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Pull-out behaviour of geosynthetic strip reinforcements in coarse fill - physical and analytical modelling

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ABSTRACT

Various types of reinforcement are used in Mechanically Stabilised Earth (MSE) structures; such as vertical or inclined walls, with different ranges of stiffness, from quasi non-extensible (steel) to much more extensible elements made of polymeric materials. Most of the knowledge regarding the internal behaviour of such structures was obtained from full scale and small scale instrumentation of steel-reinforced structures. Synthetic reinforcement, for example made of high-tenacity polyester yarns, are more extensible and lead to a more complex behaviour of the structure. In 2008, several laboratory pull-out tests of synthetic straps in fine sand were been carried out and analytical models of their behaviour have been proposed. The soil/reinforcement interaction parameters deduced from these tests will, without doubt, be different in other types of soil. This paper presents the results of pull-out tests carried out in a coarse fill and then modelled by an analytical method based on friction and strip stiffness models. Introduction of this model in calculation codes will allow one to take into account the phenomenon of soil/reinforcement interaction in structures reinforced using synthetic straps, before further optimising the design methods, based conservatively on the observation of steel-reinforced structures.

1. INTRODUCTION

The extensible reinforcement used in MSE applications like vertical or inclined walls, mostly GeoStraps and geogrids, lead to a different way of working of the structure compared to similar structures reinforced with steel elements, (strips or welded wire mesh). Adaptations in the construction procedure is just one of the ways in which the different behaviour is different. The classical justification method, used in the design of MSE structures, is known as the coherent gravity method, or the local equilibrium method. It was calibrated via measurements and modelling of steel-reinforced structures, in full scale as well as small scale tests. It is also used conservatively for the justification of the stability of the structures using polymeric reinforcements but does not allow the reproduction of the actual structure behaviour. It is thus necessary to adapt and improve these methods for better modelling and to acquire a better knowledge of the soil/synthetic reinforcement interaction.

The classical models of soil-reinforcement interaction are based on a linear strip stiffness model for the reinforcement and an elasto-plastic friction model (Cambefort 1964, Frank and Zhao 1982) for the soil/reinforcement interaction. To adapt these models for extensible reinforcement, some authors keep the same modelling (Schlosser et al. 1981, Segrestin et al. 1996) while others have modified the stiffness model (Bourdeau et al. 1990, Ling et al. 1992) or improved the friction model (Sobhi and Wu 1996, Gurung et al. 1999, Racana et al. 2003). So, to define the behaviour model of the inclusion, it is necessary to consider the reinforcement material itself, the fill material and the soil/reinforcement interaction.

Several pull-out tests have been carried out in fine sand (Abdelouhab et al 2008) in order to define the actual behaviour model of the synthetic straps (GeoStraps) used in reinforced soil structures. These tests, carried out in a metallic tank in controlled and instrumented conditions, were modelled by an analytical method combining friction and strip stiffness models. This study allowed us to qualify the behaviour of the GeoStraps and to deduce the interaction parameter at the soil reinforcement interface in fine sand. However, these parameters will be different for other types of soil more usually used in MSE structures (for example soils exhibiting cohesion, dilatancy, or those with a grading spread). The results of these tests cannot be extrapolated from those on fine sands.

This paper presents, in the first part, the pull-out tests of GeoStraps carried out in a coarse soil under diverse confinement stresses. In the second part, a modelling method based on friction and strip stiffness models is used. This method takes into account an elasto-plastic friction model with a modified strip stiffness model.

2. PULL OUT TESTS

2.1 Procedure

The tests were carried out on the GeoStraps placed in a coarse soil inside a test tank of $2m^3$ (Figure 1). The soil is set up by successive layers compacted with a metallic mass to obtain a density of $1.9\ g/cm^3$. In each test, a strip is carefully placed in the soil at the centre of the tank and an airbag is positioned between the top of the fill and the cover plate. This allows the application of a pressure and the simulation of vertical stresses applied at various depths in a real reinforced-soil structure.

The stress measured at the bottom of the tank is lower than that actually applied on the top. The stress reduction becomes more important as the pressure increases. This result is related to the friction increasing on the tank walls and arching which defers part of the load to the tank sides. Thus, horizontal stress will be more important when the vertical stress increases. Palmeira et al. 1989, show that the friction coefficient at the soil/reinforcement interface can be badly estimated because of soil friction on the internal tank walls if the real vertical stress is not measured at the level of the reinforcement. In our tests, two sensors allow control of the stresses in the tank. A pressure gauge permits measurement of the pressure applied in the airbag and a total pressure sensor installed at the bottom of the tank controls the actual vertical stress.

