Finite element simulation for the impact of Root Morphology on pulling-out process

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ABSTRACT: The Finite Element Method (FEM) has been used in recent years to simulate various root anchorage effects. This study aims at using the FEM to demonstrate the impact of individual root models in anchorage process with consideration to different rooting patterns and to estimate the stress distribution in soil during the pulling out process.

The FEM was used to carry out the 3D simulations of root pulling-out in unsaturated sandy silt soil. The anchorage model consists of a root system embedded in a soil block. Six root patterns were used and individual roots were removed to determine their contribution to anchorage.

Key Results In root anchorage formed during pulling-out was defined by the root pattern A (root with angular branches). Consequently, all other root patterns have less influence on the anchorage strength (root pattern H shows minimum effect). Removing tap root elements altered the anchorage resistance. This is due to a modification of the sleep surface affected by friction. The tap root had less influence on pulling-out resistance in comparison with other branches.

†Conclusions A simple 3-D Finite Element model was developed to better understand the mechanisms involved during root anchorage during pulling-out process. It is shown that the root system morphology (root pattern) can modify the root anchorage strengths during the pulling-out processes, which are the major components of root anchorage.

***Keywords**: root anchorage, finite element, pulling out, root architecture.*

1. Introduction

The effect of root anchorage on slop stability due resistance against pulling-out during land sliding has became a well-researched topic over the last 25 years with a huge amount of field data available (Nicoll et al., 2006a, Stokes, 1999; Ruel et al., 2003; Achim et al., 2005). However, it is not yet known which shape of root system is best to increase the resistance against pulling-out. If an optimal morphology can be defined, it may then be achievable to control the root systems or soil properties to increase the resistance when pulling out. Root anchorage resistance is regulated by several factors, e.g. root architecture, (Dupuy et al., 2005a, b, 2007) soil physical and mechanical characteristics (Moore, 2000; Dupuy et al., 2005b; Nicoll et al., 2006a). However, it is believed that the pulling out resistance depends on the root system architecture and soil properties, but only few studies have yet been accomplished to test this hypothesis. Field experiments on root anchorage for pulling out usually involve pulling the specious upside until failure and measuring the displacement and consequently force required. Variables measured can then be included with the displacement accrued during pulling out, performed force (Der-Guey Lin et al., 2010) and root system architecture (Khuder et al., 2007). However, although the pulling out test provides useful information, it is time-consuming and can be difficult or even dangerous to conduct. Therefore, the use of numerical modelling would allow us to carry out pulling out experiments and would be an ideal tool in studying how the root system morphology affects anchorage (Fourcaud et al. 2008). Models can be operated to have the same volume but different branching patterns which are never the case in the field therefore it would also be manageable to find out for instance, how the changing in branches angle or removal of one or several roots would impact the anchorage. Cultivated numerical models which simulate the pulling out already exist (Der-Guey Lin et al. 2010).These models incorporate the use of Finite Element Method techniques (Zienkiewicz and Taylor, 2000) with real or simulated root architectural data(e.g. Makina Bamboo). Simulations of uplifting can also be fulfilled at a very local level within the root system (Faisal Hj.Ali.,Normaniza O., 2009). Validation of these numerical simulation with experiment results have revealed the methodology to be adopted, therefore such models can be used with fidelity to better interpret the pulling-out process. The FEM models of root anchorage developed by this study are in three dimensions (3-D). They can be used in combining the real root system architectural data. Mechanical stresses within any part of the root–soil matrix can be visualized and how these stresses are affected by the root system morphology and the root loss can be calculated (Fourcaud et al. 2008). As a specious draw during pulling-out, mechanical stresses are concentrated in different soil partial in both tension and compaction. Soil-root matrix responds to these stresses by debonding the root from the soil and finally the failure. However, different directions of root eccentricity, i.e. above or below the root, have been found and may depend on the tree species, or differences in root architecture and soil type (Fourcaud et al. 2008). Von Mises' stress criterion, i.e. a value that represents an average of stress components has been used to describe and demonstrate the biomechanical adaptation of secondary growth as the local response to the cambium to mechanical stress (Mattheck and Breloer, 1995). Within a root system it is hard to prognosticate where the mechanical stresses will be centralized most as both the root system architecture and the soil type will ascertain the stress distribution. FEM can be employed to explore the relationship between root the system architecture, soil medium and the adaptation of growth to mechanical stress including von Mises stresses (Fourcaud et al. 2008). The purpose of this study is to predict the importance of root geometry especially the root angle to maximum stress distribution on soil and consequently performed force during the pulling-out process. As a consequence of these changes in the root–soil mechanical interaction, it is evaluated that the distribution of mechanical stresses within the soil body would also be modified, resulting in different pulling-out force required. For this purpose, a 3-D FEM model was formulated which permitted pulling-out of analytical root systems with different branching patterns to be simulated in soil types that are similar to unsaturated sandy silt. To ascertain the contribution of different root elements to anchorage, pulling-out simulations were fulfilled on root systems with single branches removed. The length of the branches also varied to approximate their role in anchorage. Stress distribution within the soil body was discovered during the pulling-out process. Results are discussed with regard to the consequences for slope stability and root geometry role in pulling-out resistance, stress and strain distribution.

