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2D/3D FEM embedded beam models for soil-nail reinforced slope analysis

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ABSTRACT: Conventional design of soil-nail structure based on Limit Equilibrium Method (LEM) is adequate, but the efficiency is questionable due to the lack of knowledge in soil-structure interaction. As the computation power nowadays is high and attainable, it becomes increasingly common to use Finite Element Method (FEM) for analyzing complex geotechnical problems. This paper demonstrates the use of 2D *Embedded Beam Row* element for soil-nail group modelling in PLAXIS 2D, comparison of response is drawn against that of 3D *Embedded Beam* element in PLAXIS 3D, as well as the field data from CLOUTERRE-1, the French National Research Project, followed by a discussion on the factor of safety obtained from FEM and LEM. It has affirmed that, the 2D Embedded Beam Row model can effectively handle groups of soil nails in the plane strain condition and produce both quantitative and qualitative predictions of deformation and structural response that concerns practitioners.

1 INTRODUCTION

Soil nailing is an in-situ soil reinforcement technique extensively applied in the slope stabilization problem due to its relatively low cost and easy installation process. Conventional design methods are generally based on limit equilibrium theories, which are adequate, but the efficiency is questionable due to the lack of knowledge on the complex soil behaviors. Finite Element Method (FEM), on the other hand, accounts for a wide range of phenomenon as observed in the real-world, typically the soil-structure interaction; that complements the conventional design method with the possibilities to achieve an economical and reliable design. As the use of Finite Element Method (FEM) prevails, and the required computational power nowadays is attainable at reasonable cost, there is growing popularity in using FEM software package to verify and optimize the design. 2D FEM package has the merits of relatively low cost, easy model execution and result interpretation over 3D FEM package. Soil nail behaviors are however three-dimensional (3D) phenomenon, and technically it is inappropriate to model the application using a 2D program. Prior studies demonstrated that, by modelling the soil nail group as a surface structural element in 2D plane strain condition, comparable results can be found to the field response; however, the numerical artefacts arising from this simplified approach remain unaddressed. The FEM package used in this study is PLAXIS 2D and PLAXIS 3D, with the focus on the structural element namely *Embedded Beam Row* (2D) and *Embedded Beam* (3D). *Embedded Beam Row* is a line element developed to model a row of piles under 2D plane strain condition, which can be extended to model soil nails in group. The performance of 2D *Embedded Beam Row* is investigated through this study, by referencing to the French National Research Project, e.g. CLOUTERRE-1. The response of 2D *Embedded Beam row* is checked against that of 3D *Embedded Beam*, as well as the available field data from the project, followed by a discussion on the factor of safety obtained from FEM and LEM, respectively.

2 MODELLING OF SOIL-NAIL IN PLAXIS 2D

Before the introduction of *Embedded Beam Row* element, modelling of pile rows or soil nails in group in 2D is nearly impossible. The closest choices of structure elements for the application are *Plate* and *Node-to-Node Anchor (N2N Anchor)*, both however have their own limitations.

Plate element, with both its axial and bending stiffness, can capture the certain structural response of the soil nail; and with the interface element around, the soil-structure interaction, in particular the skin friction, to certain extent, can be accounted for. The limitation is however that, *Plate* as a continuous element, the presence of which causes a discontinued mesh that prevents the soil from flowing through, giving rise to too rigid a lateral response. The practice of using smeared properties to account for the out-of-plane spacing in the soil-nail group, gives

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close prediction of the gross structural response; but meanwhile, the approach presents certain numerical artefacts, for instance the unrealistic shear plane, that is less relevant as observed in the field for soil nails in group. Moreover, as the soil-structure interactions take place on both sides of the *Plate* in the 2D plane strain model, the interface properties require some rigorous calibration against the 3D response. The process is cumbersome and discouraging.

N2N Anchor element has axial but no bending stiffness, its interaction with the mesh is realized through the two end points, which means lateral response due to bending, as well as, soil-structure interaction along its length cannot be considered.

