Soil substitute reinforced by geosynthetics: qualification of the effect by numerical modelling

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ABSTRACT: Soils can be reinforced by reusing the material in place beneath surface foundation footings, either instead of or in addition to the procedure for substituting a deformable soil by a stiff soil.
This article presents a comparative numerical study of various geometric configurations: an unreinforced deformable foundation soil, a deformable foundation soil reinforced by one or more flexible reinforcement sheets such as geosynthetics, and the substitution of a deformable foundation soil layer by a stiff soil layer. Only the reinforcement function of the geosynthetic inclusions is examined.
It is shown that, in spite of a few differences in the unprocessed results, the two applications used lead to the same conclusions: the geosynthetics are under fairly low stress under low loading conditions and only allow an actual reduction in settlement for heavy loads. The thickness of the substitute layer (and the type of material used) is the main parameter involved in reducing settlement, with or without geosynthetic reinforcement.

1 INTRODUCTION

The design of methods for monitoring and predicting the behaviour of geomaterials is a constantly relevant topic. Numerical modelling, boosted by the development of computerised calculation systems, is now a vital part of civil engineering projects in addition to (or instead of) experimental and theoretical models.

The work presented here focuses on modelling using numerical tools. Its aim was to assess the relevance of models representing the mechanical behaviour of flexible geosynthetic inclusions using two commercially available applications. This is achieved by means of a comparative study of a sample application of a loading platform on a reinforced or non-reinforced substitute soil layer.

2 NUMERICAL MODELS

Because the problems encountered in geotechnics are so complex, the analytical calculation methods used are often questionable because they were developed on the basis of simplifying hypotheses. The use of numerical models enables additional information to be obtained on stress and strain fields, but by dint of calculations that are often more difficult to perform.

Various numerical modelling methods have been or are being developed for reinforced soils:
- the finite element method,
- the finite difference method,
- the distinct element method,
- the boundary element method, etc.

Two codes for calculating two-dimensional problems in elasto-plasticity and major deformations were selected for the present comparative study:

- PLAXIS v6.1, a finite element computation code,
- FLAC v3.3, a finite difference computation code.

The operating principle of geosynthetic flexible inclusions requires relatively large movements of materials and their interfaces.

In addition to the possibility of modelling reinforcement sheets, the choice of applications was partly motivated by different numerical architectures:

- the finite element computation principle used in PLAXIS v6.1, referred to here as PLA, is based on the application of the virtual work theorem on a group of elements (Vermeer, Brinkgreve, 1995).
- the finite difference computation principle used in FLAC v3.3, referred to here as FLA, is based on the application of undefined equilibrium differential equations at discrete points in space with respect to the time increments Δt and space increments Δx and Δy.

Even though the finite difference and finite element methods seem to have different principles, they are both based on the expression of equilibrium, which in some cases means that the equations are identical (Cundall, 1987).

2.1 *Soil behaviour*

The models presented are defined on the basis of a type of elasto-plastic soil behaviour that corresponds to the Mohr-Coulomb model, which is the model most commonly used in soil mechanics.

The Mohr-Coulomb model is characterised by five parameters (Tab. 1, Fig. 1):

Table 1. Parameters of the Mohr-Coulomb mechanics model

Linear elasticity law:	E, Young's elasticity modulus
	ν, Poisson's coefficient
Plasticity criterion:	C, cohesion
	Φ, angle of friction
Plastic flow law:	Ψ, angle of dilatancy