The displacements and the tensile force on the reinforcement are monitored by displacement sensors connected at different locations along the length and a load sensor at the head, respectively (Figure 2).

2.2 Reinforcement

The reinforcement comprises extensible geosynthetic strips, (GeoStraps), made of high-tenacity polyester yarns protected by a polyethylene sheath. The dimensions of these straps are: 50 mm wide and about 2 mm thick.
Two type of tests were carried out, pull-out of only one strap then two parallel synthetic straps, separated by 50mm. In MSE structures, the straps are parallel and set up two by two. These two types of tests allow the influence of the layout on the friction between the soil and the GeoStraps to be highlighted.

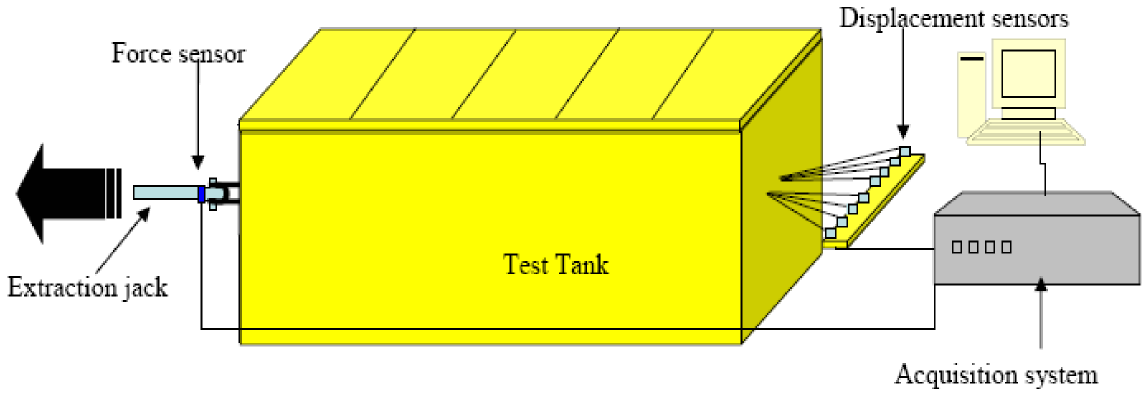


Figure 1. Pull-out test setup.

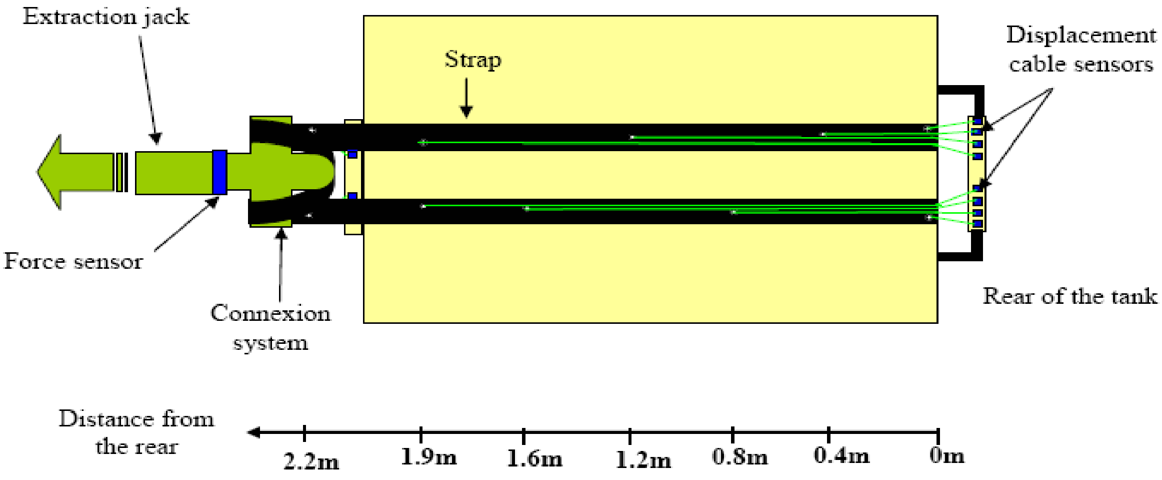


Figure 2. Geostrap and sensors positioning.