2. MATERIALS AND METHODS

A. Root system types and patterns

Three types of formal root systems H (with the horizontal branches), A (branches with the 45° angle to the horizon) and M (mixed horizontal and angular branches) with different lengths of branch were considered (Fig. 1). Each root system consisted of three pairs of roots in different directions i.e. B1, B2, B3 and B4, B5, B6, linked to the vertical rigid stem RS, tap root located just below the B3 root was named TR. The length of the tap root was 40 cm and each shallow lateral, B1 and B4 was 0.5 m, B2and B5 was 0.35 m and B3 and B6 was 0.26 m. All root elements were 10 mm in diameter. (Fig. 1) To calculate the comparative effect of tap root element on anchorage effectiveness, the tap root distal extremity TR was removed separately for each root type. Simulations were performed by application of the displacement and concentrated force at the rigid stem reference point.

A. Root and soil mechanical properties

The soil consisted of sandy silt (2% coarse sand, 60% medium sand, 32% fine sand & 6% silt) was considered in this study. The mechanical characteristics of the soil were identified by direct shear test and triaxial test on 6 soil samples. The soil was modelled as an elastic perfectly plastic material, i.e. without considering hardening (Dupuy et al. 2005a). The plastic behaviour of soil failure was given by the Mohr–Coulomb model, which assumes that the failure is controlled by the maximum shear stress (t) and that t depends on the normal stress s, conventionally negative in compression (Fourcaud et al. 2008). The elastic characteristic of the soil are assumed to be linear isotropic following the Young’s modulus Esoil and Poisson’s ratio υsoil. Values of the soil mechanical parameters that were used in the simulations are given in Table 1.

