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CONSIDERATIONS ON THE NUMERICAL MODELING OF NAILED SOIL EXCAVATIONS

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Abstract:

Soil reinforcement techniques making use of passive inclusions such as soil nailing have been steadily growing in Brazil. A research on the influence of geometrical and geotechnical parameters on the stresses and strains developed in nailed excavations has been carried out. The numerical study herein presented made use of FLAC (Fast Lagrangian Analysis of Continua), which is a computational program based on the finite difference method, largely used in geotechnical practice. This paper describes the simulation of nailed soil excavations and presents some relevant considerations regarding the use of FLAC.

1. SOIL NAILING TECHNIQUE

Soil nailing is a very efficient technique for reinforcement of natural or excavated soil slopes when stability conditions are considered unsatisfactory. Nailing is done through inclusions of semi-rigid passive elements (nails), which are resistant to tension, shear and bending loads. The reinforcement elements are installed in a horizontal or sub-horizontal direction in the soil mass. Their function is to minimize displacements of the soil mass by adding internal resistant forces. Progressive decompression of soil mass caused by staged excavation generates lateral displacements and therefore induces the internal forces in the nails.

Figure 1 illustrates the soil nailing technique, with its successive excavation stages and nail insertion. Working from top to bottom of slope, the soil mass is gradually reinforced during construction. If the material at the excavated region is stable, the nails are immediately installed. If the excavated material appears to be unstable, a thin layer of shotcrete may be applied for avoiding undesirable movements of the soil excavation face. In pre-existing cuts, nailing may also be performed from bottom to top, if this is more convenient.

During successive excavations, the slope is subjected to lateral decompression. At end of construction, maximum displacements in both horizontal and vertical directions occur at the top. For soil nailing, horizontal displacements may be up to 0,5%H, where “H” is the total excavation depth (Shen et al., 1981; Juran e Elias, 1987). The most important factors controlling these displacements are: construction sequence, excavation depth, nail spacing, nail length and nail inclination angle (Springer et al., 2001; Gerscovich et al., 2002; Lima, 2002).

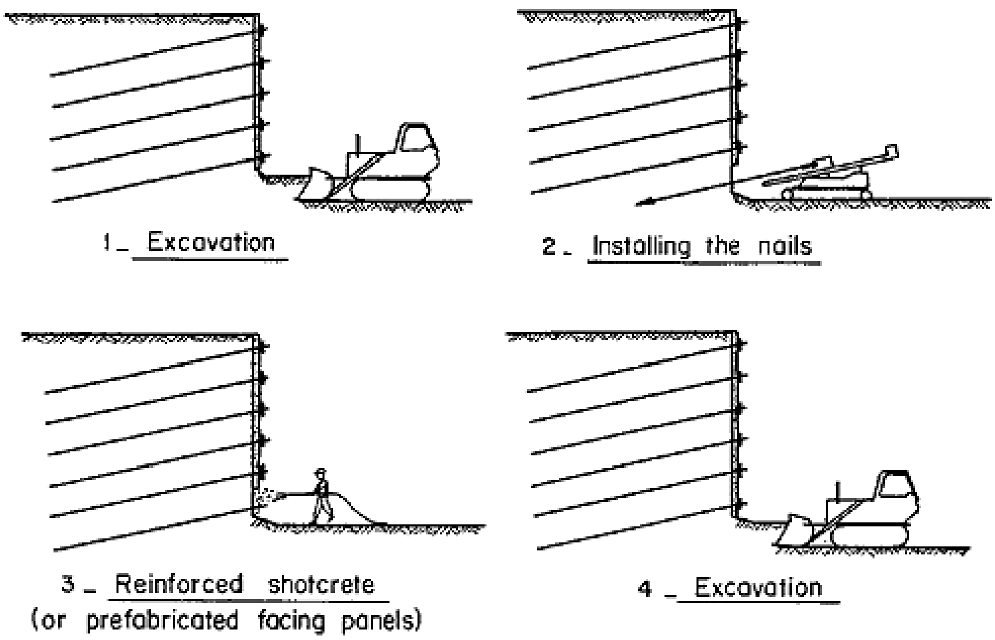


Figure 1 – Construction cycle for nailed soil wall (Clouterre, 1991).