The 2D *Embedded Beam Row* element (introduced in 2012) can be used to model a row of piles at a certain spacing perpendicular to the model area. *Embedded Beam Row* is implemented in such a way that, it is not directly coupled with the mesh, but through the special line interfaces (consisting of spring elements and sliders). The program asks for input properties per pile, and calculates the smeared properties based on the out-of-plane spacing defined.

3 THE FRENCH NATIONAL RESEARCH PROJECT, CLOUTERRE-1

3.1 *Project information*

In France, a National Research Project called CLOUTERRE has been conducted from 1986 to 1991 with the objective of better understanding the behaviors of soil-nailed walls during construction, in service and at failure. Within the framework of the first National Research Project CLOUTERRE, three full-scale experimental soil nailed walls were constructed and then pushed to failure by three different modes. The analyses of these three different modes of failures have been performed using limit equilibrium methods and the multi-criteria approach (Plumelle and Schlosser, 1991; Schlosser et al., 1992).

The soil-nailed wall was constructed in an experimental backfill, 7 m high, built with special care at the CEBTP site (Centre Expérimental de Recherches et d'Etudes du Bâtiment et des Travaux Publics) near Paris on a dense sand formation as shown in Figure 1. In particular, the homogeneity and density of the backfill were controlled at each phase of its construction. ontainebleau sand, as the backfill material is in a medium-to-dense state (relative density, D_r =0.6) and has an average unit weight of 16.1 kN/m^3.

The underlying foundation sand is of similar properties but much stiffer. The groundwater table is well below the foundation sand, throughout the construction of the nailed wall. Effect of groundwater can thus be ignored since it is below the reinforced zone.

3.2 *FEM modelling*

15 noded triangular element (4th order shape function) was used in the 2D analysis, while 10 noded tetrahedral element (2nd order shape function) was used in the 3D analysis. The compromise in accuracy, as a result of lower order element used in 3D, was compensated by denser mesh refinement. Soil nails were modelled using *Embedded Beam Row* element, and *Embedded Beam* element in 2D and 3D, respectively.

The 2D and 3D numerical model boundary and mesh discretization are shown in Figure 2 and Figure 3, respectively.

The mechanical properties of the backfill and foundation soils were evaluated based on published data on