TABLE 1. Soil properties used in the simulations

Property	soil
E (MPa)	24
υ	0.34
c (MPa)	0.02
ɣ (N/mm3)	2.03E-05
ϕ(˚)	27-29

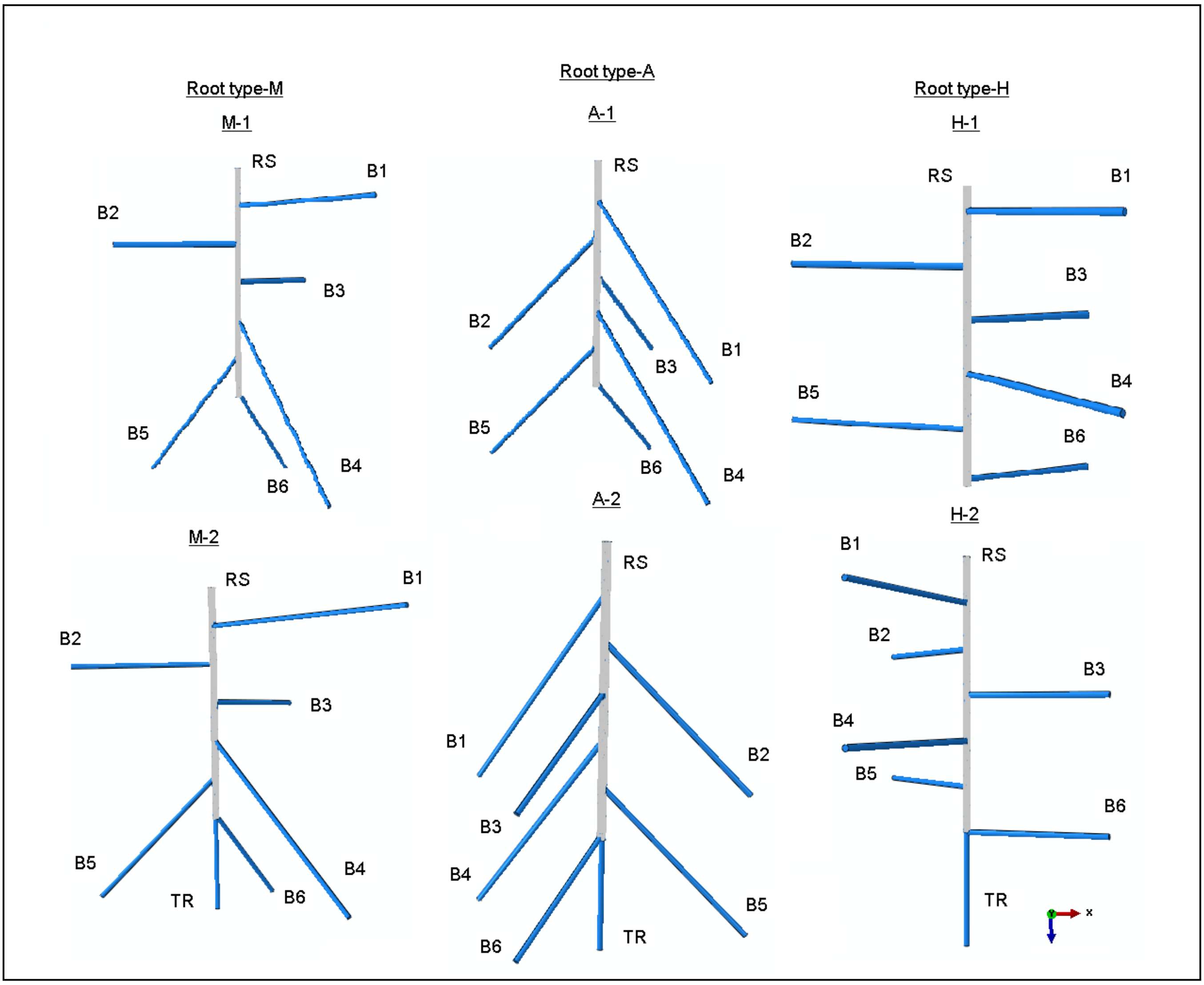

Fig.1, Geometrical description of the 6 root patterns with different branch lengths, angle to horizon, and with or without tap root element

The root material is considered to be elastic linear with a plastic threshold modelled by a von Mises yield criterion (Kachanov, 2004). Density and mechanical characteristics of root material used for simulation were found based upon the tensile test performed on 12 root samples by the tensile test machine Instron 5565 based upon ASTM F2516 (Table 2).

TABLE 2. Root properties used in the simulations

Property	Root
E (MPa)	1500
υ	0.3
MOR (MPa)	14
ɣ (N/mm3)	5.4E-06

B. Finite element model of root anchorage

Numerical simulations of pulling-out were carried out with the Finite Element Method (Zienkiewicz and Taylor, 2000) using the software ABAQUS 6.10-EF1-Explicit (semi static). The explicit method was chosen for this study because of the different branches that vary based on their failure type and the effect of the compression of different root patterns for the stress distribution in the soil during the pulling-out process.

Dupuy et al. (2005 a, b) and Fourcaud et al. (2008) developed a 2D FEM anchorage models similar to this study. The difference between those models and this study consists of three parts: (1) for the root was developed a 3D model (2) a rectangular surrounding soil domain (0.92 m large _ 0.7 m deep) (3) a rigid stem (0.55 m long). The contact property between root and soil was considered as tangential behaviour with the friction coefficient=0.4 for interaction. Boundary conditions were applied fixed to the lower edge of the soil domain. Soil and root domains were meshed using 10-node modified quadratic tetrahedron, C3D10M, available in the ABAQUS element library. Simulations of pulling-out tests were carried out imposing a vertical displacement to the rigid stem at its reference point. The total vertical displacement was 0.4 m as it was approved by the field pulling-out test.