2.3 Studied Fill Material

The fill studied in these tests is a coarse soil according to the USCS classification procedure (United Soil Classification). This classification distinguishes coarse from fine soils, according to the percentage of the particles < 0,075mm in size. (Valle 2001).
Table 1 gives the principal characteristics of the coarse soil studied in the current tests, and the fine sand (Hostun RF) used in 2008. The parameters which differentiate these two soils are: the granulometry, the Hazen's uniformity coefficient (Cu), the cohesion and the unit weight.

Table 1. Caracteristics of coarse soil and Hostun'RF sand.

Characteristics	Coarse soil	Fine sand
Granulometry (mm)	0-31.5	0.16-0.63
Hazen's uniformity coefficient Cu	25	2
Angle of friction (°)	36	36
Cohesion (kPa)	61 (w = 8.2%)	0
Dilatancy (°)	-	8
Maximum dry unit weight (kN/m^3)	20.5 (w = 9.2%)	15.99
Minimal dry unit weight (kN/m^3)	19.1 (w = 10.2%)	13.24

w (%) : the water content of the soil.

3. TESTS RESULTS

Several tests were carried out on the GeoStraps under different levels of confinement stress and with the two layouts. 2 tests were carried out on only one Geostrap and 6 tests on two parallel GeoStraps.
Confinement stresses of 20 kPa, 45 kPa and 80 kPa were applied in the tests to simulate various depth levels.
The density values obtained by compaction in the tests varied between 1.9 and 2.0. g/cm^3

3.1 Friction at the soil/reinforcement interface for one and two Geostraps

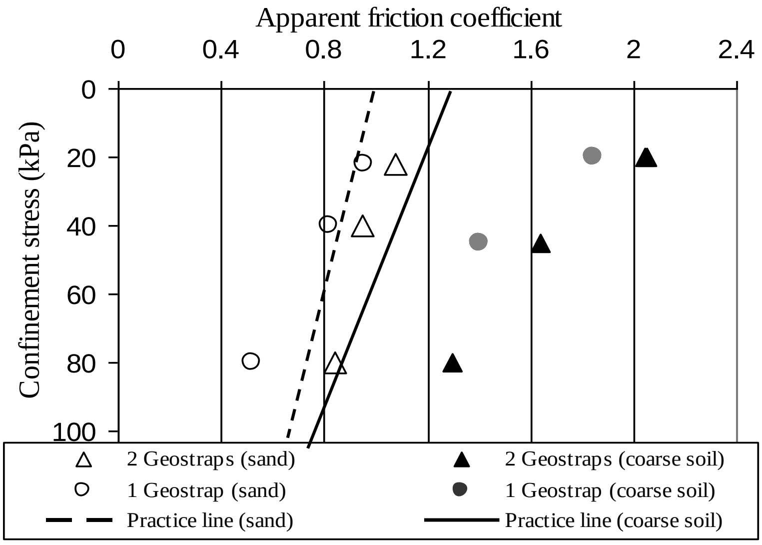
Two types of information are deduced from the pull-out test results (Figure 3):

- Friction coefficients are higher in the case of two parallel GeoStraps. This friction improvement is probably related to the arching effect and dilatancy of the soil which is created between the two straps and thus increases the stress area around inclusions

- In the case of two parallel GeoStraps, friction coefficients at the soil/reinforcement interface are slightly higher in the sand (approximately 10%) and significantly higher in the coarse soil (approximately 50%) than those usually used in practice in reinforced soil structure design. These results show that the friction parameters normally used generate a high safety margin in the reinforced soil structure design for coarse soils.

3.2 Friction at the soil/reinforcement interface in the sand and coarse soil

Comparison of the tests results obtained in the fine sand (Abdelouhab et al. 2008) with those obtained in the coarse soil, show that for the same confinement stress, different friction coefficients are obtained (Figure 3). This parameter is higher in coarse soil. The difference is related to the density (Schlosser 1981; Finlay 1984) and the Hazen's uniformity coefficient (Cu) which are higher in the coarse soil and lead to higher dilatancy and friction at the soil/reinforcement interface.
For the two types of soil (sand and coarse soil), the friction coefficients are higher in the case of two parallel GeoStraps when compared to the single strip arrangement. The improvement of this parameter is estimated between 10% and 15% for the two types of soil, except for a confinement stress of 80 kPa in the sand, where the improvement of the friction coefficient reaches 35%.