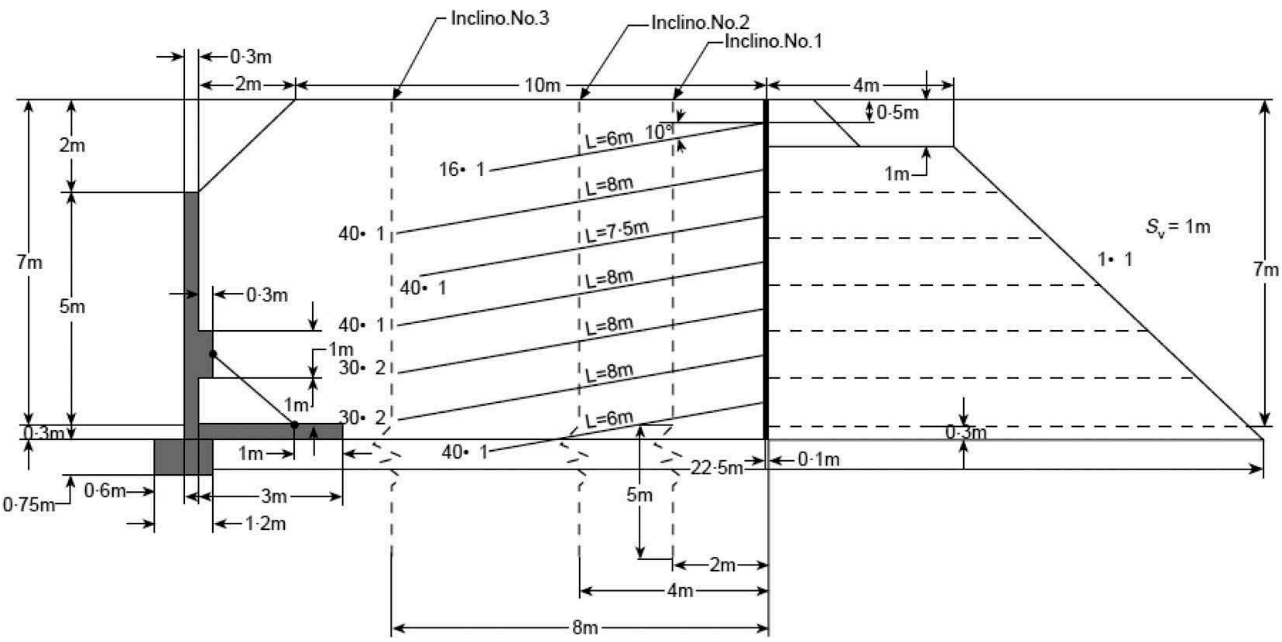

Figure 1. Cross-section of the full-scale experimental nailed wall.

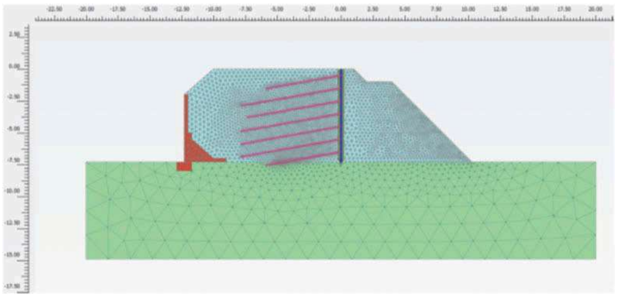

Figure 2. 2D model boundaries and mesh discretization.

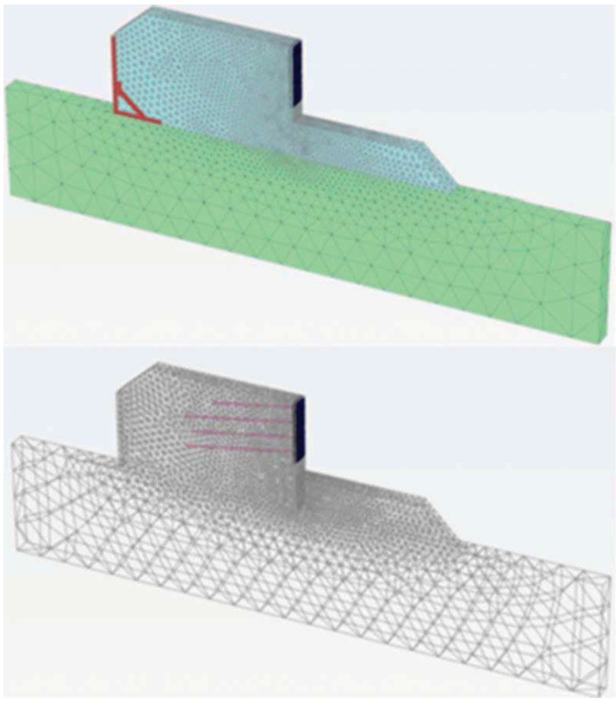

Figure 3. 3D model boundaries and mesh discretization.

Fontainebleau sands, pressuremeter tests conducted at the site, and triaxial tests performed at the CERMES-ENPC=LCPC (Plumelle and Schlosser, 1991).

Two pressuremeter tests were performed within the backfill before construction of the soil nailed wall (Plumelle and Schlosser, 1991). The average Ménard pressuremeter modulus over the 7 m height was 10 MPa.