There is no standard method for designing soil-nailing structures. Several papers have been reported in the literature emphasizing different failure mechanisms (Shen et al., 1981; Stocker et al., 1979; Juran et al., 1988; Bridle, 1989; Anthoine, 1990). Limit equilibrium is usually considered, neglecting deformations of the reinforced mass and the load distribution in the nails.

Numerical modeling is therefore an attractive tool for simulating the sequential construction steps of reinforced excavations and for estimating the nail's loads and the soil's displacements.

This paper presents several considerations related to the numerical simulation of nailed soil works using the FLAC computational program. The main focus is to report some aspects to be considered by designers and FLAC users when modeling nailed excavations.

2. BASIC CHARACTERISTIC OF FLAC

FLAC (Fast Lagrangian Analysis of Continua) is a 2D computational program based on the finite difference method for simulating the stress-strain behaviour of soil and rock structures. Nine different constitutive models are made available for this simulation. The FLAC's iterative computation cycle is illustrated in Figure 2.

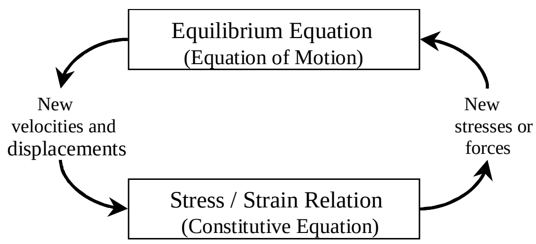


Figure 2 – Basic explicit calculation cycle (Itasca, 1996).

First, the equilibrium equations are considered for obtaining the displacements and velocities. Strain rates are then computed and considered in the stress-strain (constitutive) equations. As a result, the new state of stresses and forces is obtained. A new cycle may be then initiated, considering again the equilibrium equations (Itasca, 1996).

Geotechnical engineering works usually consist of a sequence of operations which may be easily simulated with FLAC by a series of entry commands. The results of each construction stage may be stored in an independent file, making the final analysis easier. Details may be obtained elsewhere (Itasca,1996; Springer, 2001; Lima, 2002).

FLAC uses 1D elements for representing the nails, which are resistant to tension and present no resistance to bending. The strength at the soil-nail contact is represented by the relation between F_s^{max} / L (axial force normalized by the nail length) and the normal load (Figure 3a), as shown in Equation 1.

$$\frac{F_s^{max}}{L} = s_{bond} + p' \times \ perimeter \times \ \tan(S_{friction}) \tag{1}$$

In this equation, S_{bond} represents the adhesion; p' is the effective mean normal stress; and $S_{friction}$ is the friction parameter at the soil-nail contact.

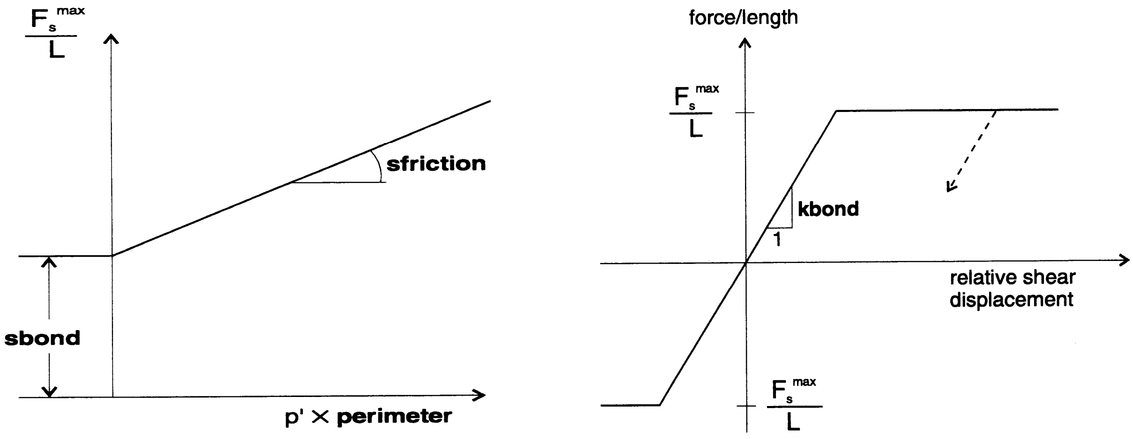
The shearing behavior of the cement grout is represented by the stifness parameter k_{bond} , as a function of the soil-nail relative displacements, as shown in Figure 3b.