The Finite Element calculation performs consideration forces due to the gravity for the soil domain (otherwise the friction between soil and root was not effecting in the analysis). For simplicity, soil water pressure was not clearly computed. Mass scaling technique and antialiasing filter were performed in this simulation to reduce the CPU run time and unnecessary vibration during the analysis. On the other hand, the calculation time (CPU) increased exponentially with the number of soil elements; therefore, a mesh with 8488 elements was finally used for the comparative analysis. Furthermore, in the explicit analysis the time period step can be determined, which is effective on the CPU run time and consequently on the result accuracy (by the time of the load effect). Based on the experiment, 300 seconds was chosen for this research. This choice provided a good compromise between the accuracy of the numerical results and the calculation time required for the simulations. However, other techniques can also be used to decrease the CPU time such as parallelization available in the ABAQUS software.

1meter depth of the soil in the model was chosen to catch all the stress distribution contours. We suppose that the stress is damping in 1 meter; therefore, the soil block is fixed in the base in 1 meter.

3. OUTPUT OF THE MODEL

Output results were analysed with regard to the following criteria.

A. Response curve of the root–soil system

The response curve is representative of the behaviour of the whole mechanical system and was defined as f-d, i.e. force against displacement, calculated at the top end of the rigid stem (as reference point). In this approach, as the simulation was motivated by a compulsory displacement (simulation input), the resulting force was defined as the 'reaction force' RF (simulation output) calculated at the reference point. At any point of the movement the stiffness of the system is distinct by the slope of the tangent at the recent point of the f-d curve. Anchorage strength corresponds theoretically to the maximum force reached before failure. In the current analyses, strength is defined as the maximum reaction force considered in the certain displacement range, as it was supposed that severe plasticization of the system had already occurred at this period. In each root type, the relative differences in pulling-out force between root patterns H1, A1, M1 and H2, A2, M2 were defined to compare the relative effect of removing tap root.

Stresses and strains in soil elements were visualized using the ABAQUS CAE visualization module. This information is suitable to explain the difference in pulling-out force and displacement in each root model. Stress and strain components were normal components of S11, LE11, PE11 and S22, LE22, PE22 as defined in the ABAQUS list of variables. The location of high positive LE11 and LE22 values indicated the zones where the opening modes of failure were in progress.

4. RESULTS

A. Response curves and anchorage strength

The response curves, i.e. the force-displacement (f-d) curves, of the soil–root systems were derived from the FEM simulations of pulling-out (Fig. 2).

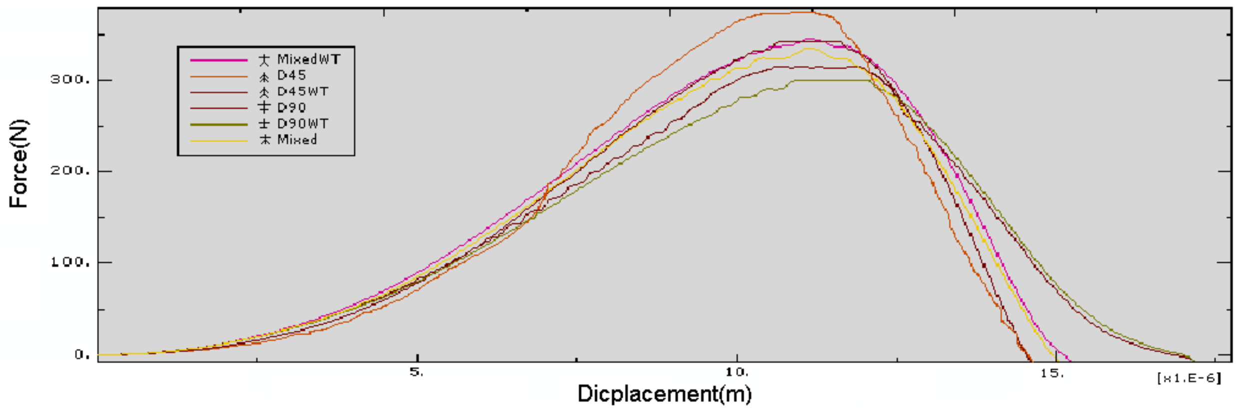

FIG. 2. Reaction force versus displacement curves resulting from the simulations

Reaction forces were computed in the stem at the point where a horizontal displacement was imposed. The maximum displacement considered in the simulations is illustrated in fig 3.