Two other pressuremeter tests were carried out down to 6 and 20 m in the foundation soil as shown in Figure 4. The results of these deep pressuremeter tests showed the existence of a very hard soil layer (Ménard modulus, E_M=50 MPa and limit pressure, p_l =5 MPa) between 7 and 11 m beneath the backfill in which the soil-nailed wall was constructed. The mesh of the numerical model, therefore, ends at the top of this hard layer. The average pressuremeter modulus in the foundation soil, between 0 and 7 m is 35 MPa.

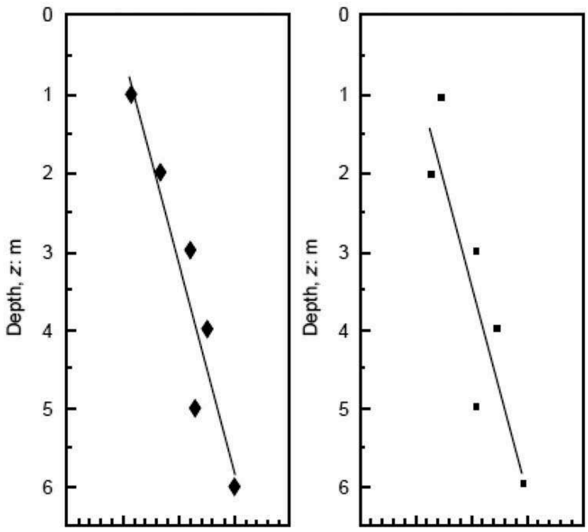

Figure 4. Pressuremeter test result of Fontainebleau sand.

The above mentioned triaxial tests carried out at CERMES (Plumelle and Schlosser, 1991) give an angle of friction in compression varying between 36° and 40° depending on the confining pressure.

The apparent cohesion was found to depend upon the strain level due to the rearrangement of the grains. For the considered sand, with an average water content of 5-8%, the cohesion varies between 2 and 6 kPa (Luo, 2001).

The numerical analysis was carried out using advanced soil model, e.g. Hardening Soil (HS) model, which requires (3) stiffness input of E_{50}^{ref}, E_{oed}^{ref} and E_{ur}^{ref}, that governs the deformation behaviors under deviatoric loading, volumetric loading and unloading, respectively.

For sandy material, the E_{50}^{ref} and E_{oed}^{ref} is in the same order according to Benz (2007), the quantity at reference stress level of 100 kPa can be deduced based on the stress-dependency formula, together with the aforementioned stiffness derived from pressuremeter test.

$$E_{50} = E_{50}^{ref}\left(\frac{c\cos\varphi - \sigma_3^{'}\sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^m \tag{1}$$

For (quartz) sand, stiffness is supposed to vary linearly with relative density, RD, according to Brinkgreve et al. (2010).

$$E_{50}^{ref} = 60000\ RD/100\ \left[\mathrm{kN/m^3}\right] \tag{2}$$

The $E_{ur}^{ref}/E_{oed}^{ref}$ ratio falls in the range of 3 to 5 for the material, in this study a lower bound of 3 is considered, which is in line with Brinkgreve et al. (2010),

Table 1. Input parameters for hardening soil model.

Description.	E_{50}^{ref},kPa	E_{oed}^{ref},kPa	E_{ur}^{ref},kPa	m -	c', kPa	φ' °	ψ °
Fontainebleau Sand	36000*/30000	36000*/30000	108000*/90000	0.5	$3^{\#}$/8	$38^{\#}$/35*	$25^{\#}$/10/5.5*
Foundation Sand	100000	100000	300000	0.5	$3^{\#}$/8	$38^{\#}$/35*	$20^{\#}$/10/5.5*

*# - Unterreiner et.al. (1997) * - Brinkgreve et al. (2010)*

$$E_{ur}^{ref} = 180000\, RD/100\ \left[\mathrm{kN/m^3}\right] \tag{3}$$

The quantity m measures the rate of dependency that is similar to Janbu's number, except in PLAXIS the range is from 0.5 to 1. For sandy material, m is close to 0.5, correlations to relative density is observed according to Brinkgreve et al. (2010).

$$m = 0.7 - RD/320 \tag{4}$$

Besides the stiffness parameter, Brinkgreve et al. (2010) has the recommendations on strength parameters,

$$\varphi' = 28 + 12.5RD/100\ (deg.) \tag{5}$$

$$\psi = -2 + 12.5RD/100\ (deg.) \tag{6}$$

The soil parameters suggested by different literatures are summarized in Table 1.

