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Suitability of a 3D numerical code to soil reinforced by geosynthetics applications

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ABSTRACT: The article deals with 3D numerical modeling of soil structure interaction especially on geosynthetic high extensibility reinforcement based on *FLAC^{3D}v2.0*. The first part of the article is dedicated to analyses of basic tests with an aim of justifying the modeling processes and defining the best compromise for studies on complex geometries. The second part focuses on a problem of localized stresses on reinforced soil with one geosynthetic layer ; the goal of such analysis is to point out the influence of the form factor *B/L* (width over length) on the loading.

1 INTRODUCTION

Numerical modeling, boosted by the development of computerized calculation systems, brings considerable help to the analysis of civil engineering projects.

The real behavior of structures reinforced by geosynthetic sheets subjected to a local loading is still badly defined. For this three-dimensional operating mode, the development of a model integrating the reinforcement system contribution is undertaken on *FLAC^{3D}*v2.0. The process of discrete modeling is adopted: the soil and the reinforcement sheets are modeled respectively using volumetric 3D elements and structural elements.

Numerical simulations are shown according two distinct parts.

In the first part, three straightforward application tests are presented (Bénéïto & Gotteland 2001). Some results of these numerical simulations are compared to the observed behavior. The aim of such tests is to characterize limits of each model and to define the best compromise for analyses on complex geometries.

In the second part, the best modeling process found, investigations are focused on a problem of local stresses on a sandy substitute soil overlying soft clay reinforced by one geosynthetic layer. The objective is to outline the influence of the form factor *B/L* (width over length) on the loading.

2 NUMERICAL MODELING

The *FLAC^{3D}*v2.0 software is suitablefor 2D and 3D modeling for the ability to integrate structural elements using specific interface relations and for solving complex tasks in small –and lrge- strain mode. This software bases on three-dimensional explicit finite-difference units as programmed by Billaux & Cundall 1993 and as explained in the Flac-3D V2.0 users manual.

2.1 Flexible reinforcement sheets

The reinforcement system is modeled by the structural elements provided by the software:

- the Cable elements (Fig. 1),
- the Shell elements (Fig. 2).

The Cable elements are unidirectional elements composed of two nodes (Fig. 1). Each node has only one degree of freedom, namely a freedom of translation according to the longitudinal axis of the element.

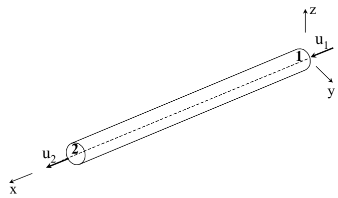

Figure 1. Cable element model, *FLAC^{3D}* v2.0.

The forces are mobilized thanks to the shear strength developed along the Cable element. The mechanical behavior is governed by a rigid elastoplastic law. No bending moment is supported by this structural element. Only stresses of tension and compression are generated by default. In order to model geosynthetic sheets, the compressive resistance is assigned to zero.

The Shell elements are plan triangular finite elements with a low thickness made of three nodes (Fig. 2). Each node is free to be driven according to six degrees of freedom: three degrees in translation and three degrees in rotation.

The mode of Shell element stress mobilization is defined by the theory of thin shells and plates, in which displacements caused by transverse distorsions are neglected. It considers the mobilization of membrane and bending stresses.

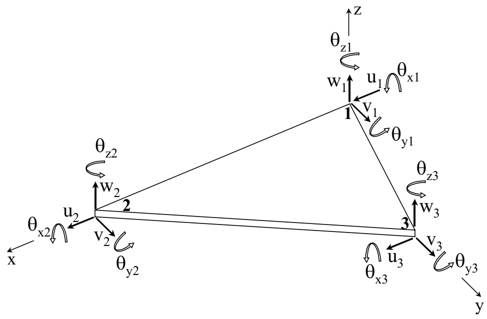

Figure 2. Shell element model, *FLAC^{3D}* v2.0.

