Two-Dimensional Numerical Modelling ~~O~~of Earth Structures Reinforced By Geosynthetic ~~A~~and Metallic Strips

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ABSTRACT
The reinforcements used in reinforced soil walls are usually ribbed steel strips, but in aggressive environments, geosynthetic straps are preferred due to their non-corrodible properties. However, the synthetic reinforcement presents a complex behaviour due to their extensibility and leads, according to their stiffness, to different behaviours of the structures. An experimental study, which concerns laboratory pull-out tests, enabled us to define and to compare the interaction parameters at the soil/reinforcement interface of the synthetic and metallic strips. The use of these parameters in the numerical calculation codes allows to improve the modelling and the inherent safety of such reinforced soil structures. This paper presents a parametric study of reinforced soil wall by two-dimensional finite difference modelling. It highlights the importance of each parameter and then allows the authors to provide a better structure design.

1. INTRODUCTION

Because of their significant development, the need for looking further into the comprehension of the Mechanically Stabilised Earth structures behaviour seems to be necessary. It is essential to study the influence of some modifications in the geometry of these walls and the new reinforcement types which are increasingly developed. Since 2004, a new system is used in this field by Terre Armée Internationale. It consists of setting up horizontal synthetic straps connected directly to the concrete facing of the wall without metallic intermediate elements. This new type of layout induces a new behaviour and new parameters of ground/reinforcement interaction. To deduce these new parameters, experimental and analytical studies were carried out (Abdelouhab et al. 2008). However, a numerical modelling seems to be necessary to better understand the behaviour of reinforced soil structures using the new system.
The reinforced soil structures constitute, by the geometry of the reinforcements (metallic strip or geosynthetic straps) and their installation by respecting horizontal and vertical spaces, a three-dimensional problem. However, the three-dimensional modelling is time consuming in terms of calculation time and creation of the model. That is why the modelling of this kind of structures was commonly simplified to a two-dimensional problem which, nevertheless, allows taking into account of several parameters. Bastick (1983) has carried out a bi-dimensional numerical modelling to study the influence of the metallic reinforcement length in reinforced soil walls. This study showed that walls with short reinforcements present a behaviour very close to the ordinary reinforced soil walls (length of the reinforcements is equal to 0.7 times the height of the wall). These results have been confirmed by Sellali-Haraigue (1999) from a three-dimensional modelling in finite elements. Bergado and Teerawattanasuk (2007) have compared the results of two-dimensional and three-dimensional numerical modelling. They concluded that good results can be obtained from the two methods if the geometry effect is considered.
This paper present two numerical modelling carried out by a two-dimensional explicit finite difference program:

- the first modelling is carried out on soil walls reinforced by synthetic reinforcements using reference parameters resulting from experimental tests, standards and real characteristics of the structural elements. Variation of three parameters (elastic modulus of the reinforcements; strip interface shear stiffness and initial apparent friction coefficient at the soil/ strip interface) allows to study their influence on the stability and the behaviour of these structures.
- the second modelling, compare the deformations, the behaviour and the failure mode of two reinforced soil walls. A wall reinforced by synthetic reinforcement and a wall reinforced by metallic strips.

2. TWO-DIMENSIONAL MODELLING

Modelling was made by a two-dimensional calculation program developed by Itasca. It is based on explicit finite difference and adapted to the geotechnical problems.

2.1 Presentation of the numerical model

The considered wall is of 6m height. It is made up, horizontally and vertically, of 4 superimposed panels and reinforced by 8 levels of reinforcements of 4 meters length (Figure 1).
Cruciform geometry of the panels (Figure 2a.), leads to a complex geometry of the wall. Simplify this three-dimensional geometry to a two-dimensional numerical model, it is necessary to carry out some simplifications. Two panels are considered as width of calculation and 4 reinforcing strips are set up for each panel. The panels are modelled like rectangular plates of 1,5m by 1,5m. The reinforcements of the two columns are then aligned on the same line of 4 reinforcements for a width of calculation of 3meters (Figure 2b.). The simplification of the geometry makes it possible to take into account a two-dimensional column of panels with continuous reinforcements. The characteristics of these reinforcements are calculated as being the ratio of characteristics for the width of considered ground (Figure 2c.).