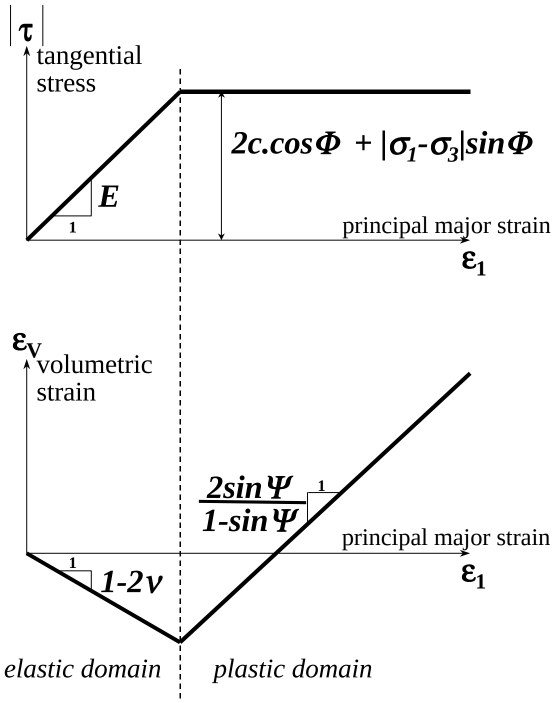

Figure 1: Mohr-Coulomb elasto-plastic behaviour model

2.2 *Behaviour of geosynthetics*

Various modelling approaches may be considered using numerical models (Gotteland et al. 1996). In this study, the geosynthetic sheets are modelled using the individual structure elements of each application.

The "geotextile elements" in PLA are controlled by a perfectly elastic behaviour law with no limitation of internal tension. They cannot tolerate any bending moment; they are characterised only by their axial stiffness EA, i.e. by the stiffness modulus J (kN/m) of the geosynthetic sheet (Fig. 2).

The "cable elements" of FLA are controlled by a perfect elasto-plastic law (Fig. 2). The parameters to be included in the model are the area and perimeter of the inclusion, the elasticity modulus E of the geosynthetic (equal to J/area), and the yield tension (equal to the tensile stress T_r) of the reinforcement. By default, the "cable" elements have round sections. The equivalent round section giving the same external surface in contact with soil as a rectangular section of sheet is calculated beforehand.

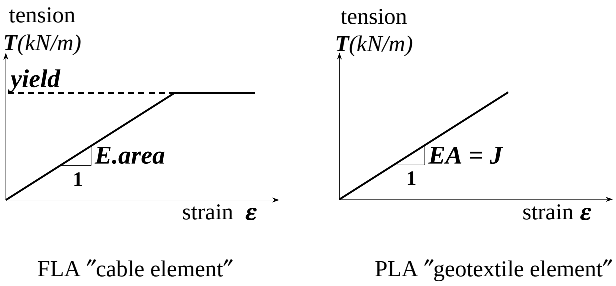

Figure 2: Modelling geosynthetic sheet behaviour

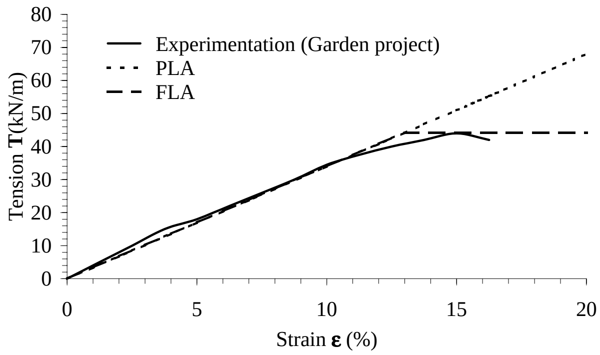

Figure 3: Comparison of numerical models - experimental model of the behaviour of geosynthetic sheets under simple tensile stress

These model results are similar to the actual behaviour of geosynthetics used for reinforcement (Fig. 3). If the limit tensile stress is not reached, they are acceptable.

2.3 *Behaviour of interfaces*

The soil-geosynthetic interfaces were modelled in order to meet the conditions for reducing soil-inclusion friction forces that can be effectively absorbed (Long P.V. et al. 1997).

In the PLA code, the behaviour of the soil-inclusion interface follows the Mohr-Coulomb elasto-plastic law. The angle of friction was reduced by considering the following relation: $tg\Phi_{sg} = \mu . tg\Phi_{soil}$ (with $\mu \leq 1$). A minimum cohesion C_{sg} (imposed by the software) was set at 1 kPa. The elastic characteristics E and ν are identical to the characteristics of the soil in contact with the geosynthetic.

In the FLA code, the soil-inclusion interface is included in the definition of the "cable" structure elements. The interface is also governed by a Mohr-Coulomb elasto-plastic law (Fig. 4). The parameters involved are the curve gradient in the elastic domain, the angle of friction and cohesion at the soil-inclusion interface (*kbond*, *sfriction* and *sbond*).