Practice line coresponds to the design value according to the standard NF P 94 270: 2009

Figure 3. Influence of the confinement and the GeoStraps layout on the friction coefficient.

3.3 GeoStraps behaviour under different confinement stresses

The results obtained with two parallel straps in coarse soil show that the behaviour of this reinforcement is highly influenced by the confinement stress and the displacement at the head (Figures 4 and 5).

Figure 4 shows that, under low confinement (20 kPa) the GeoStrap behaviour at the head is stiff followed by linear-behaviour up to 50mm displacement, after which it fails (elasto-plastic), for a confinement stress of (80 kPa) on the other hand, Figure 5 shows that displacements along the GeoStrap are gradually mobilised from the head to the rear. The mobilised length is small for small head displacements and high confinements.

Comparison of the curves obtained in the sand (Abdelouhab et al. 2008) and the coarse soil (Figures 6 and 7), allows deducing that in the two cases, for the same tensile force, the behaviour of the GeoStraps is similar. However, to obtain the same tensile force, the confinement in the sand must be two times higher.

In conclusion, the behaviour of the GeoStrap is influenced by the shear strength which varies with the confinement stress, the soil type and the reinforcement layout.

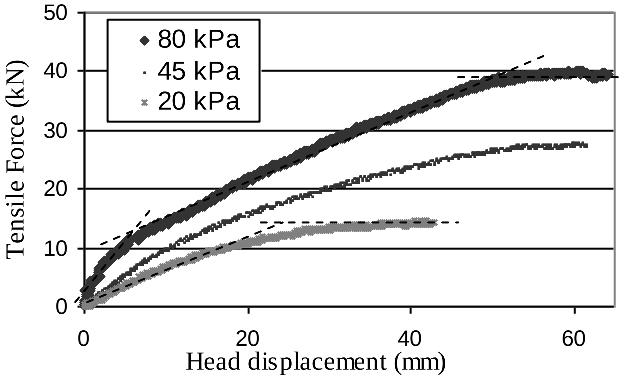


Figure 4. GeoStraps behaviour at the head under three different confinements stresses (two parallel GeoStraps).

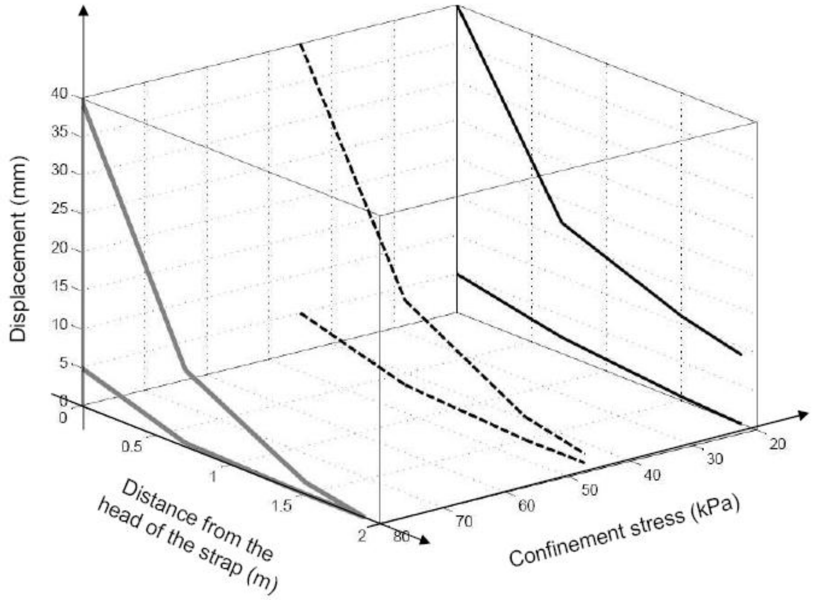
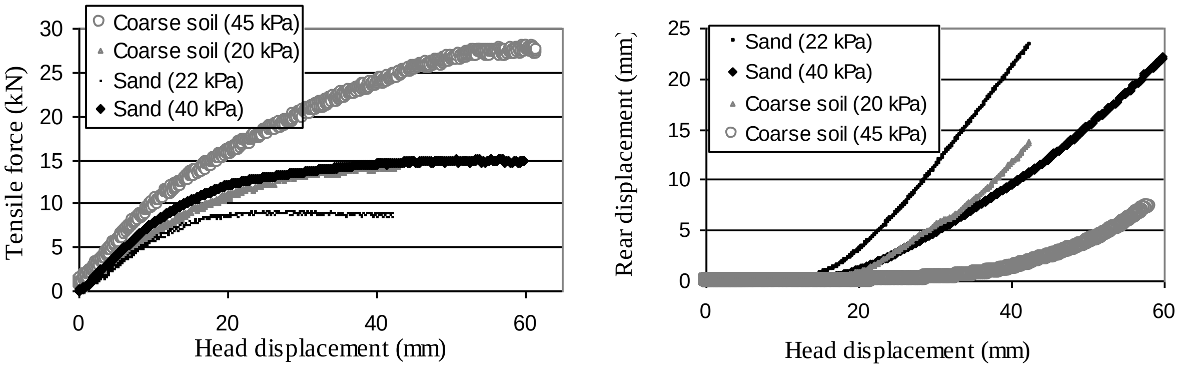