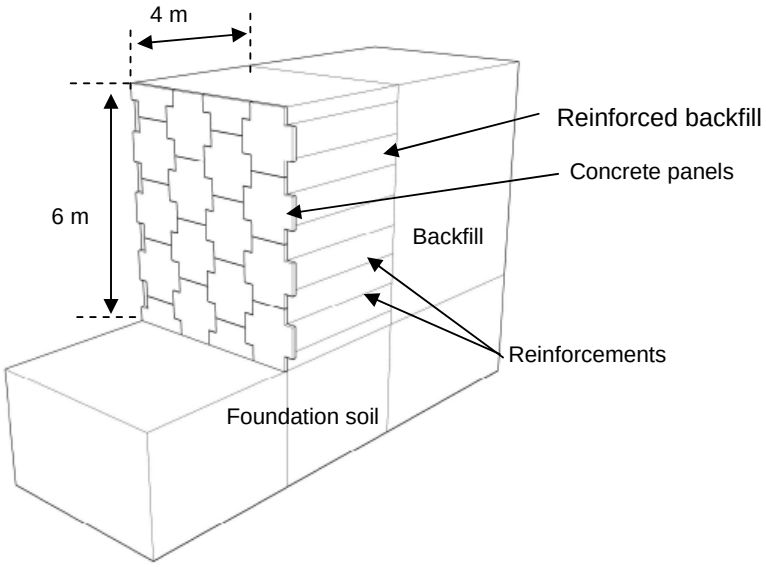
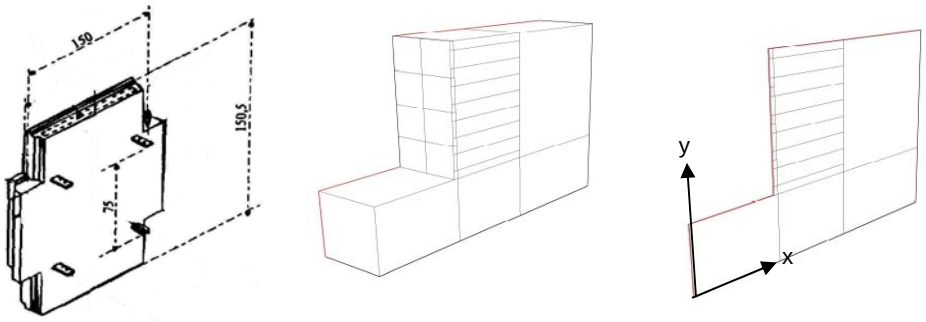


Figure 1 : Geometry of the modelled wall



a. Cruciform panel. b. Panels simplification. c. two-dimensional model

Figure 2. Representation of a three-dimensional structure by a two-dimensional model

The boundary conditions imposed on the model are:
- horizontal displacements blocked on the side limits.
- horizontal and vertical displacements blocked at the bottom of the model.

In order to model with accuracy the constructions stages of real structure, the modelling is carried out in several phases with equilibrium for each phase.

2.2 Elements and reference parameters of the numerical model

The elements and reference parameters used in the modelling are described below. They result from experimental tests, standards and real characteristics of the structural elements.

2.2.1 Soils

The constitutive models and parameters retained for the soils as reference are presented in table 1.

Table 1: Soils characteristics

	Reinforced backfill	Backfill	Foundation soil
Constitutive model	Mohr Coulomb	Mohr Coulomb	Elastic linear
Young modulus (MPa)	60	30	50
Poisson's ratio	0.3	0.3	0.3
Density (Kg/m^3)	2000	1800	2000
Friction angle (°)	36	30	36
Dilatancy (°)	6	0	6
Cohesion (KPa)	0	0	10

2.2.2 Concrete panels and interfaces

The panels are modelled by *Beam* elements. They are used to represent a structural member, including effects of bending resistance and limited bending moments. Tensile and compressive yield strength limits can also be specified. Interface elements can be attached on both sides of beam elements in order to simulate the frictional interaction of a foundation wall with a soil or rock.