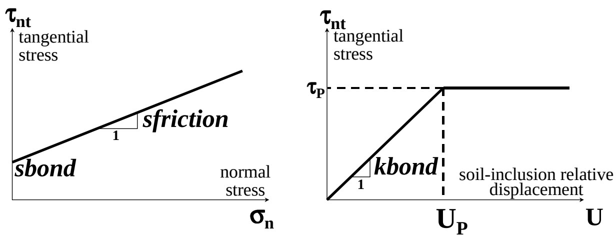

Figure 4: Modelling the soil-inclusion interface on FLACv3.3

A calculation must be performed before the *kbond* parameter can be obtained. In the cases studied, it is assumed to be a direct function of:

– τ_P, the tangential stress at the plasticity limit imposed by the soil confinement $\tau_P = (\gamma h + q).tg\Phi_{soil}$
– U_P, the displacement obtained from τ_P determined experimentally.

3 BEHAVIOURAL STUDY OF A LOADING SLAB PLACED ON DEFORMABLE SOIL

Geosynthetics are widely used as internal reinforcement in supporting structures. Less is known about their use in the reinforcement of foundation soils, but there is interesting potential for development, as base reinforcement beneath water or gas pipelines, beneath buildings or civil engineering structures, beneath paving slabs, etc.

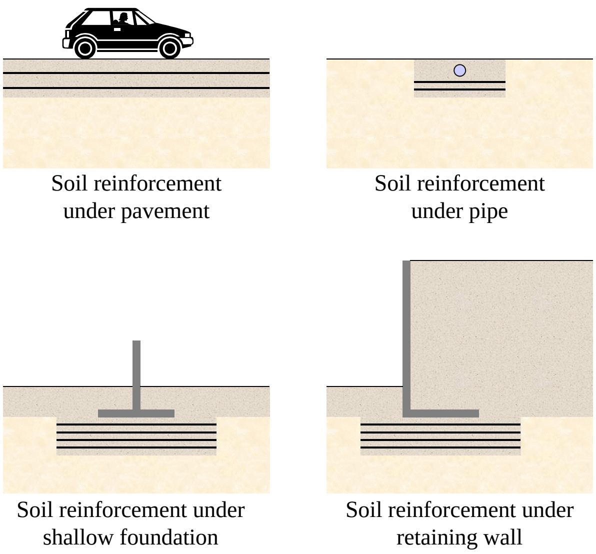

Figure 5: Examples of soil reinforcement by geosynthetic sheet

The aim of the study consisted in assessing the contribution of geosynthetic sheets to limiting, under a light load (operating load), settlement under localised stresses in highly deformable soils and soils with little supporting capacity. Only the reinforcing role of the geosynthetics was examined. The material-separating role was not taken into account, even though it is real and preserves the mechanical characteristics of the upper layer.

The simplified case of the study involved a load footing placed on the soil surface (Fig. 5).

The study examined various configurations:

- load footing on a layer of unreinforced loamy soil in place (case 0),
- load footing on a layer of loamy soil in place reinforced by one or more geosynthetic sheets (case 1.i),
- load footing on a layer of sandy substitute soil (case 2).

The load footing is defined so as to be stiff enough to satisfy the assumption that settlement at the base is uniform. Its width B is defined for the study as 1 m.

The reinforcement sheet is laid at a depth H; in cases where several sheets are used, H_{max} is the maximum depth at which they are laid. The width of the sheets is L = 5B corresponding to the width of the substitute layer, i.e. 5 m.

The maximum thickness of the substitute layer D is variable and limited to 1.5B, i.e. 1.5 m (Fig. 6).

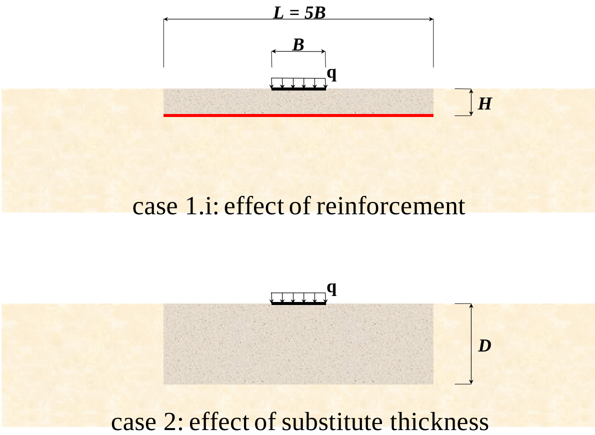

Figure 6: Geometries of the study

Given the symmetry of the problem (geometrical and mechanical symmetry), the numerical model mesh covers only half of the study geometry (Figs. 7-8).