Figure 5. Progressive mobilisation of the GeoStrap versus the displacement at the head and the confinement stress (two GeoStraps).



a. evolution of the tensile force at the head

b. delayed mobilisation at the rear

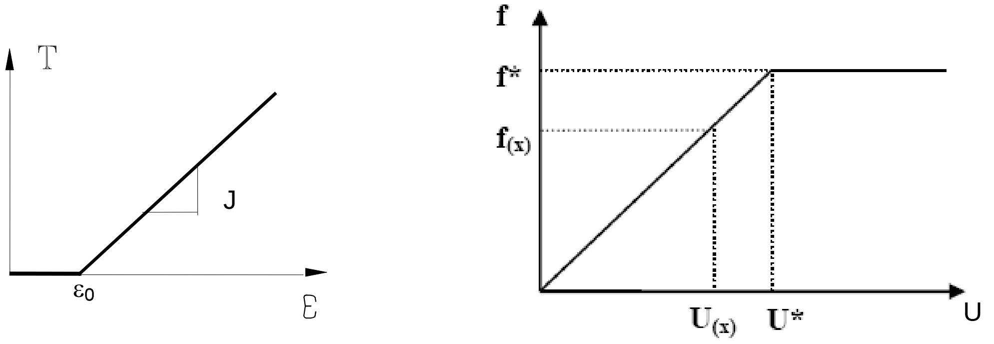
Figure 6. GeoStraps behaviour in fine sand and coarse soil (two GeoStraps)

4. ANALYTICAL MODELLING

4.1 The analytical model

The experimental results were modelled using an analytical method which combines a modified strip stiffness model (Tension “T” versus strain “ε" Figure 7a.) with an elasto-plastic friction model (friction coefficient f versus relative soil/reinforcement displacement U, Figure 7b., Segrestin et al. 1996). The strip stiffness model is modified to permit an initial threshold strain ε_0 at the origin. This parameter ε_0 allows modelling of the delayed extension mechanism (Bourdeau et al 1990).

Parameters in this friction model (f*: maximum friction coefficient and U*: relative soil/reinforcement displacement corresponding to the total mobilisation) and the strip stiffness model (ε_0: initial threshold strain and J: tensile stiffness) allows characterise action of the behaviour model for GeoStraps



a. Strip stiffness model

b. Local friction model

Figure 7. Behaviour models

The principle of this analytical method consists in evaluating the equilibrium forces in each infinitesimal strap section by combining the modified strip stiffness model with the elasto-plastic local friction model. This combination leads to simple differential equations which are solved analytically. Considering three mobilisation stages of the strip (Gourc 1982, Bourdeau 1990, Segrestin et al. 1996), the solution of the differential equations makes it possible at each stage to calculate tensile force and displacements at each point x along the reinforcement.