The Shell behavior law is purely elastic linear isothropic or orthotropic without limitation of the forces. It is possible, thanks to the introduction of users' procedures, to integrate into the model a brittle failure criterion like the Von Mises type and thus to delete Shell elements as soon as the failure criterion is reached. Unfortunately, the stress recovery procedure within the elements is available only in the small-strain mode. When the large-strain mode is activated, failure cannot be managed by the stress tensor calculation.

2.2 *Soil-geosynthetic interaction law*

Two interface models are provided by the software:

- a volumetric grid connection with rigid attachment conditions in translation and free attachment conditions in rotation.
- an elastoplastic rigid law formulated in order to satisfy conditions of soil-geosynthetic friction strength reduction.

2.3 *3D volumetric mesh generation*

The considerable difference between 2D and 3D models concerns meshes and limit conditions applied to the models.

2D meshes (Fig. 3) are constituted by nodes contained in the only study plan. The study is generally driven in a plan strain state. This plan strain state is characterized by null movements according to the perpendicular axis of the study plan. It allows to govern strain mechanisms developing uniformly according to one direction. These mechanisms are comparable to those observed on linear works ($B/L \approx 0$). On *FLAC*^{3D}v2.0, volumetric meshes consist of a pile of cubic blocks on a slice of thickness equal to the unity.

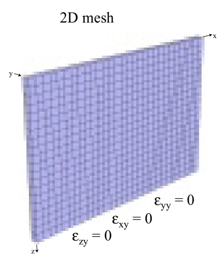

Figure 3. 2D meshes on *FLAC*^{3D}v2.0.

3D meshes (Fig. 4) considering the three dimensions of the space do not appear under the shape of study slices. Strain mechanisms are generated in real volumes. The conditions of null movements are only applied to the limits of the volumetric model. Inside the model, the conditions of movements are not imposed.

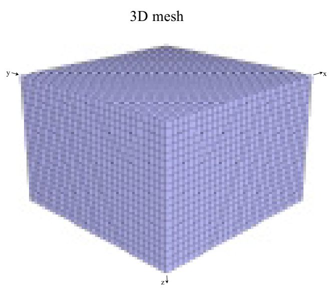

Figure 4. 3D meshes on *FLAC*^{3D}v2.0.

3 COMPARE MODELING RESULTS WITH OBSERVED BEHAVIOR

3.1 *Tensile behavior – simple tensile test*

The first test consists in modeling the behavior of a geosynthetic pattern in tension (Bénéïto & Gotteland 2001).
A geotextile used for a significant experimental project (Haza et al. 2000) is used as reference to the study. For comparison, calculations are made with the Shell and Cable elements.

The results in small-strain mode (Fig. 5) obtained with these two modeling processes are very close to experimental measurements. Nevertheless, the brittle failure of the Shell elements seems more suitable than the rigid behavior of the Cable elements.

Calculations in large-strain mode (Fig. 6) show a very strong sensitivity to the large-strain mode of the Cable elements. Modeling appears incoherent with observed behavior. The Shell elements appear less sensitive to the large-strain mode, but the version of the software used does not make it possible to recover internal stress and consequently to calculate a brittle failure criterion.

Because of the strong sensitivity of the Cable elements, we prefer to draw aside this solution for calculation in large-strain mode.

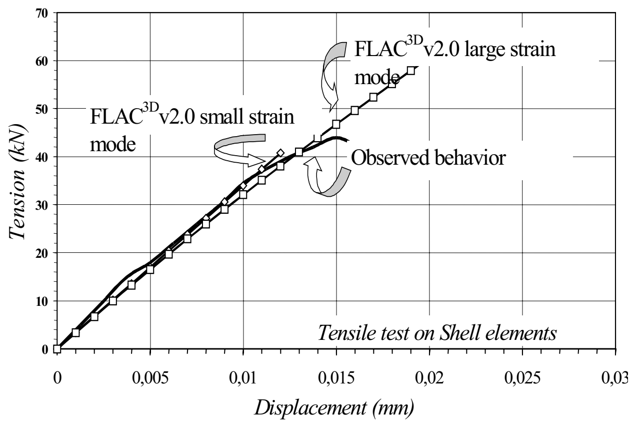

Figure 5. Results of the simple tensile test on shell elements, geotextile, J=340kN/m, T_r=44kN/m.