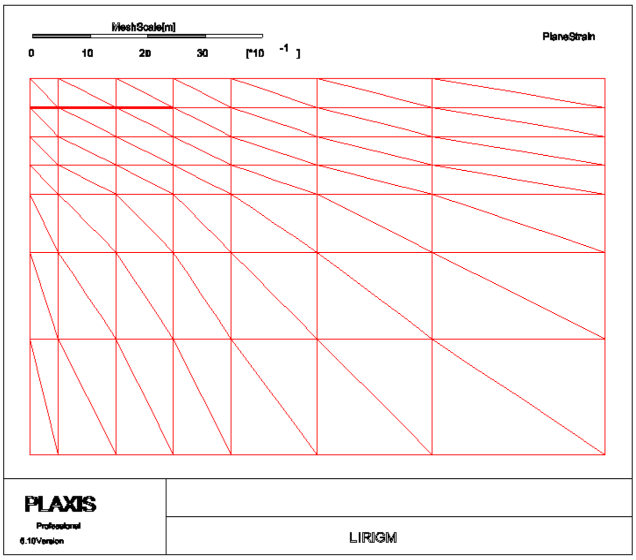

Figure 7: Mesh created on PLA

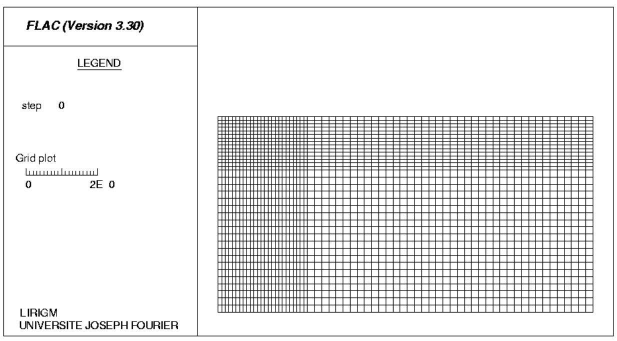

Figure 8: Mesh created on FLA

The mechanical properties selected for the soils are those of two materials frequently found in geotechnical problems: a deformable loamy material for the soil in place and an ungraded sandy material as substitute soil (Tab. 2). Note that, after the reinforcement has been placed, the replaced soil keeps its initial properties in the present study. In reality, the soil properties would be improved by compacting.

Table 2. Mechanical properties of soils

	Soil in place	Substitute soil
Density γ_s *(kN/m³)*	17	20
Elastic modulus *E (MPa)*	3	15
Poisson's coefficient ν	0.3	0.3
Angle of friction Φ_s (°)	25	28
Cohesion C_s *(kPa)*	3	3
Angle of dilatancy Ψ (°)	0	8

The stiffness moduli J (kN/m) of the geosynthetics are taken with regard to the existing range of materials: geosynthetics (non-woven, woven, geogrids, etc.) and metal reinforcement meshes. Four representative values were selected (Tab. 3):

Table 3. Mechanical properties of geosynthetics selected

Stiffness modulus J (kN/m)
100
500
1000
5000

For the general study, friction at the interfaces is assumed to be constant. The relation $\mu = tg\Phi_{sg} / tg\Phi_s$ was generally set at 0.6, although the interfaces differ depending on the type of material.

Table 4. Mechanical characteristics of the soil-geosynthetic interface

	Soil-geosynthetic interface
Angle of friction Φ_{sg} (°)	18
Cohesion C_{sg} (kPa)	1
U_p (m)	$0.0019 + 4.10^{-5}\sigma_v$

3.1 *Settlement under the load footing*

Given the unprocessed results (Fig. 9-10), it appears that the amount of settlement calculated by FLA is generally lower than that calculated by PLA.

The relative differences between the two applications can be considered substantial. On average, they are up to 10% on the configuration of the unreinforced soil in place (case 0), 20% on the configuration of the soil in place reinforced by a geosynthetic sheet (case 1) and 60% on the substitute soil configuration (case 2). There is a major difference between the two model results. However, the trends obtained by the two applications are similar.