4.2 Modelling of the experimental results

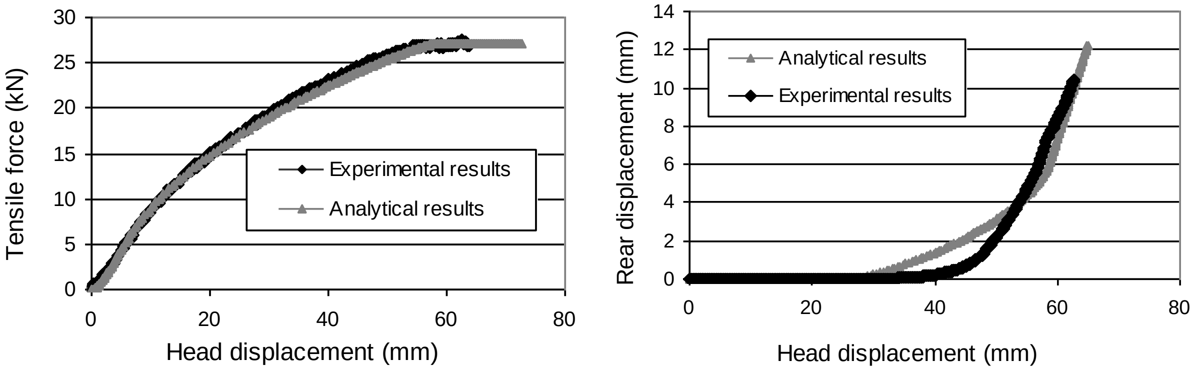
The test modelled in this analytic study is that carried out under a confinement stress of 45 kPa. The parameters f* and J are determined from experimental tests. U*and ε_0 are deduced by an optimisation proces (Table 2). The parameters obtained for the anchorage models are those which lead to the smallest error between the model result and experimental results. The criterion used to estimate this error (E) is:

$$E = \sqrt{\sum (u_{i\,calculated} - u_{i\,measured})^2}$$

Table 2. Parameters of the analytical model

Parameters	Vertical stress (kPa)	Strip length (m)	Strip width (m)	J (kN)	U* (m)	ε_0	f*
Values	45	1,9	(0,05) x 2	500	0.006	0.003	1.6

The analytical method allows, from the tensile force data in the experimental results, good predictions of the head displacements. The theoretical curves correlate well with the experimental curves (Figure 8a.). For the rear displacement, this method, allows us to simulate a small delay of mobilisation at the strap end. However, a small discrepancy between the theoretical and the experimental curves is still observed (Figure 8b.). This discrepancy is due to the fact that this method adopts an elasto-plastic behaviour of the friction and strip stiffness models. The experimental results show that the synthetic reinforcement behaviour is more complex. Using a new anchorage models will allow better simulation of GeoStrap behaviour in coarse materials.



a. evolution of the tensile force at the head

b. delayed mobilisation at the rear

Figure. 8. Confrontation of the experimental and modelling results (two GeoStraps - confinement stress = 45 kPa)

5. CONCLUSIONS

Pull-out tests highlighted the influence of soil type, layout and confinement stress on the synthetic strip (GeoStraps) behaviour.

Comparison of results obtained in the coarse soil and sand shows that the friction at the soil/reinforcement interface is higher in the coarse soil. This difference is related to the high density and Hazen’s uniformity coefficient (Cu) in the coarse soil which leads to a high dilatancy and friction at the soil/reinforcement interface.

For the two types of soil (fine sand and coarse soil), the use of two parallel, closely spaced, GeoStraps as used currently in reinforced soil structures, gives higher friction coefficients than in the case of one GeoStrap. This friction improvement is probably related to an arching effect or to dilatancy of the soil between the two straps and thus increases the stress area around inclusions

Comparison of the results obtained in the sand and the coarse soil shows that, for the same confinement stress, the behaviour of the GeoStraps is different because of the high friction in the coarse soil. Indeed, the high friction at the soil/reinforcement interface leads to a high tensile force and then to a high elongation of the GeoStrap. However, for the same tensile force, the behaviour of the GeoStraps is similar for the two type of soil.

The analytical method presented in this article allows modelling, of the head and local displacements of the GeoStrap in pull-out tests carried out under a confinement stress of 45 kPa. The initial threshold strain $\varepsilon_{0,}$ taken into account in the strip stiffness model, allows good simulation of the delayed extension mechanism of the GeoStrap. However, this method is developed from a bilinear friction model and a perfectly elastic strip stiffness model. The experimental curves show that the behaviour of GeoStraps is more complex. This leads to some discrepancies between the experimental and the analytical results. The use of a more realistic friction model (tri-linear model such as Frank and Zhao 1982 or more complex) and strip stiffness model (non linear elastic model) seems to be necessary for better modelling. The new models should be implemented in numerical codes and will permit a better understanding of the behaviour and inherent safety of reinforced soil structures.

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