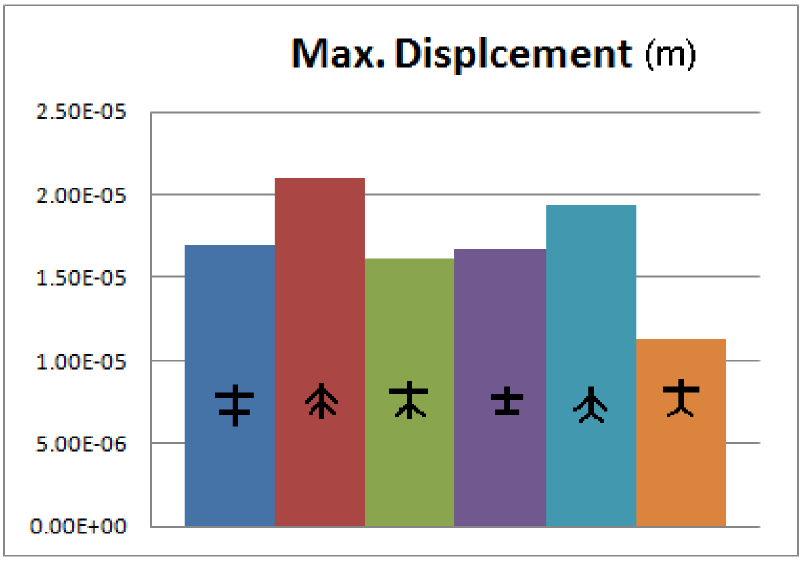

FIG. 3. Maximum displacement during the pulling-out process relevant to each root pattern.

Based on the f-d curves, the stiffness of the root–soil systems was calculated at a maximum amount of RF for each root model. Stiffness at any given displacement corresponding to the maximum RF in each root model is defined as the tangent to the f-d curve at the related point.

In the cases where tap root was removed, the f-d curves followed different trajectories. Thus analysis of the tap roots contribution to pulling-out force and the accordingly anchorage strength showed that the tap root effect was sensible. The pulling-out force loss due to the removal taproot was approximately 5%. Maximum tap root effect on pulling-out force belonged to root type A (7.92%) and minimum was belonged to root type M (2.98%). In the cases of root pattern, the analysis of the root pattern contribution to pulling-out force showed that the root pattern has significant role in pulling-out force and consequently anchorage strength. Maximum strength was shown in the root pattern A and root patterns H and M showed respectively 15.55% and 10.01% less in pulling-out force. The effects of root pattern and tap root were more considerably on stem displacement during the pulling-out test. The displacement loss due to the removal of tap root which was almost 13%. Maximum tap root effect on displacement belonged to root type M (30.51%) and minimum belonged to root type A (1.76%). In the cases of root pattern, maximum displacement during pulling-out process was shown in the root pattern A and root pattern H and M showed respectively 19.09% and 22.88% less in displacement.

In the root pattern A, the local opening modes of failure initiated in zones with more value of LE11 and LE22 in comparison with the patterns M and H (Fig. 4). Related stress and plastic strain are also shown for all root patterns, which revealed the priority in values of stress and plastic strain for root pattern A in comparison with H and M (Fig. 5).