3. CONSIDERATIONS ON THE FLAC PROGRAM

Strain analysis of nailed soil slopes have been carried out with FLAC. Output results (initial stresses, displacements and axial nail loads) are shown to be strongly dependent on input data, such as geometry of element mesh, boundary conditions, constitutive model, soil parameters, nail parameters and number of iterations (Lima, 2002).

3.1 Specification of “in situ” stresses

When modelling a physical problem, several ways are made available in FLAC for indicating if the mesh is already consolidated, or, in other words, if “in situ” stresses are applied and equilibrium conditions are achieved. The best way seems to be to monitor the velocity vectors (“xvel, yvel”) while the number of iterations (steps) increases. The mesh may be considered fully consolidated when the magnitude of these vectors are noted to stabilise at a value very close to zero, which characterises a condition of static equilibrium.



a) Grout shear strength criterion. b) Grout shear force *vs* displacement.

Figure 3 – Grout material behavior for nail elements.

For evaluating the number of iterations needed to equilibrium, similar simulations were repeated with different maximum number of iterations. Figure 4 shows the geometry considered in this study. The velocity vectors were monitored at points A, B e C.

The results shown in Figures 5 and 6 indicate that equilibrium may be considered achieved for a minimum of 400 iterations. At this value, velocity vectors are null. It should be noted that a different number of iterations may be required for other conditions of mesh geometry and material properties.

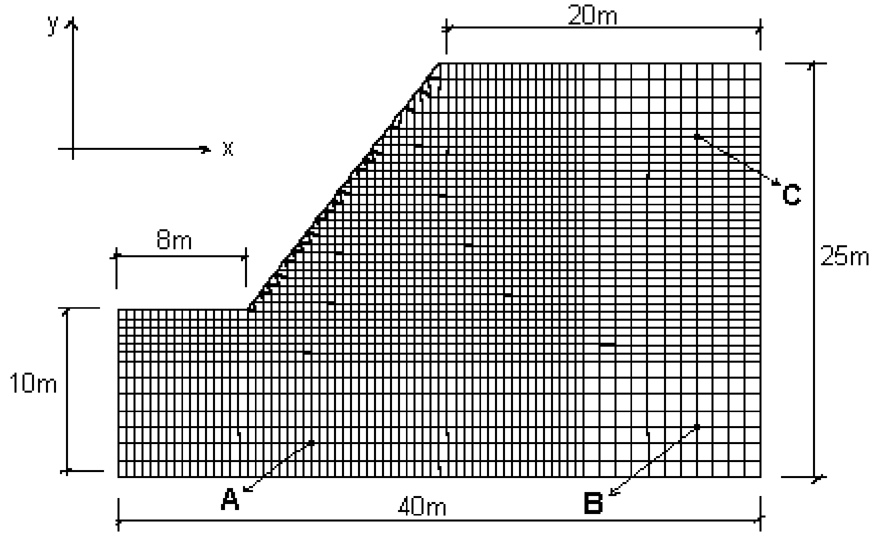


Figure 4 – Geometry considered in the study of maximum number of iterations.

