décharge. Le comportement du géosynthétique a été modélisé avec des éléments de flexion/« plaque » au lieu d'éléments axiaux/« géogrille » traditionnellement utilisés. Le comportement du sable a été simulé à l'aide du modèle de Mohr-Coulomb. Les résultats prédits des analyses par éléments finis ont été comparés aux résultats des tests de modèles correspondants rapportés par Bhowmik et al. (2019) et Bhowmik (2019). Les résultats ont montré que l'approche conventionnelle de modélisation des géosynthétiques à l'aide d'éléments axiaux est inefficace pour simuler leur comportement d'arrachement incliné. Lorsque les géosynthétiques en feuille ont été modélisés à l'aide d'éléments de flexion, les valeurs de force d'arrachement maximales à différentes inclinaisons ont été prédites avec une précision raisonnable. Cependant, la réponse post-pic n'a pas été modélisée de manière satisfaisante en raison de l'incapacité de la relation constitutive de Mohr-Coulomb à capturer la réponse de ramollissement de la déformation post-pic. Les essais sur modèle et la FEA ont montré que les valeurs de la force de traction maximale augmentaient d'environ 20 à 25% lorsque l'inclinaison de la force de traction augmentait de 0 ° à 30 °. Cette amélioration des valeurs de force d'arrachement avec des inclinaisons de traction croissantes peut être attribuée à la mobilisation de contraintes normales plus élevées à l'interface sol-renfort en raison de la composante verticale de la force d'arrachement inclinée.

KEYWORDS: Geosynthetics, Inclined Pullout, Finite Element Method, PLAXIS 3D

1 INTRODUCTION.

High-strength geosynthetics, like woven geotextiles and geogrids are often used as veneer reinforcement to stabilize landfill cover and liner systems on steep slopes. In turn, the stability of these veneer reinforcements depends on the efficacy of the anchorage at the top of the slope of landfills. Owing to its geometrical configuration, the pullout force induced on the veneer reinforcement is in an inclined direction. However, the reported studies on the inclined pullout behaviour of geosynthetics are scarce (Villard and Chareyre, 2004).

Finite element method (FEM) has proven to be an effective tool to study the stresses and strains, and load-transfer mechanism in reinforced soil problems. However, the reported studies in the literature on FEM modelling of the anchored geosynthetics have primarily focused on horizontal pullout (Sugimoto and Alagiyawanna, 2003; Balakrishnan and Viswanadham, 2016; Chawla and Shahu, 2016). This paper presents the results of the three-dimensional (3D) finite element (FE) analyses conducted to study the inclined pullout behaviour of sheet geosynthetics (e.g. woven geotextiles). The results obtained from the numerical studies are compared with the corresponding results obtained from laboratory model tests reported in Bhowmik et. al. (2019, 2020a) and Bhowmik (2019).

Fig.1 shows the photograph of the test set-up used in laboratory model tests.

It may be noted that the details of the 3D FE studies conducted on inclined pullout behaviour of geogrids are reported in Bhowmik et al. (2020b). Since the mode of failure of a grid geosynthetic and sheet geosynthetic are different, the present study is important to understand the modelling and behavioural aspects of inclined pullout behaviour of a sheet geosynthetic. The influence of the inclination of pullout on the peak pullout force of the sheet geosynthetic is examined in this study. The limitation of FEM for modelling the problem is also discussed in this paper.

Fig. 1 The inclined pullout test set-up (Bhowmik, 2019)

2 NUMERICAL MODELLING.

2.1 *Modelling of Components*

The numerical modelling of the anchored geosynthetic system was done using the Finite Element based software PLAXIS 3D (version AE). This commercially available FE software provides the features of modelling complex soil profiles, structural elements like geosynthetics, piles, and other reinforcing elements, and prescribing loads and displacements. It also offers the option of automatic meshing procedure and different calculation types, along with a wide range of choice of constitutive models to simulate soil and rock behaviour.

The dimensions of the numerical model were kept the same as the dimensions of the components of the geosynthetics and the test box used in laboratory model tests. Only one-half of the laboratory set-up was modelled considering the symmetry as shown in Figure 2. The bottom part of the numerical model is fixed in all directions, while the top part is kept free. The vertical surfaces were fixed in such a way that any perpendicular movements to the plane were restricted.

The load input was set in displacement-controlled mode, with a prescribed maximum displacement of 90 mm. This was done to simulate the displacement-controlled loading condition used in experiments. The details of modelling the sheet geosynthetic, soil, and interfaces are given in the following sections.