Table 2: Concrete panels and interfaces characteristics

	Concrete	Panel/soil interface
Constitutive model	Elastic linear	Coulomb sliding
Young modulus (MPa)	15000	-
Normal stiffness (MPa)	-	1000
Shear stiffness (MPa)	-	1000
Poisson's ratio	0.2	-
Density (Kg/m^3)	2500	-
Friction angle (°)	36	24
Dilatancy (°)	6	0
Cohesion (KPa)	1 E17	0

2.2.3 Reinforcements

Two types of reinforcement, used in the reinforced soil structures, have been modelled:
- Synthetic straps (GeoStraps) containing high tenacity polyester yarns protected by polyethylene sheath;
- Metallic strips made of galvanised and ribbed steel.

The reinforcement parameters are summarized in table 3. These parameters refer to a GeoStrap and a metallic strip.
The second column of the table 3, indicates the applied parameters variation in this parametric study of the synthetic reinforcements.
The reinforcements are modelled by *Strip* elements, specifically designed to simulate the behaviour of thin, flat reinforcing strips in reinforced soil structures. The strip element can yield in compression and tension. They provide shear resistance but cannot sustain bending moments. The shear behaviour at the strip/soil interface is defined by a nonlinear shear failure envelope that varies as a function of confining pressure.

Table 3: Reinforcements characteristics

	Synthetic strap	Variable	Metallic strip
Elastic modulus of the strip (GPa)	2.5	1 – 5	210
Width (m)	0.1	-	0.05
Thickness (m)	0.0030	-	0.0040
Strip tensile yield-force limit (KN)	50	-	100
Strip compressive yield-force limit (N)	0.0	-	100
Strip/interface shear stiffness (kN/m/m)	220	100 – 500	1600
Initial apparent friction coefficient at the soil/ strip interface “f_0”	1.2	1 – 1.6	1.5
Minimum apparent friction coefficient at the soil/ strip interface “f_1”	0.6	-	0.727
Tensile failure strain limit of strip.(MPa)	0.12	-	0.1

3. PARAMETRIC STUDY

A first modelling carried out on soil walls reinforced by synthetic reinforcements using reference parameters allowed to study the influence of three parameters (elastic modulus of the reinforcements; strip interface shear stiffness and initial apparent friction coefficient at the soil/ strip interface) on the behaviour of the walls. Two criterions are used, deformation (serviceability limit state “SLS”) and the stability (ultimate limit state “ULS”).

3.1 Studied parameters

3.1.1 Friction coefficient at soil/reinforcement interface

The actual friction coefficient at soil/inclusion interface f is expressed:

$$f = \frac{\tau_{\max}}{\sigma_{v0} + \Delta\sigma_v} \qquad [1]$$

- τ_{max} is the maximum shear stresses exerted by reinforcements;
- σ_{v0} the initial vertical stress applied on the inclusion;
- $\Delta\sigma_v$ is the increase of vertical stress due to the phenomenon of the constrained dilatancy.

For a compacted granular soil, the soil/inclusion shearing will lead to volumetric dilation that will be constrained by the surrounding soil and causes locally increasing of the vertical stress. To take into account this three-dimensional phenomenon in the two-dimensional design methods. Schlosser and Elias 1978, defined an apparent friction coefficient f*:

$$f^* = \frac{\tau_{\max}}{\sigma_{v0}} \qquad [2]$$

The increase in the friction coefficient due to the constrained dilatancy effect will only be significant at a low vertical stress, but will be negligible when the volume of soil can not increase under a high vertical

stress. This coefficient decreases as the confinement stress increase. It varies between f_0 and f_1 from the surface of the soil mass to 6 m depth (Figure 3, NF P 94 220).

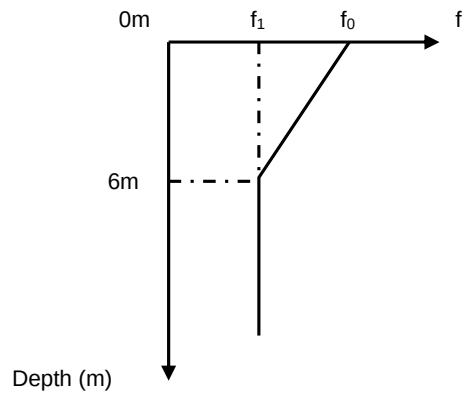


Figure 3. Variation of the friction coefficient in the soil mass.