The nails are driven hollow aluminium tubes grouted in the 63 mm borehole. Structure element, e.g. *Embedded Beam Row* was used to model the soil nail. The structural response, in particular the mobilization of skin friction, is dependent on the complex soil-structure interaction, which is a result of the constitutive response of the selected soil model to the inequilibrium. The key to a realistic numerical structure response greatly depends on the accurate input skin resistance profile besides the appropriate parameters used in the constitutive soil model.

Data have been compiled on more than 450 pullout tests carried out by contractors in this field (Plumelle and Schlosser, 1991). This data bank makes it possible to estimate for the preliminary design of the soil/nail interaction parameters.

As the geomaterial considered in this study is sandy material, we hereof refer to the corresponding chart from the data bank, as shown in Figure 5.

Based on the pressuremeter result of a limiting pressure of 1.5 MPa, the corresponding ultimate skin friction for driven nail grouted in sand, is approximately 80 kPa. FEM pullout test was carried out to investigate the numerical response. The mobilization of shear stress, and the corresponding failure mechanism

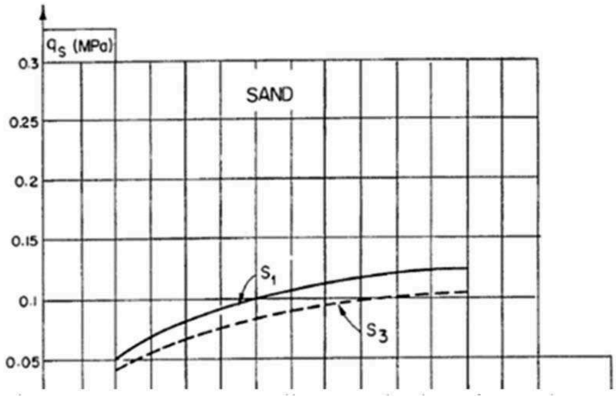

Figure 5. CLOUTERRE pullout test database for sand.

developed, during the numerical pull-out test is shown in Figure 6.

The load-displacement curves from 2D and 3D pull-out test are shown in Figure 7.

A summary is given in Table 2 for the numerical pull-out test.

The input parameters for soil nail as *Embedded Beam Row* are summarized in Table 3. The skin resistance profile is set to *Layer dependent*, whereby the mobilized skin resistance of the soil nail is governed by the failure criterion of the surrounding soil.

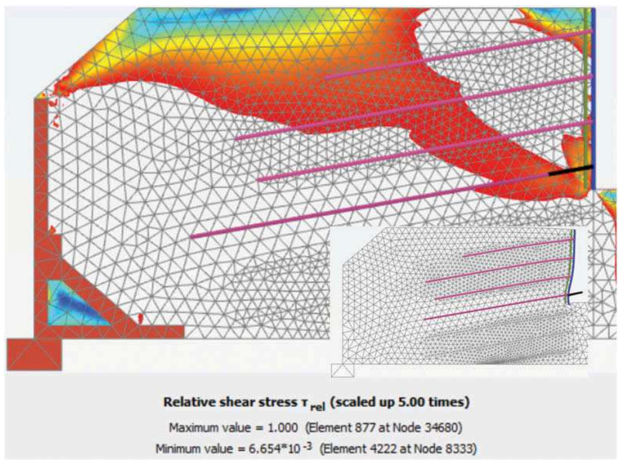

Figure 6. Mobilization of shear stress in FEM pullout simulation.