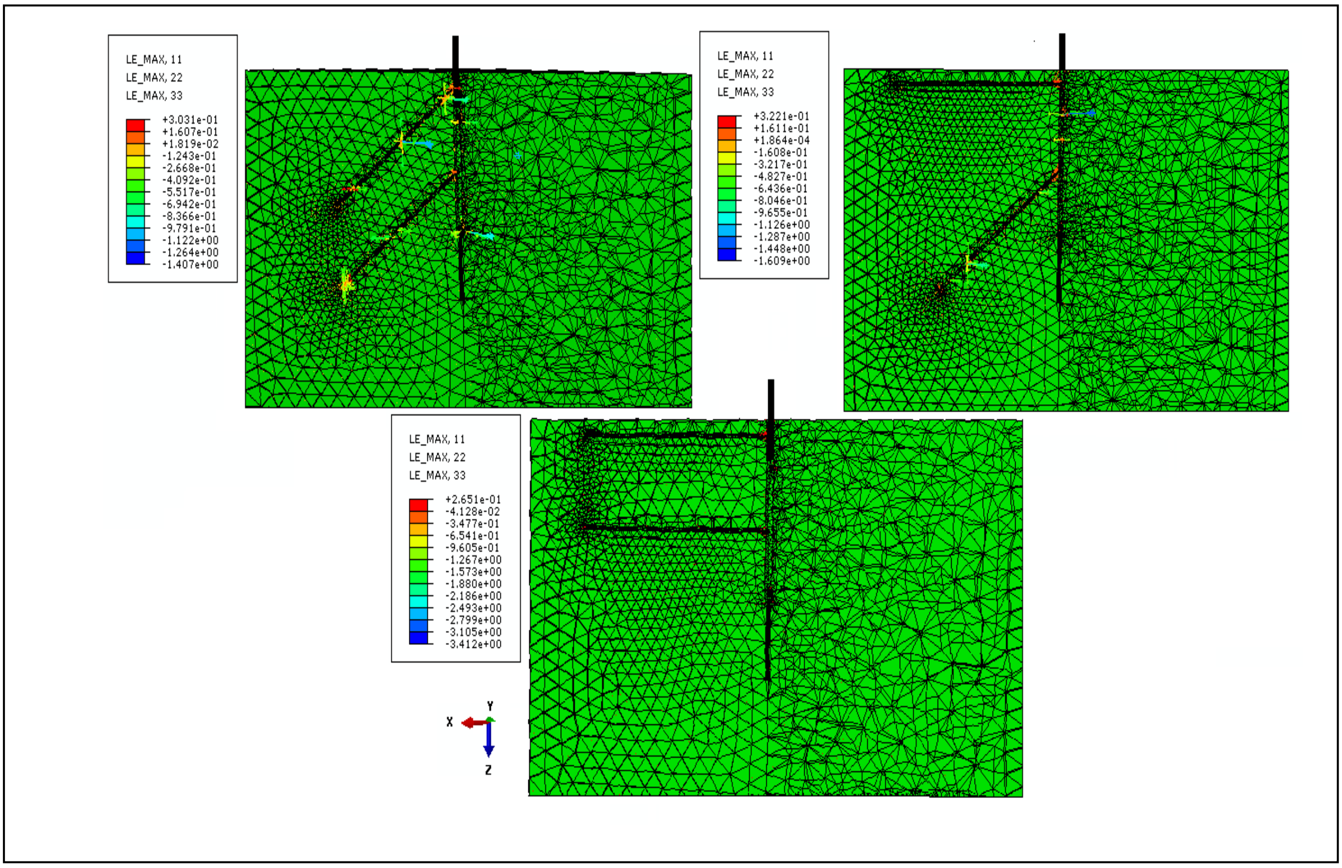

FIG. 4. Field of logarithmic strain components, LE11 and LE22 for the root pattern A, H and M.