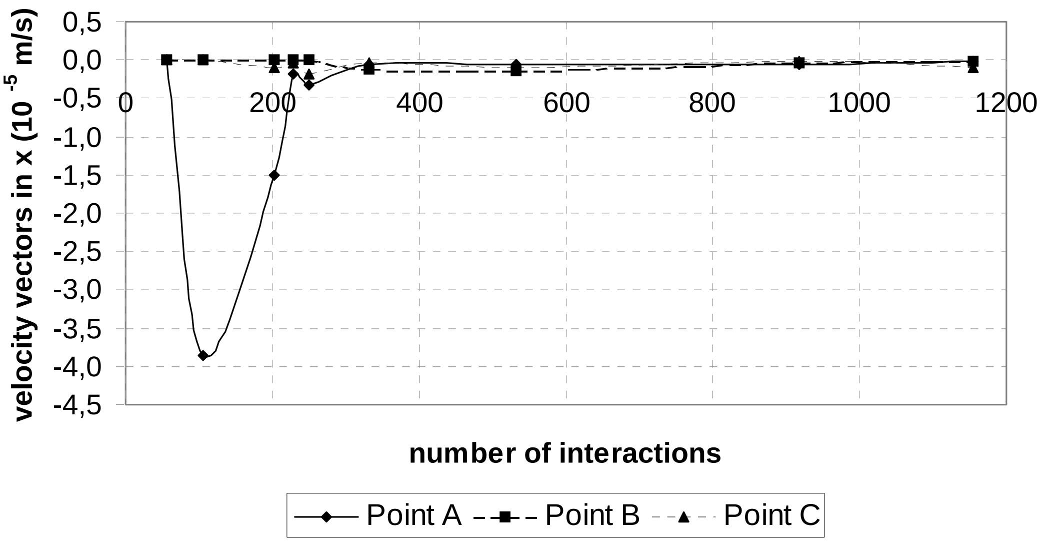


Figure 5 – Variations of "in situ" stresses (velocity vectors in x) as a function of number of iterations.

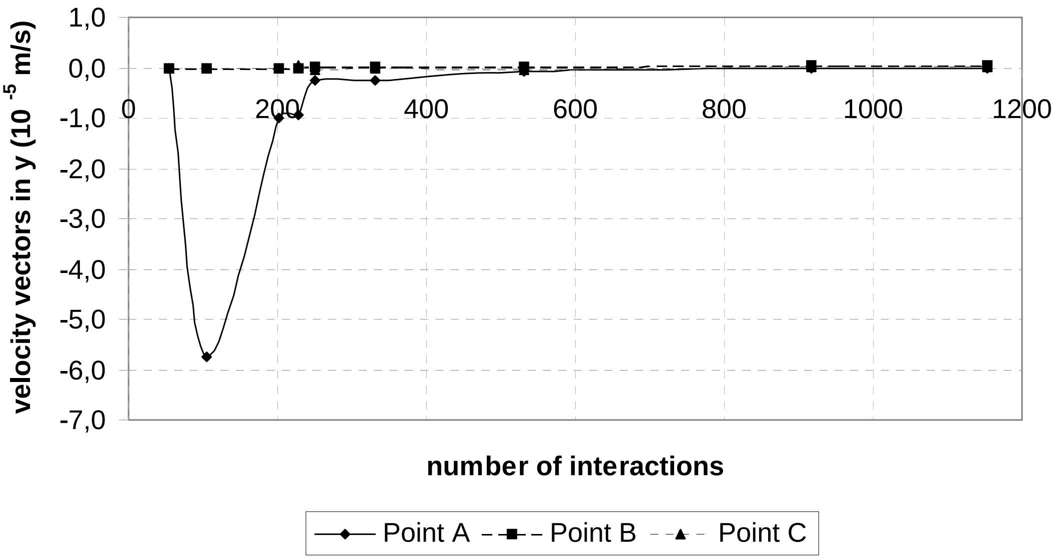


Figure 6 – Variations of "in situ" stresses (velocity vectors in y) as a function of number of iterations.

3.2 Boundary conditions and mesh geometry

A study was also carried out on the influence of lateral boundaries and mesh geometry on the displacements of nailed soil excavations. The magnitudes of horizontal displacements at the excavation top were observed for different boundary conditions and mesh geometry relations. An elastic-plastic constitutive model was chosen for this study. The model is associated to the Mohr-Coulomb failure criterion. Table 1 presents all parameters considered for representing the soil, nails and excavation face.

All analysis considered a fixed excavation height H = 12m. Initial geometry is shown in Figure 7. Soil nailing excavation was simulated in a single stage.