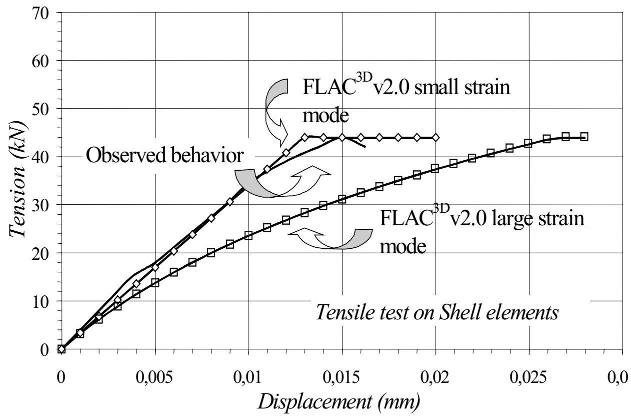

Figure 6. Results of the simple tensile test on cable elements, geotextile J=340kN/m, T_r=44kN/m.

3.2 Membrane behavior – deflection test

The second test considers the membrane behavior of a flexible reinforcement sheet by measuring the maximum deflection recorded in the center of a sheet subjected to a uniform top-load (Bénéïto & Gotteland 2001).

The numerical results obtained with the Shell elements are compared with the theoretical Delmas' solution (1979).

The main result of this simulation relates the importance of the calculation mode to be used (Fig. 7). The membrane effect can be generated only in large-strain mode. The results in small-strain mode are completely incorrect. The use of the rotational effect of the movement is essential for a good modeling.

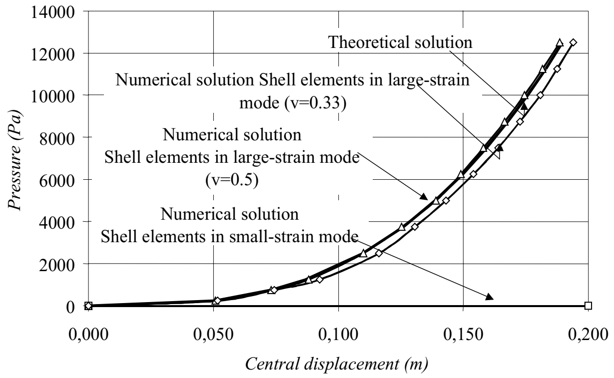

Figure 7. Results of the deflection test (J=1435kN/m).

3.3 Anchorage behavior – pull-out test of a sheet in contact with soil

The third test treats the behavior of a buried geosynthetic layer subjected to a pull-out force (Bénéïto & Gotteland 2001).
The geometrical and mechanical parameters are extracted from an experimental study. This work is the subject of theoretical analyses (Bourdeau et al. 1997). But, only experimental results are used as a basis of comparison with the numerical results.
The study relates to two distinct models:
- the first one considers rigid attachment conditions between the soil and the geosynthetic layer,
- the second one integrates attachment conditions allowing taking into account a soil-inclusion interface strength reduction.

The objective is to compare displacements recorded in various points P_i regularly placed along the sheet and to outline the progressive mobilization phenomenon of the reinforcement sheet.

It appears impossible to model the observed behavior suitably with the interface model considering strength reduction (Fig. 8).

However, the results obtained with the model with attachment conditions are very encouraging (Fig. 9). We notice the good correspondence between observed behavior and calculation. The phenomenon of progressive mobilization of the geosynthetic layer is correctly highlighted by the numerical approach.

4 TRANSFER OF LOCAL LOAD USING GEOSYNTHETIC REINFORCED SAND LAYER

The modeling process by Shell elements in large-strain mode is retained for the study of a sandy substitute soil overlying soft clay reinforced by a geosynthetic layer and subjected to local loads.