The most significant reduction in settlement was obtained with the substitution procedure (case 2). Settlement was actually reduced at a very early stage in the loading program. The reduction rate was constant regardless of the load applied to the loading slab.

The effect of the reinforcement in the reinforced soil configurations (case 1) seems to be governed by a minimum loading threshold, of about 30 kPa in our study.

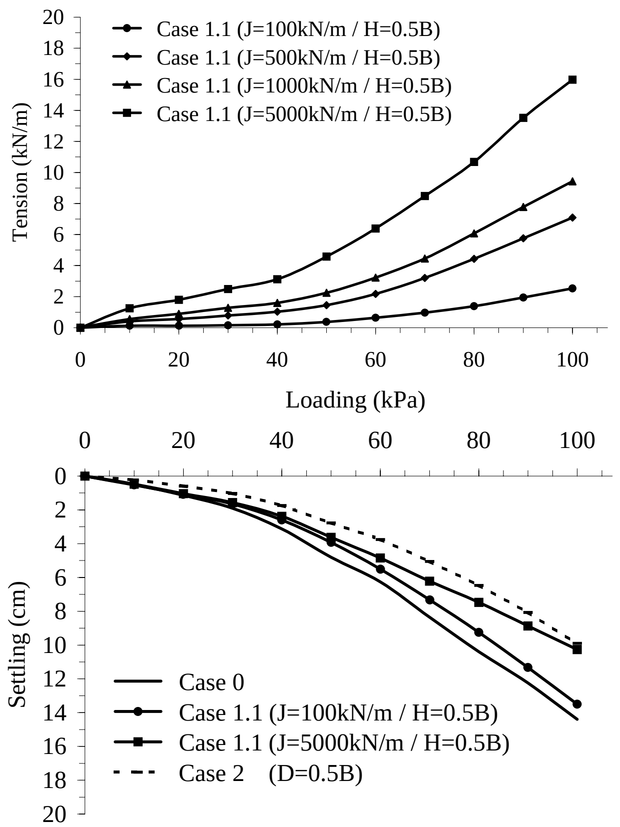

Figure 9: Settlement and reinforcement tensile stress - loading curves: FLA

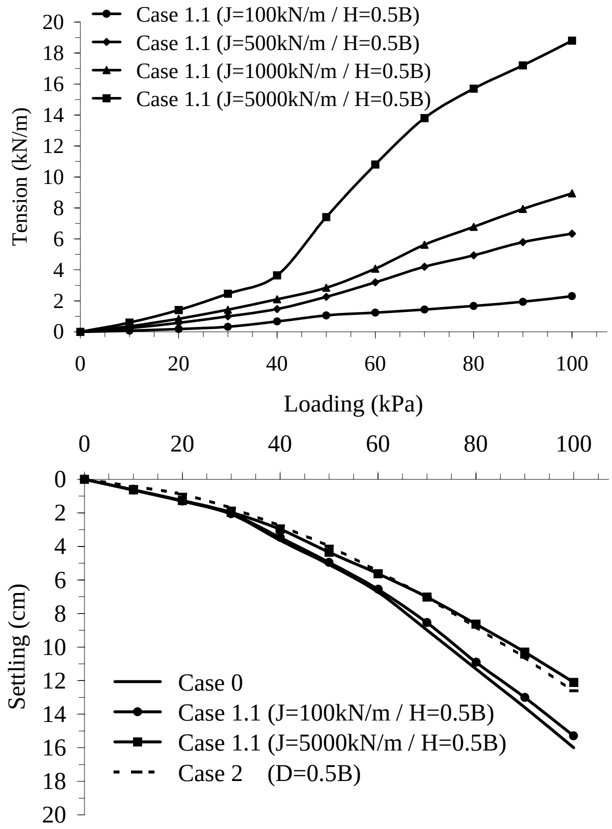

Figure 10 : Settlement-loading curve - PLA

Table 5. Summary of settlement under q=100kPa

	PLA		FLA		Difference
	Δ	Incr./ Case 0	Δ	Incr./ Case 0	PLA / FLA
	(cm)	(%)	(cm)	(%)	(%)
Initial configuration: Case 0					
	16.0		14.4		+11.1
Effect of substitute thickness: Case 2					
D=0.25B	13.8	13.8	12.4	13.5	+11.3
D=0.5B	12.6	21.2	9.90	31.2	+27.3
D=0.75B	11.3	29.4	8.12	43.6	+39.2
D=1B	10.2	36.2	6.87	52.3	+48.5
D=1.5B	9.12	43.0	6.31	56.2	+44.5
Influence of modulus J: Case 1.1 – H=0.5B					
J=100kN/m	15.3	4.4	13.5	6.2	+13.3
J=500kN/m	14.3	10.6	11.9	17.4	+20.2
J=1000kN/m	13.6	15.0	11.3	21.5	+20.4
J=5000kN/m	12.1	24.4	10.3	28.5	+17.5

Effect of number of sheets i: Case 1.i – J=500kN/m					
Case1.1: H_{max}=0.25B	13.3	16.9	12.6	12.2	+5.6
Case1.2: H_{max}=0.5B	12.8	20.0	10.9	24.3	+17.4
Case1.3: H_{max}=0.75B	12.2	23.8	9.67	32.9	+26.2
Case1.4: H_{max}=1	12.1	24.4	9.18	36.2	+31.8
Effect of sheet position: Case 1.1 – J=500kN/m					
H=0.25B	14.0	12.5	12.6	12.5	+11.1
H=0.5B	14.3	10.6	11.9	17.4	+20.2
H=0.75B	14.3	10.6	11.9	17.4	+20.2
H=1B	14.3	10.6	11.9	17.4	+20.2
Effect of interface friction: Case 1.1 – J=500kN/m					
μ=0.6	14.3	10.6	11.9	17.4	+20.2
μ=0.8	13.8	13.8	11.9	17.4	+16.0
μ=1	13.5	15.6	11.9	17.4	+13.4

3.1.1 *Effect of substitute thickness*

The thickness of the substitute layer (case 2) has a major influence on the settlement reduction effect. With a constant load, settlement is observed to decrease as thickness increases (Tab. 5). This result appears to be logical, because a layer of deformable soil is replaced by a layer of stiffer material.

3.1.2 *Effect of reinforcement sheet position*