Table 1 – Geomechanical properties

Wall		Soil						
E_{wall} GPa	h_{wall} cm	E_{soil} MPa	ν	γ kN/m^3	c’ kPa	ϕ’ degrees	ψ degrees	k_0
50	5	10	0.2	20	25	29	0	0.52

Nails					Anchors					
ϕ_{steel} mm	ϕ_{hole} mm	σ_{steel} MPa	E_{steel} GPa	G_{grout} GPa	q_s kPa	ϕ_{steel} mm	ϕ_{hole} mm	σ_{steel} MPa	E_{steel} GPa	T tf
25	100	500	205	9,0	63/102	32	100	500	205	10/30

ϕ_{steel} = *diameter of steel bar*, ϕ_{hole} = *borehole diameter*, σ_{steel} = *yielding stress of steel*, E = *Young’s modulus*, G = *shear modulus*, q_s = *pullout strength of nail*, T = *working load of anchor*, h_{wall} = *wall thickness*, ν = *Poisson’s coefficient*, γ = *natural unit weight*, c' = *effective cohesion*, ϕ’= *friction angle*, ψ = *dilatancy angle*, k_o = *coefficient of lateral stress at rest*.

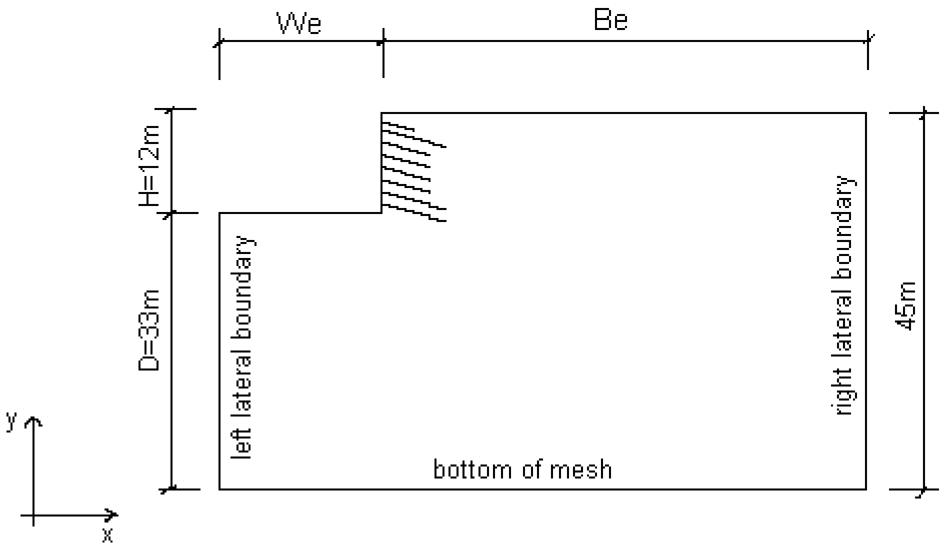
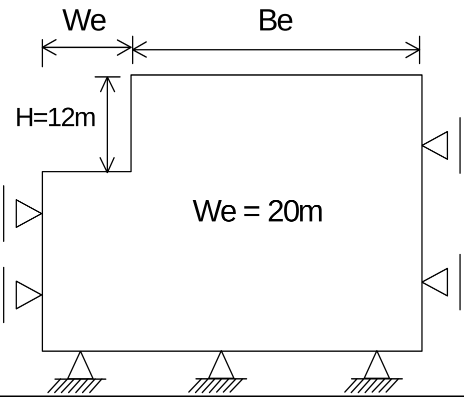
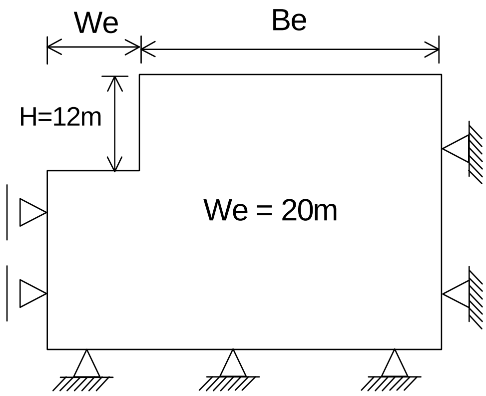


Figure 7 – Mesh geometry considered in this study.

Table 2 – Summary of cases considered in this study

Free vertical displacements at right lateral boundary Be/H = 1 to 10	Fixed vertical displacements at right lateral boundary Be/H = 1 to 10
	

Horizontal displacements at excavation top have been plotted against different mesh geometries (Be/H and We/H varying from 1 to 10) and different boundary conditions (free or fixed vertical displacements). Table 2 shows a summary of all cases herein considered.