3.1.2 Elastic modulus of the synthetic reinforcement

The elastic modulus (E) of the strip is defined by the tensile stiffness (J) of the synthetic strap per the cross-sectional area.

$$E = \frac{J}{S} \qquad [3]$$

This parameter could present a high influence on the deformations and the flexibility of the reinforced soil structures.

3.1.3 Shear stiffness at the soil strep interface

The shear stiffness at the soil/strip interface (K) is defined maximum shear force on the strip (F_{max}), strip length (L) and relative soil/strip displacement at the total mobilisation of the strip (U*) in pull out tests for one meter width of wall.

$$K = \frac{F_{\max}/L}{U^*} \qquad [4]$$

The shear behavior of the strip/soil interface is defined, in reality, by a nonlinear shear failure envelope that varies as a function of confining pressure. So, the value of K varies as a nonlinear function from the top to bottom of the wall. However, the numerical software used for the calculation in this study does not allow taking into account the variation for this parameter. An average value is taken on all the height of the wall.

3.2 Used criterions

The deformation (SLS)
The deformation of the wall is calculated from the absolute maximal displacement lUl measured on the element presenting the highest displacements:

$$|U| = [(Ux)^2 + (Uy)^2]^{0,5} \qquad [5]$$

The stability (ULS)
Analysis of the walls stability has been carried out by calculation of Factor of safety (Fs). This factor was calculated by reducing the strength parameters of the soil (Phi-c reduction). In the Phi-c reduction approach the strength parameters of the soil (friction and cohesion) are successively reduced until failure of the structure occurs. At this point the factor of safety is given by:

$$Fs = \frac{initial\ strength}{strength\ at\ failure} \qquad [6]$$

3.3 Results

The results of the deformations and the factor of safety obtained by the first calculation using reference parameters of the synthetic reinforcement are reported on table 4.

Table 4. Reference calculation results on synthetic straps.

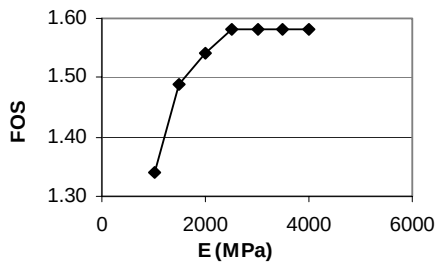
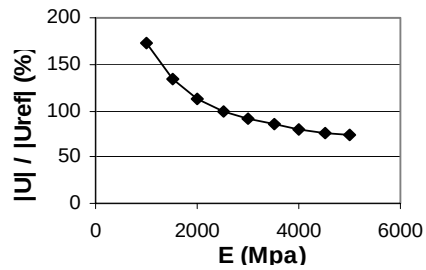
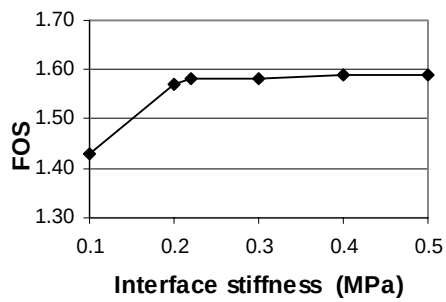
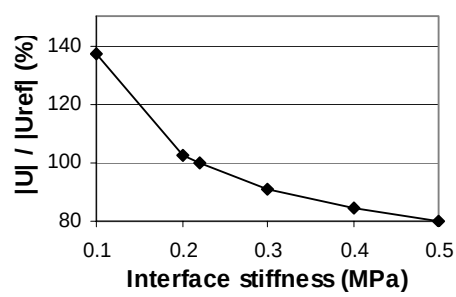
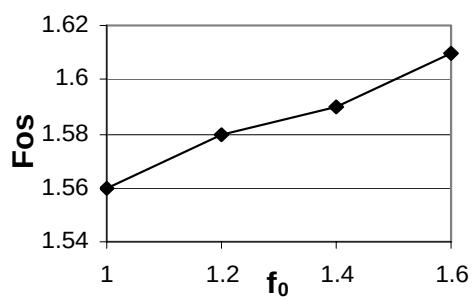
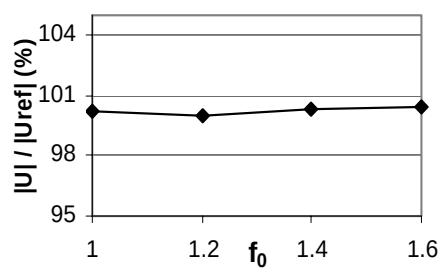
Fs	|U| (mm)	Ux (mm)	Uy (mm)
1,58	106,6	-75,17	-75,6

The results of the parametric study analysed in table 5 are reported in graphics (Table 6)

Table 5. Analysis of the parametric study results.