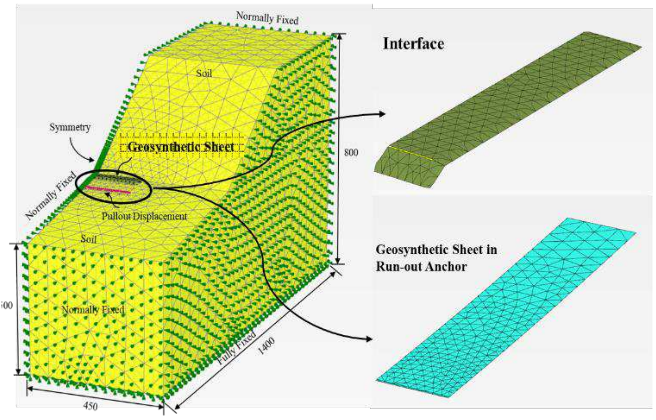

Figure 2. Half-model of the soil-geosynthetic system.

2.2.1 *Modelling of Geosynthetic Sheet*

The dimensions and the properties of the geosynthetic sheet were kept the same as that of the sheet used in laboratory model tests. The axial pullout behaviour of geosynthetics is usually simulated by using axial elements (such as 'Geogrid' elements in PLAXIS 3D) for geosynthetics in three-dimensional FEM studies. However, it was observed that axial elements could not model the inclined pullout behaviour of the geogrids adequately. As shown in Figure 3(a), as the geosynthetic sheet is pulled in an inclined direction, the axial element undergoes local bending and then moves vertically downward before moving horizontally forward. Similar observations were also made by Shahu and Hayashi (2009) and Bhowmik et al. (2020).

Since the axial element was found unsuitable for modelling of the inclined pullout, bending elements ('Plate' element in PLAXIS 3D) was adopted to model the geosynthetic sheet as shown in Fig. 3(b). Table 1 lists the parameters and their corresponding values for both 'geogrid' and 'plate' models used in the analyses.

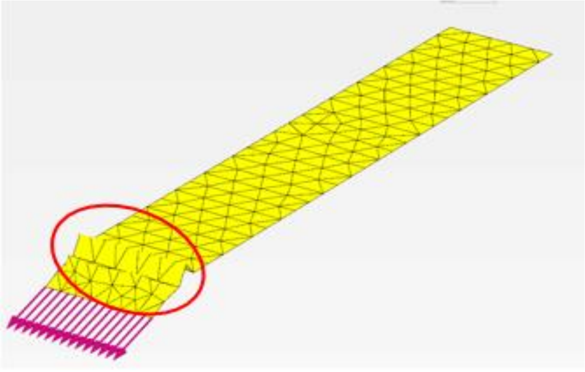

Figure 3(a). Deformation of the sheet under 20° inclined pullout when the Axial/'Geogrid' elements are used.

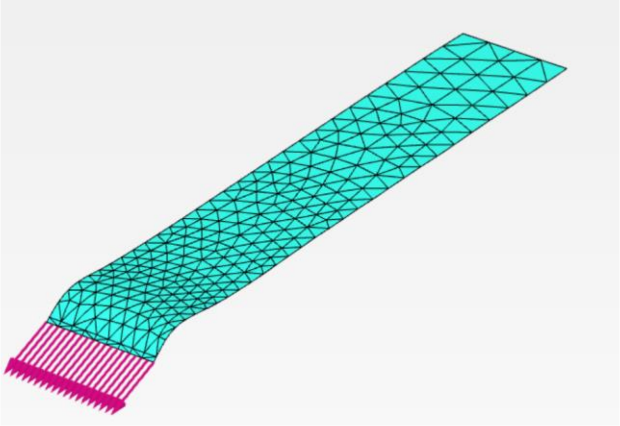

Figure 3(b). Deformation of the sheet under 20° inclined pullout when bending/'Plate' elements are used.

Table 1. Material properties of 'Geogrid' and 'Plate' elements considered in the analysis.

Properties	*'Geogrid' element*	*'Plate' element*
Axial Stiffness, EA, (N/mm)	1470	
Unit Weight, γ, (N/mm^3)	-	6.5×10^{-6}
Thickness, d, (mm)	-	1.2
Young's modulus, E, (N/mm^2)	-	1275
Poisson's Ratio, ν	-	0.33

2.2.2 *Modelling of Soil*

Elastic-perfectly plastic Mohr-Coulomb constitutive relationship was used to model the soil behaviour. Table 2 lists the values of each of the parameters used in analyses. 10-noded tetrahedral elements were used for the discretization of the soil body. Each node of the elements has only translational degrees of freedom per node. The parameters used in the Mohr-Coulomb relationship are given in Table 2. Most of these parameters, such as values of unit weight, γ, Young's modulus, E, and angle of internal friction, φ were all determined from laboratory tests. Though the value of cohesion intercept was obtained as 0 for the alluvial Yamuna sand, a negligible value of 0.5 kPa was considered for the numerical stability of the analyses (Mosallanezhad *et al.*, 2016). The value of the dilatancy angle was obtained from the difference among the peak and the residual values of angle of shearing resistance (Shahu and Reddy, 2011). The value of Poisson's ratio of 0.35 was assumed from the reported data in the literature.