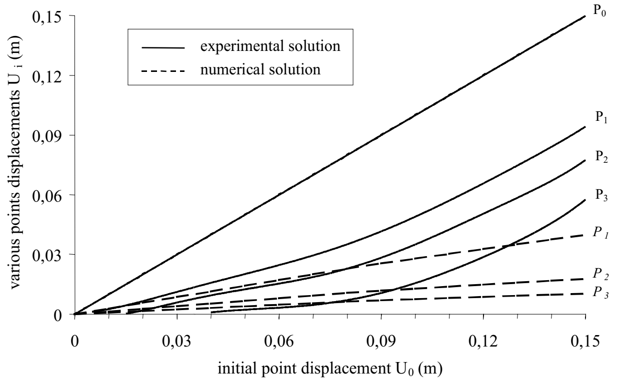

Figure 8. Results of the pull-out test with cable attachment conditions on geosynthetic, Stiffness modulus J=1300kN/m, interface friction angle Φ_{sg}=33°.

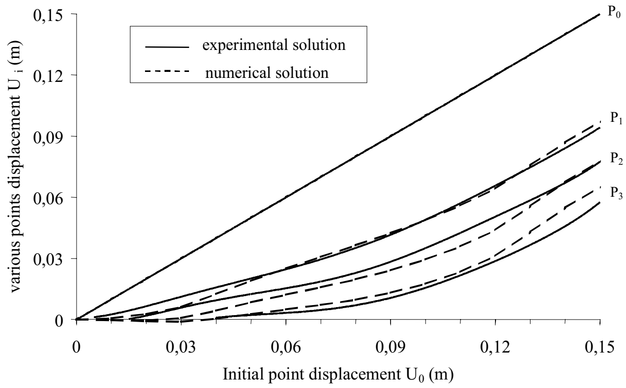

Figure 9. Results of the pull-out test with rigid attachment conditions on geosynthetic, stiffness modulus J=1300kN/m, interface friction angle Φ_{sg}=33°.

The 2D experimental study of Love et al. (1987) (Fig. 10, Tables 1 and 2) is used for the calibration of the 3D numerical model. The shape factor *B/L* is equal to 0 and all the mechanical and geometrical parameters of the numerical modeling are adjusted to the experimental measurements (Fig. 11). This configuration will be the reference of the comparisons. It is anticipated to obtain a satisfactory extrapolation of the study in a 3D behavior field by variation of the length *L* of the spread footing.

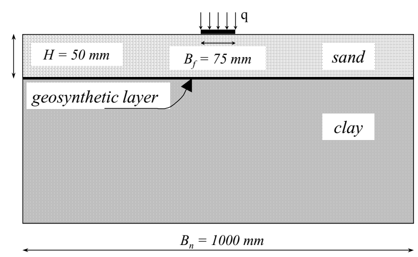

Figure 10. Geometry of the 2D study (Love et al. 1987).

Table 1. Geometric parameters (Love et al. 1987)

Width of the spread footing B_f	75 mm
Sandy layer thickness H	50 mm
Width of the geosynthetic sheet B_n	1000 mm

Table 2. Characteristics for the 3D numerical modeling

	sand	clay
Density γ	19kN/m³	17 kN/m³
Elastic modulus E	4.2 MPa	0.9 MPa
Poisson's ratio ν	0.35	0.49
Angle of friction Φ	41°	0°
Cohesion C	0 kPa	9.5 kPa
Angle of dilatancy Ψ	21°	0°
Geosynthetic Stiffness Modulus J Rigid attachement conditions	28 kN/m	

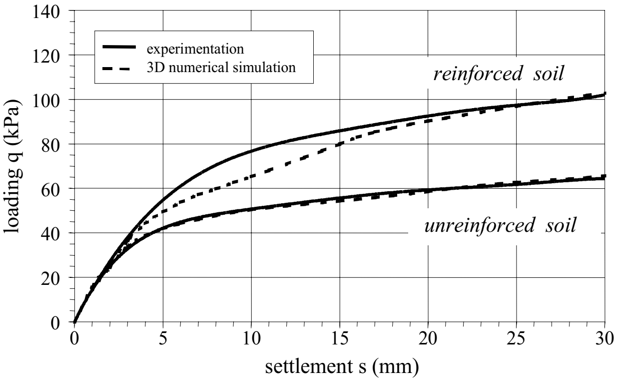

Figure 11. Calibration curves for the 3D numerical modeling, B/L=0, shell elements.