Reinforcement sheet position has little influence on the reduction of settlement in the foundation footing (Tab. 5). The positioning depths tested in our study are close to the surface (≤B). Greater positioning depths appear to be unrealistic.

3.1.3 *Influence of stiffness modulus*

The stiffness modulus of the reinforcement sheets (case 1.i) affects the reduction of settlement. The reduction rates increase as the reinforcement sheet modulus increases (Tab. 5). For an identical worked soil thickness (H=D=0.5 B), the reinforcement process (case 1) and substitution process (case 2) produce similar performance levels if the stiffness modulus is high (J=5000 kN/m).

3.1.4 *Effect of number of sheets*

By increasing the number of sheets (and, consequently, the depth H_{max} of the reinforced zone), calculated settlement can be reduced significantly. However, with the same H_{max} and D value, the substitution procedure is observed to be better (Tab. 5). The deeper the zone in which the soil in place is worked, the greater the difference between these two technical solutions. The differences tend to diminish at shallow depths (H=D≤0.5B); the results are even similar.

3.1.5 *Influence of interface friction*

The soil-geosynthetic interface characteristics have very little influence on the settlement values calculated. Replacing low interface frictions (μ = 0.6) by high interface frictions (μ = 1) has very little influence on the results obtained. The settlement values beneath the loading slab and the maximum tensile stress values in the geosynthetic sheet vary very little. This implies that the soil-geosynthetic interface remains in a general state of elasticity.

3.2 *Forces in the geosynthetics*

Even though the tensile stresses in the reinforcement sheets increase considerably with the stiffness modulus J, the sheets proved to be under fairly low stress (Figs. 9-10). The strain calculation corresponding to the maximum tensile stresses obtained (ε = T/J) confirm that the modulus J is inversely proportional to the maximum strain. (Tab. 6)

Table 6. Geotextile sheet strain

		Geosynthetic sheet strain ε = T/J (%)	
		PLA	FLA
Case 1.i	J = 100 kN/m	2.3%	2.5%
	J = 500 kN/m	1.3%	1.4%
	J = 1000 kN/m	0.9%	1.0%
	J = 5000 kN/m	0.4%	0.3%