2.2.3 *Modelling of Interfaces*

The modelling of interfaces is one of the most vital parts of numerical modelling using FEM. PLAXIS 3D offers the feature of modelling the interface using 12-noded zero thickness interface elements. The details of the interface elements in PLAXIS 3D are further given in Brinkgreve et al. (2015a). These elements having only translational degrees of freedom in each nodes, allow slipping and gapping (separation) two adjoining materials; thus, simulating the interfacial interactions among two different materials. Though the interface elements are zero thickness elements, a default value of 0.1 was considered as a virtual thickness value. This consideration was necessary to calculate the stiffness properties of the interface. The stiffness and other material properties of the interface are calculated with respect to the adjoining soil properties using a strength-reduction factor, R_{inter}. This factor relates the interface strength to the surrounding soil strength. The value of R_{inter} was obtained from the back-analysis of the simulation of the laboratory tests on sheet geosynthetics. The R_{inter} value was varied repeatedly in each analysis till the numerical results were coincident with the laboratory test results. For the present case, R_{inter} was evaluated as 0.85.

It may be noted that the R_{inter} value obtained for the numerical modelling of geogrid was 0.3 (Bhowmik et al. 2020). The significant difference in these two values can be attributed to the different modes of behaviour among the grid and the sheet geosynthetics. While the sheet geosynthetic mobilizes only frictional resistance on its contact area, the grid geosynthetic has the additional resistance imparted by the bearing behaviour of the transverse members of the grid.

Table 2. Material properties of soil considered in the analysis.

Properties	*Yamuna Sand*
Density of sand, γ, kN/m^3)	16.50 (D_r=83%)
Angle of shearing resistance , φ (°)	42
Cohesion, c (kPa)	0.5
Dilatancy angle, ψ (°)	6
Poisson's Ratio, ν	0.35

3 RESULTS AND DISCUSSION.

3.1 *Horizontal Pullout of Sheet Geosynthetics*

Fig. 4 shows the comparison among the horizontal pullout response of sheet geosynthetic obtained from laboratory model tests (Bhowmik *et al.* 2019, 2020) with the corresponding values obtained from the 3D FE analysis. The numerical model displayed a reasonably good match in pre-peak and peak behaviour for the peak pullout force and secant stiffness values. However, the post-peak response could not be modelled satisfactorily. It was observed that the pullout force value decreases drastically once the peak is attained. This post-peak drop could be attributed to large movement in the top soil observed during laboratory pullout model tests (Bhowmik *et al.* 2020). Even though similar top soil movements were observed in the numerical model, the same did not reflect in the force-displacement response. Similar observations were made during the numerical modelling of inclined pullout behaviour of geogrids too (Bhowmik et. al. 2020). This may be due to the use of elastic-perfectly plastic Mohr-Coulomb model for the soil. The fixed yield surface of the Mohr-Coulomb constitutive model doesn't allow the pullout force to drop once the peak value is attained (Brinkgreve et al., 2015b). For this reason, only the peak pullout force values of the numerical analyses are compared with the corresponding values of the laboratory model tests.

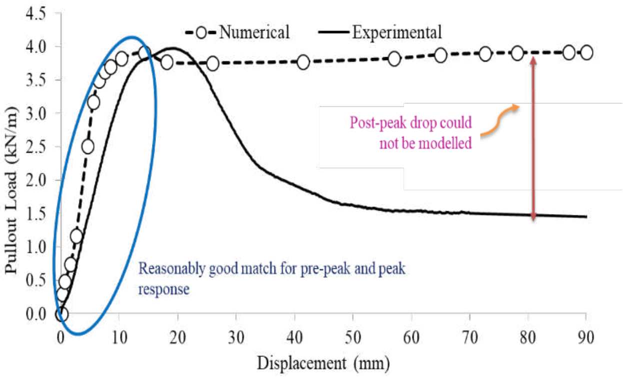

Figure 4. Comparison of experimental results under horizontal pullout for sheet geosynthetic with corresponding numerical results

3.2 *Inclined Pullout of Sheet Geosynthetics*

Fig. 5 shows the comparison among the results from the numerical analyses of inclined pullout on sheet geosynthetics at 30° inclination with the corresponding values of laboratory model tests. Although the secant stiffness values among the two responses are similar, the peak value in the numerical model is achieved at a larger displacement when compared to the experimental results. Similar to the observations made before, the post-peak behaviour in this case also could not be modelled satisfactorily for similar reasons.