Figure 8 shows displacement values at excavation top as a function of Be/H. The results indicate that the influence of lateral boundary conditions is significant only when Be/H values are lower than 4. For higher values, the horizontal displacements at excavation face become independent of the restrictions imposed to vertical displacements at the lateral boundary. Analysis of Figure 8 therefore indicates that Be/H ≥ 4 may be considered as adequate for modeling nailed soil excavations with FLAC. For the left lateral boundary, the geometry herein considered was shown to be adequate for symmetrical excavations. Other configurations may require further studies for determining the minimum distance of left lateral boundary in the excavation mesh.

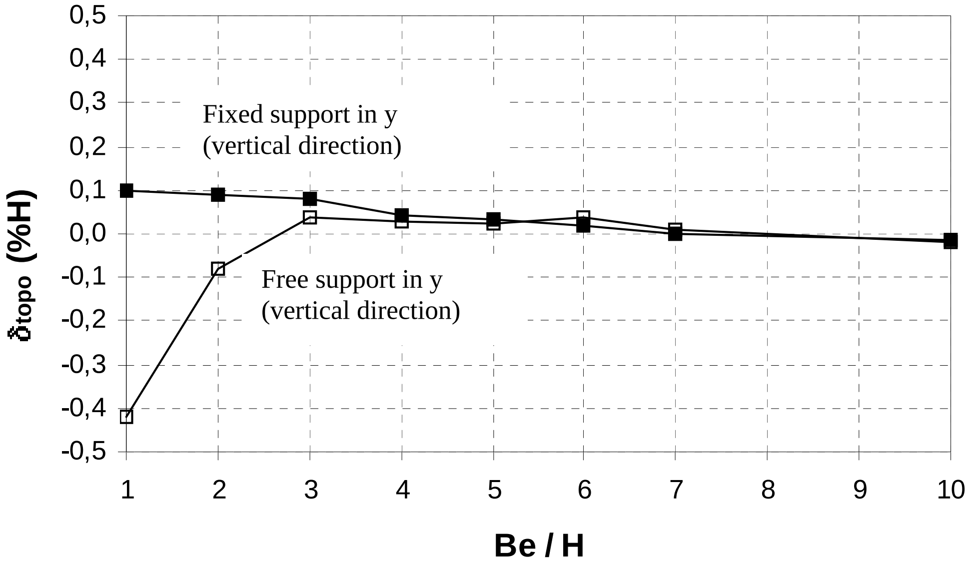


Figure 8 – Horizontal displacements at top *vs.* relative distance Be / H.

3.3 Wall thickness

The influence of wall thickness was also investigated through studies of horizontal displacements along excavation depth. The wall was modeled as a beam element with constant Young's modulus (E_{wall} = 50GPa). Different values of inertial moment (MI_{wall}) and cross-sectional area (a_{wall}) were considered, for representing the varying wall thickness.

Figure 9 shows geometry and boundary conditions. Geomechanical parameters of nails anchors and soil were identical to those shown in Table 1. Wall thicknesses of 0, 50, 100 and 200mm have been considered in this study.

Results in Figure 10 suggest that wall thicknesses of 100mm and 200mm correspond to similar values of displacements. Moreover, the influence of anchor position on the face horizontal displacements may be clearly noted, with particular relevance for flexible structures (h_{wall} = 50mm).

At excavation top, positive displacements are associated to thick walls (h_{wall} = 100mm and 200mm), while negative values correspond to thinner walls.