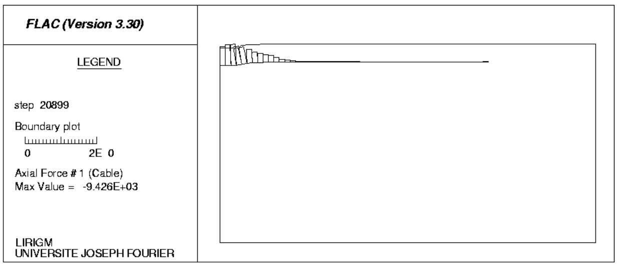

Figure 11: Distribution of tensile stresses in a geosynthetic sheet
J=1000kN/m - q=100kPa - FLA

The maximum tensile stresses in the reinforcement sheets are located beneath the local load footing (Fig. 11). With this type of localised stress, the reinforcement sheet was observed to be punched by a corner of the slab. The maximum tensile stresses are located along the boundary shear planes of the stiff corner. These results confirm the experimental results of (Binquet and Lee, 1975) and (Dubreucq, 1999).

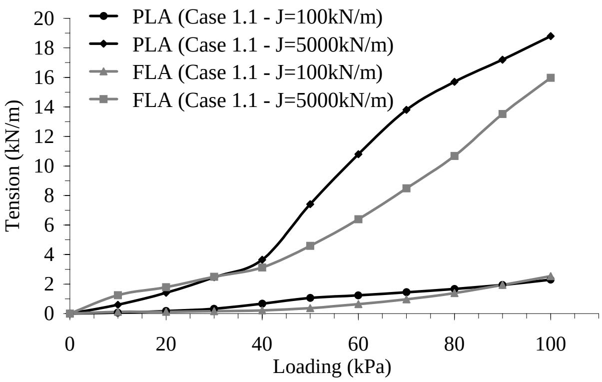

Figure 12: Reinforcement tensile stress - foundation loading curve
Comparison of FLA and PLA

The differences between the tensile stresses calculated on FLA and PLA are visible (Fig. 12). The differences seem to be amplified with the stiffness modulus J (kN/m). The differences between the numerical resolution methods and the definition differences in the mechanical parameters of the behaviour models of the soil-geosynthetic interface may explain these differences.

4 ASSESSMENT

The comparative study carried out using the two applications, PLA and FLA, was based on the reinforcement of the foundation soils placed under stress from localised "service" loads. This study demonstrated the following points.

The results obtained on settlements and tensile stresses in the reinforcement sheets differ depending on which code is used. The differences can sometimes be quite substantial. There is no explanation for these differences, especially since the behaviour models used are fairly similar.

The trends obtained on the reduction of settlement beneath the loading slab nevertheless appear to be similar.

The procedure for substituting a layer of compressible soil by a supporting soil leads to reductions over the entire loading range, while the sheet reinforcement procedure only gives a significant reduction in settlement above a certain load threshold.

The isolated effect of the variation in the angle of friction at the soil-geosynthetic interface is negligible.

The depth at which a single reinforcement sheet is placed has very little effect. However, a maximum value should not be exceeded.

For a given excavation depth H_{max} = D (H ≤ 0.5 B), the stiff soil substitution technique and the technique of reinforcing the initial soil using several geosynthetic sheets (J = 500 kN/m) perform fairly similarly. Beyond H = 0.5 B, the substitution procedure produces better results.

Reinforcement through a single sheet (H = 0.5 B) seems to be efficient provided that reinforcements with a high stiffness modulus are used.

In general, geosynthetic reinforcement sheets are not subject to very high stresses when under low operating loads. This confirms the work performed by Dubreucq (1999) who, on the basis of experiments using centrifuged scale models on reinforced soil, estimated that the role of reinforcement using flexible inclusions is to provide additional bearing capacity in the event of accidental loading, rather than to make a significant reduction in settlement under the operating load. The scale model study of single-layer reinforced clay by Mandal and Sah (1992) also showed that the increase in bearing capacity produced by the reinforcement can be quite significant, up to 35%.

5 CONCLUSION

The comparative study presented here shows the difficulties in using numerical methods for modelling reinforced soils. Nevertheless, the results show the advantage of the techniques for reinforcing foundation soils under localised loads and the influences of various parameters that can aid design.

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