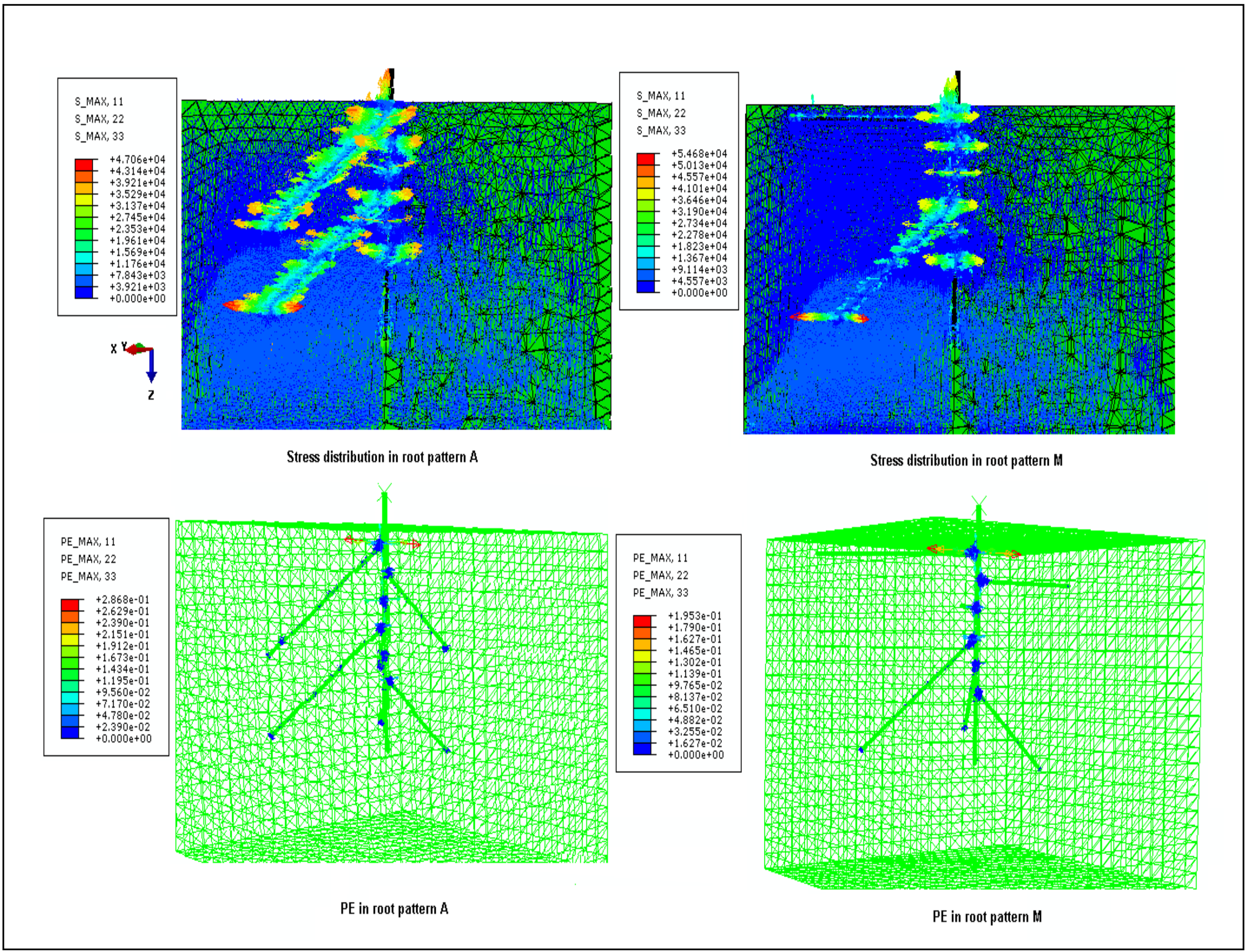

Fig.5. Stress and plastic strain distribution for root patterns A and M.

As it is denoted above, the stress and plastic strain were distributed mainly in the region of angular branches, for instance in root pattern M where the horizontal branches were almost not switched to the distribution process. Therefore it is found out that maximum distribution occurred in root pattern A and minimum in root pattern H.

5. DISCUSSION

Tree anchorage strength is the result of a number of fixed factors, as well as the material properties of roots and soil, the location of the slip surface in the soil, the shape and weight of the root–soil plate (Coutts, 1986; Ennos, 1994; Dupuy et al., 2005b, 2007) and the location of the normal (vertical) axis with regard to the pulling-out vector. All these factors are dynamically correlated together and it has been shown that the root architecture, i.e. root pattern, can play an important role in defining these interactions. Simulations performed in six different root patterns showed that the pulling-out force and relevant displacement were essentially defined by the root architecture (root pattern). In our 3-D calculations most of the deeper root elements were involved in the pulling-out resistance. The first important outcome of this result is that the roots located deeper inside the soil are contributing to more anchorage strength because the effects of the soil column weight in the upward of the root. This result indicates that the total root biomass cannot be always related to the pulling-out resistance, except when a large proportion of this total biomass is allocated to the main roots that defined the soil-plate formation. (Fourcaud et al. 2008). However, the present numerical study considered roots with comparatively large cross-section, i.e. quite stiff roots, and did not take into the reflection of reduce in root cross-section because of the modeling complexity. As defined by Wilson (1975), the thinner distal parts of the roots should cross the potential slip surface and consequently increase the anchorage resistance. This component of the resistive moment is proportional to root tensile strength as a major factor involved in root anchorage (Coutts, 1986; Stokes, 2002). Additional numerical investigations should clarify the relationship between the root angle and soil mechanical properties influencing the root anchorage. Mickovski and Ennos (2003) reported that asymmetry in the lateral root system did not appear to cause asymmetry in anchorage rigidity. Simulations in this research were performed for all root patterns. During the analyses it was found out that the horizontal branches show a slight role in root anchorage due to the negligible soil column weight in the top of the branch surface and consequently low friction force. Meanwhile the angular branches play more effective role in root anchorage. As it is demonstrated in fig.6 W1>>W2, consequently the friction force and subsequently anchorage force is sufficiently higher for angular branches in comparison with the horizontal one.