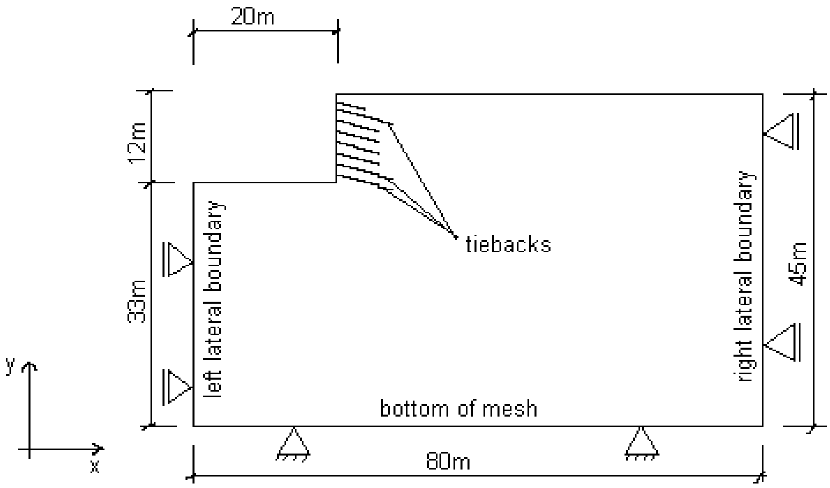


Figure 9 – Mesh geometry and boundary conditions in studies of wall thickness.

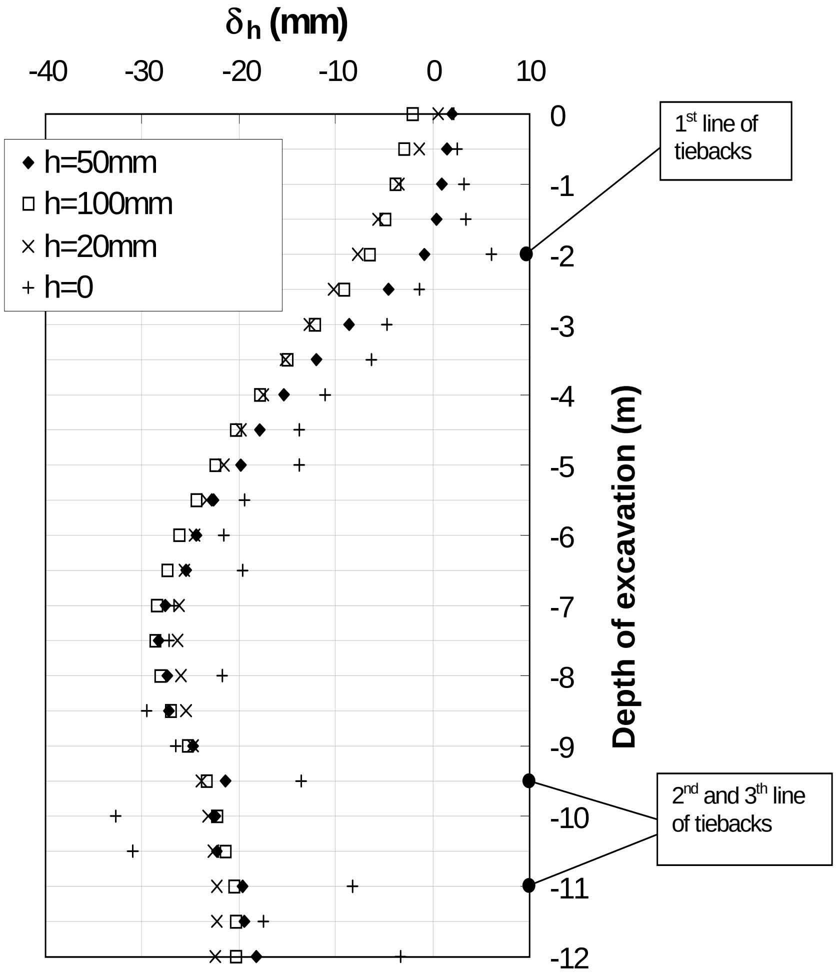


Figure 10 – Influence of wall thickness on horizontal displacements at excavation face.

4. CONCLUSIONS

The computational program FLAC is shown to be a useful tool for simulating the stress-strain behaviour of nailed excavations in soil. However, the studies herein presented demonstrate the great importance of adequately prescribing the geomechanical parameters.

The influence of boundary conditions (geometry and restraints) is shown to be very significant when modelling nailed excavations. Values of $Be/H \geq 4$ may be considered adequate with FLAC. Lower values of Be/H may result in different values of horizontal displacements, depending on the vertical restraint condition imposed to the lateral boundary.

In non-symmetrical excavations, the left lateral boundary must be sufficiently far from the excavation region for not affecting the results predicted with FLAC.

The effect of wall thickness in nailed soil excavations was also investigated. Results show the influence of wall stiffness on horizontal displacements at excavation face. Concrete walls thicker than 10cm correspond to similar values of face displacements.

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