	Influence on the Factor of safety	**Influence on the deformations**
Strap elastic modulus	The stability of the wall increases as the elastic modulus increases up to a value of 1.58 for a modulus of 2500 MPa. After this threshold, the increase of the modulus seems to have no influence on the stability of the wall (Table 6a.).	The variation of the modulus has a high influence on the deformations of the wall. When the modulus decreases, the deformations of the wall increase in the two directions; horizontal and vertical (Table 6b). Settlement and displacements along the wall facing increase because of the elongation of the reinforcements.
Shear stiffness at the soil/strap interface	The variation of shear stiffness seems to have an important influence on the stability of the wall in particular when these values are lower than 0.2 MPa. (Table 6c).	The shear stiffness have also a high influence on the deformations. On the horizontal and vertical displacements (Table 6d).
Initial apparent friction coefficient f_0	The variation of initial apparent friction coefficient has a low influence on the stability of the wall. (Table 6e and 6f). However, it is important to indicate that the smallest coefficient used in the calculation (f_0 = 1) is not very different than that recommended by standards (f_0 = [1 - 1.3]).	

Table 6. influence of strip elastic modulus; soil/strip interface shear stiffness and initial apparent friction coefficient at the soil/ strip interface on the security, displacement and deformation of the wall.

Ultimate Limit State "ULS"	Serviceability Limit State "SLS"
 a. Factor of safety versus strip elastic modulus	 b. Deformation versus elastic modulus
 c. Factor of safety versus strap/interface shear stiffness	 d. Deformation versus strap/interface shear stiffness
 e. Factor of safety versus initial apparent friction coefficient	 f. Deformation versus initial apparent friction coefficient

3.4 Influencing parameters

In order to highlight the parameters having a large influence on the stability and the deformation of the wall, we have created a scale by discretising the results on several categories. The unit of each category is represented by "+ or 0". The categories used are specified in table 7.

The analysis of table 8 makes it possible to deduce that the four parameters have an influence on the calculated Fs and deformation of the wall. This influence is important for elastic modulus of the straps and shear stiffness at the soil/straps interface. Concerning the strip/interface shear stiffness, the smallest coefficient used in the calculation (f_0 = 1) is not very different than that recommended by standards (f_0 = [1 - 1.3]), so the variation made on this parameter have a low influence on the wall behaviour.

Table 7. Definition of the different categories

Scale	Fs	|U|
0	0-1,25	0-25%
+	1,25-2,5	25-50%
++	2,5-5	50-100%
+++	>5	>100%

Table 8. Recapitulation of the parameters influence on the synthetic straps

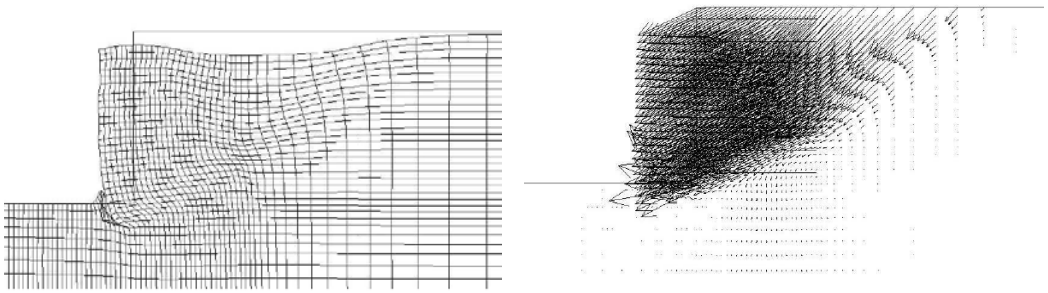
	Fs	|U|
Elastic Modulus	+	++
Soil/strap interface shear stiffness	+	++
Initial apparent friction coefficient f_0	0	0

4. COMPARISON OF SYNTHETIC AND METALLIC REINFORCEMENT

The results obtained for the reference parameters with the GeoStraps and metallic strips are compared. The deformations (maximum displacement), stability and failure mode of the walls are analysed. The results are discussed in the table 9. The Figures 4 and 5 present the deformation and the vector velocities of the elements at the failure of the wall.