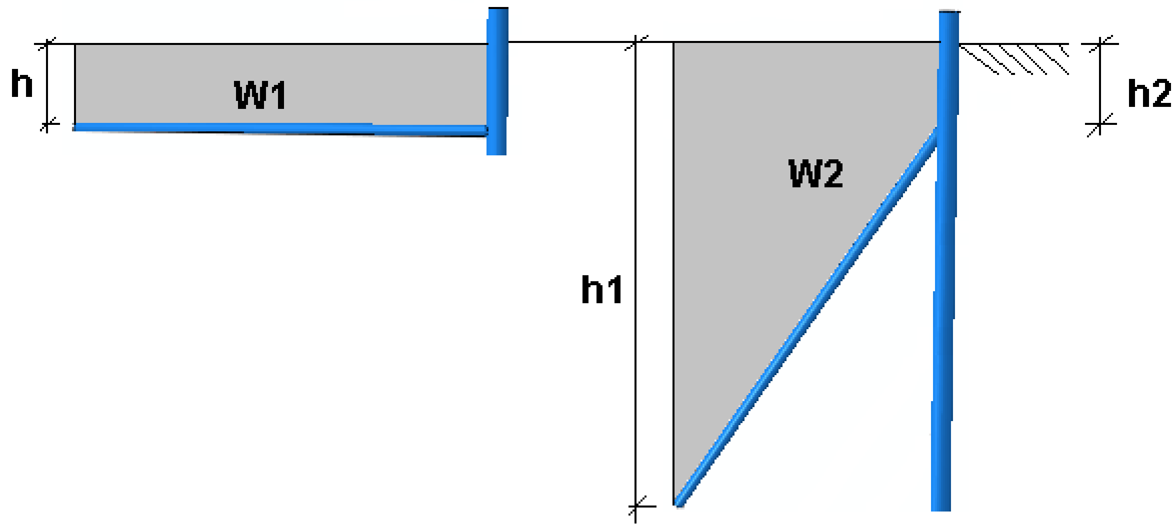

Fig.6 comparison of soil column weight for horizontal branches with angular branches

6. The soil weight is a component which contributes to the friction force counter balancing the pulling-out forces on the root anchorage. The importance of root–soil weight on root anchorage was quantified by Coutts (1986) as 13–45% that of the total anchorage system. This effect therefore indicates why pulling-out resistance is much more in root pattern A in comparison with the root pattern H. During the analyses it was found out that the effect of tap root is too short with regard to the effect of branches because of the limited soil surface which is surrounding the tap root and causes less friction effect. In other word, tap roots are short and thick compared with the lateral roots and play only a small role in root anchorage (Danjon et al., 2005). To reach the full potential with regard to anchorage depth, the tap root acts as a rigid stake held in place with lateral roots holding it in position like guy ropes (Ennos, 1994).The FEM model developed here allowed changes in root anchorage capacity to be quantified when structural elements of the root system were removed. More information is also needed on the mechanism of root anchorage in different soil hydrological situations such as the matric sauction, particularly with regard to variations in moisture content throughout the soil profile. Again, the FEM is ideally suited to modelling such behaviour, especially when appropriate field experiments would be difficult to carry out and interpret.

7. References

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