On this configuration of sandy soil overlying soft clay, the 3D effect is double. The shape factor *B/L* acts, first on the load of the unreinforced soil (Fig.12), second on the load gain generated by the geosynthetic sheet (Fig.13). We note that the loading intensity grows appreciably on reinforced and unreinforced configurations when the geometry of the loading surface approaches a square shape (*B/L = 1*).

Table 3 gives the gain of the load intensity due to the combined actions: 3D effect of soil, and 3D effect of reinforcement. Effect of reinforcement seems to be more efficient for small B/L.

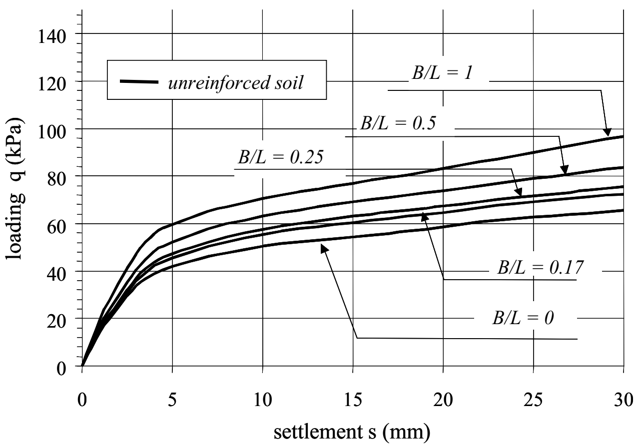

Figure 12. Shape factor *B/L* influence on the settlement loading intensity curve, unreinforced soil, Shell element .

Table 3. 3D evolution of the load intensity according to the shape factor *B/L*. Base of comparison: 2D unreinforced soil (s/B=40 %, s=30mm).

B/L	unreinforced soil	reinforcement	reinforced soil
1	49 %	26%	75 %
0.5	29 %	20%	49 %
0.25	15 %	17%	32 %
0.17	11 %	14%	25 %
0	reference (2D)	08 %	08%

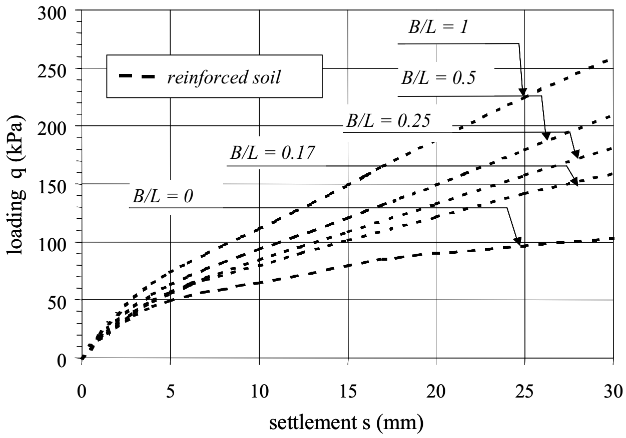

Figure 12. Shape factor *B/L* influence on the settlement loading intensity curve, reinforced soil, Shell element .

5 CONCLUSION

The Shell element of *FLAC*^{3D}v2.0 relevantly models the geosynthetic behavior and mobilizes sheet reinforcement effects as caused by anchoring and by membrane effect, as long as the large strain mode is selected. We note that the interface behavior with strength reduction is incorrectly modeled with the version 2.0 software used. That implies to consider configurations in which the soil-geosynthetic interface strength properties are equal to those introduced for the soil, or to disregard the characteristics reduction observed between soil and inclusion.

The 3D-modeling of a simple geometry proves effective, wich leads to conclusion that rather complex geometry modeling is an option for the future. The 3D application on geosynthetic reinforced sand layer overlaying soft clay proves the point of much higher resistance compared to the conventional 2D analysis due to the load distribution capacity in the plane directions. In that way the 3D effect of soil behavior seems to be more efficient that reinforcement behavior.

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