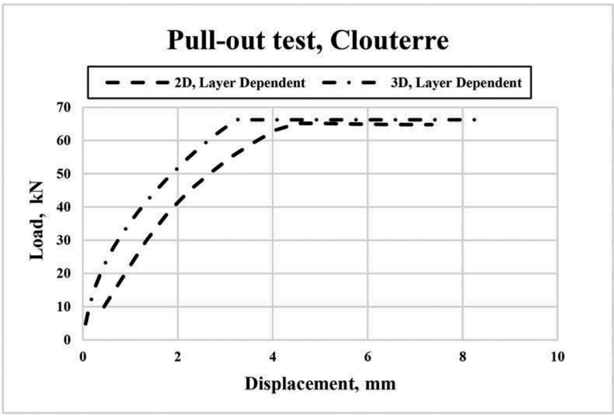

Figure 7. 2D and 3D pullout response.

Table 2. Summary of pullout test.

Description.	τ_{max}, kPa	τ_{min}, kPa	T_{max}, kN
PLAXIS 2D	45.61	39.60	64.745
PLAXIS 3D	47.57	34.59	66.25
CLOUTERRE Recommendation	80	80	–

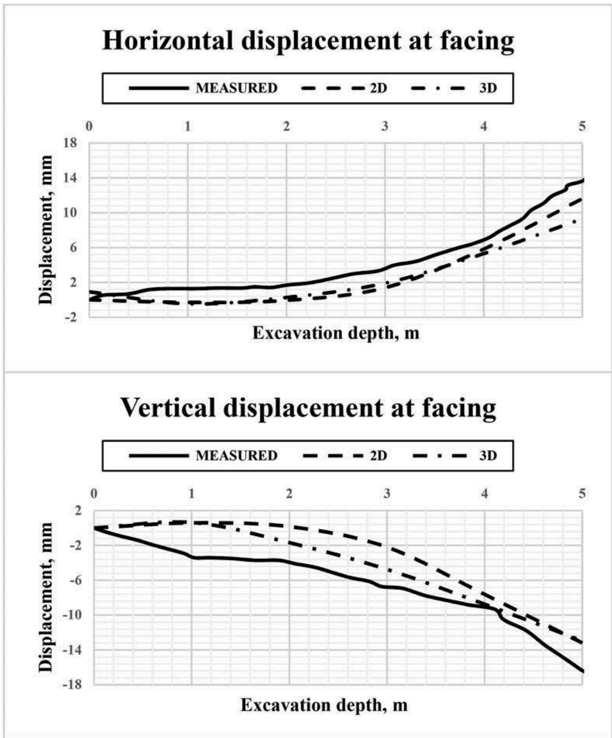

Figure 8. Horizontal and vertical displacement at facing.

Table 3. Input parameters for soil nail.

Description.	E,kPa	γ,kN/m^3	d,mm	$L_{spacing}$, m	M_p, kNm	N_p,kN	Skin Resistance
Soil Nail	30000000	8	63	1.15	1	55	Layer Dependent

3.3 *FEM result, CLOUTERRE-1*

3.3.1 *Displacement at facing*

The horizontal and vertical displacement over the top point of the facing, are monitored at different excavation depth and presented in Figure 8. The PLAXIS prediction of displacement at the facing, is in general slightly stiffer than field measurement.

3.3.2 *Horizontal deflection*

Inclinometers are placed at distance of 0, 2, 4 and 8 m from the facing. In PLAXIS 2D and 3D, the horizontal displacement profiles are extracted at the inclinometer locations and charted against the field measurement, as shown in Figure 9.

In general 3D response is stiffer than 2D, especially when it is close to the ground surface, both 2D and 3D response however tends to converge at larger depth. As compared to the field curve, PLAXIS predicts closely the deflection profile, except for the first 5 m down the ground surface at facing, e.g. d=0 m, where PLAXIS predicts a softer response in horizontal deformation; nevertheless, it still captures the deflection well at the ground surface.