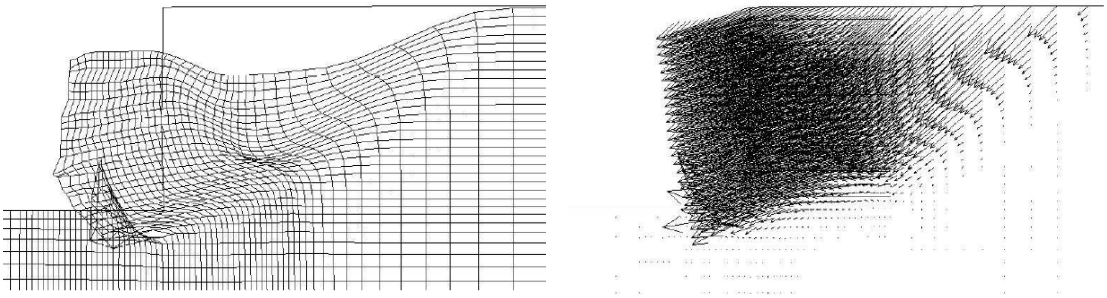
Table 9. Analysis of the behaviour of the walls reinforced by synthetic and metallic strips.

Parameter	Observation
Deformations	The principal differences between the synthetic and metallic reinforcement is their elongation when they are subjected to a tensile load. The displacements observed for synthetic straps are 7 times higher than those observed on the metallic strip. These high displacements are observed in the horizontal and vertical directions. The synthetic straps, because of their flexibility, present a low sustain of the transversal stresses. Reduction of settlement in the reinforced soil is lower compared to the metallic reinforcement. Horizontal displacements are also much higher in the case of the synthetic reinforcements (approximately 10 times higher). So the facing wall displacement is much higher.
Stability	Concerning the stability of the wall, the calculation of the Fs gives a higher stability for the GeoStraps than for the metallic reinforcements Indeed, the use of the GeoStraps two times larger (width = 100mm) than metallic strips (width = 50 mm) increases in the capacity of adherence and compensate the effect of their extensibility.
Failure mode	The failures modes seem relatively similar. The soil mass is not coherent at the failure for the two cases. The failure is related to the adherence default between the soil and the reinforcement which leads to the sliding of the unstable part of the ground (Figures 4a and 5a). However the synthetic reinforcements allow higher deformations of the wall before the failure. Figures 4b and 5b show the vector velocities of the elements at the failure. Their direction is the same for the GeoStraps metallic strips.



a. Deformation (the grid is magnified by a factor 30) b. velocity vectors

Figure 4. Failure mode of the wall reinforced by metallic strips.



a. Deformation (the grid is magnified by a factor 5) b. velocity vectors

Figure 5. Failure mode of the wall reinforced by synthetic straps.

5. CONCLUSION

This two-dimensional modelling based on explicit finite difference programme made it possible to study the influence of many parameters on the wall behaviour.
The study of the synthetic reinforcement parameters showed the importance of the elastic modulus and the shear stiffness at soil/reinforcement and their influence on the deformations and the stability of the reinforced soil wall. For the initial apparent friction coefficient, the smallest value used in the calculation is not very different than that recommended by standards, this leads to observe a low influence of this parameter on the stability of the wall.
Comparison of modelling results shows that the use of the synthetic straps two times larger than metallic strips increases in the capacity of adherence. The extensibility of the synthetic straps leads to a higher deformation but provide a higher stability.
To validate the numerical model parameters, comparison with experimental results seems to be necessary.
A parametric study using three-dimensional modelling would be more realistic. It will permit to take into account the three-dimensional phenomenon of the friction coefficient and the interfaces around the reinforcement strips.

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