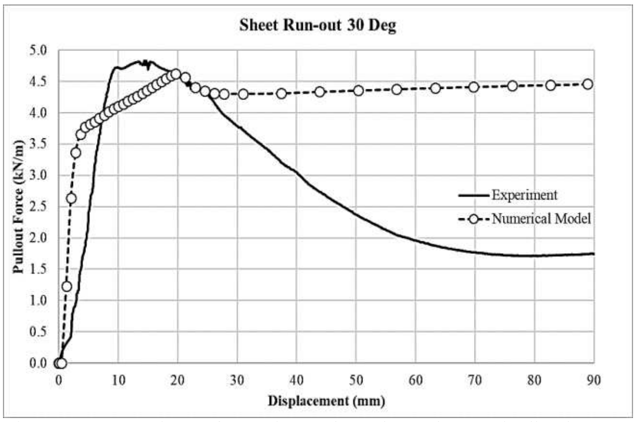

Figure 5. Comparison of experimental results under 30° inclined pullout.

Nevertheless, the peak pullout loads obtained from the numerical analysis are similar to corresponding values obtained from experiments for all inclinations of pullout force and hence are compared with the corresponding experimental values. Figure 6 shows this comparison. The experimental results show that the peak pullout force values increase by as much as 20% when the pull inclination increases from 0° to 30°. The corresponding increment obtained from numerical analyses is 26%. Since an inclined force has two force components: one in horizontal and another in vertical, the vertical component of the pullout force imparts an additional resistance at the soil-geosynthetic interface along with the typical frictional resistance mobilized due to the horizontal component of the pullout force. This additional resistance results in higher values of pullout capacities. It can also be inferred from the results that the inclination of pullout force should also be a governing factor for the design of veneer reinforcement.

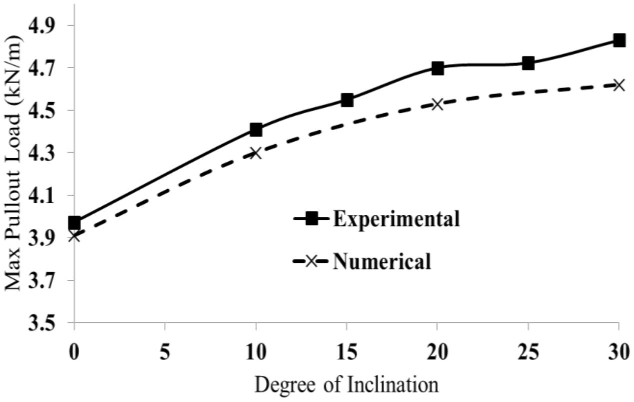

Figure 6. Variation in peak pullout force with change in inclination of pullout.

4 CONCLUSIONS

This paper presents the results of a numerical study conducted to investigate the effect of inclination of pullout force on the behaviour of sheet geosynthetics used as veneer reinforcement in landfill covers. The three-dimensional numerical modelling was done using commercially available Finite Element platform PLAXIS 3D. The results obtained from the numerical study are compared with the experimental results reported in Bhowmik et al. (2019, 2020a) and Bhowmik (2019). Based on the analyses, the following conclusions are drawn:

1. The behaviour of the sheet geosynthetic was satisfactorily modelled only when bending element/ 'Plate' elements were used to model its behaviour. The conventional approach of using axial/ 'Geogrid' elements to model pullout response of anchored geosynthetics was unable to model the inclined pullout response.
2. The adopted numerical modelling approach resulted in a satisfactory agreement between the numerical and experimental results in pre-peak and peak behaviour. The secant stiffness and the peak pullout load values were consistently similar among the numerical and experimental results.
3. The post-peak fall in pullout resistance observed in experiments due to the large movement of top soil could not be modelled in numerical analyses. This may be due to the fixed yield surface of the elastic-perfectly plastic Mohr Coulomb soil constitutive model used in the study. The fixed yield surface in the constitutive model results in an almost constant value of pullout force once the peak is attained.
4. The results show a significant increase of almost 20-25% with an increase in the pull inclination from 0° to 30°.
5. This increment in pullout force may be attributed to the additional resistance imparted by the vertical component of the inclined pullout force, along with the frictional resistance mobilized by the horizontal component of the pullout force at the soil-geosynthetic interface.
6. The results show that while designing veneer reinforcement for landfill cover systems, the effect of inclination of the pullout force should be considered as this may lead to a comparatively economical design.

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