3.3.3 *Axial force of soil-nail*

The axial force distribution of the four soil nails are extracted from PLAXIS 2D and 3D, and plotted against the field measurement, as shown in Figure 10. It is observed that PLAXIS predicts higher axial force at the nail head, e.g. T_o/T_{max} ratio up to 0.9, which deviates from CLOUTERRE Recommendation that the T_o/T_{max} ratio, close to 1 at the beginning of tension, reaches progressively much smaller values, as a function of the level of the layer considered, going from 0.3 to 0.7 in the case of the soil nailed wall CETBP No.1.

3.4 *Factor of safety*

Limit equilibrium method considers the strength limit state, by ensuring that the design combined strengths of the nails and the soils, exceed the applied load with a factor of safety appropriate to the level of uncertainty associated with the loads due to the excavation.

Gässler (1988) studied the behaviors of steep slope and had the conclusion that if not a planar, a bi-linear failure surface is critical,

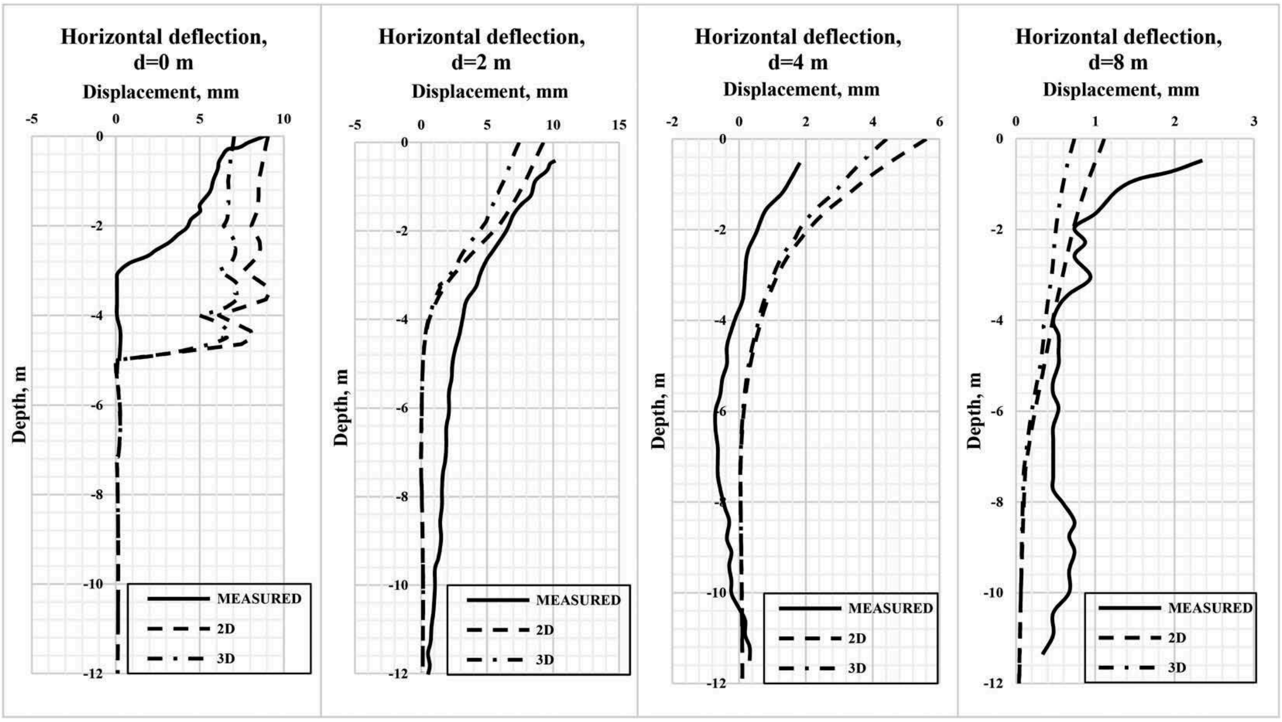

Figure 9. Horizontal deflection profile at 0, 2, 4, 8 m from facing.

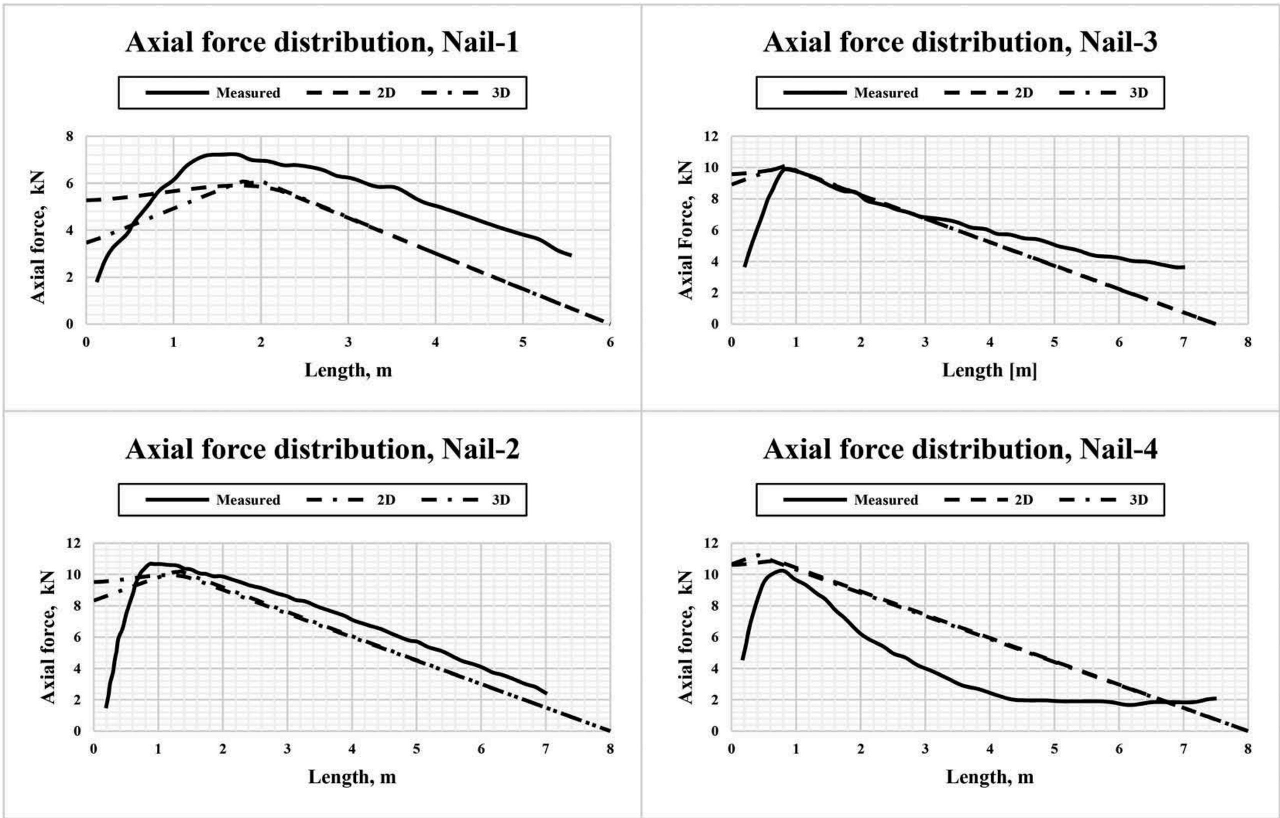

Figure 10. Axial force, Nail-1, 2, 3 & 4.

whereas, for gentler slope, a circular failure surface is critical. This is further affirmed based on the predicted planar failure surface by PLAXIS 2D and 3D.

According to Luo (2001), Global factor of safety (LEM) for both internal and mixed failure modes is checked by Eq. (7) for potential failure surface as shown in Figure 11.

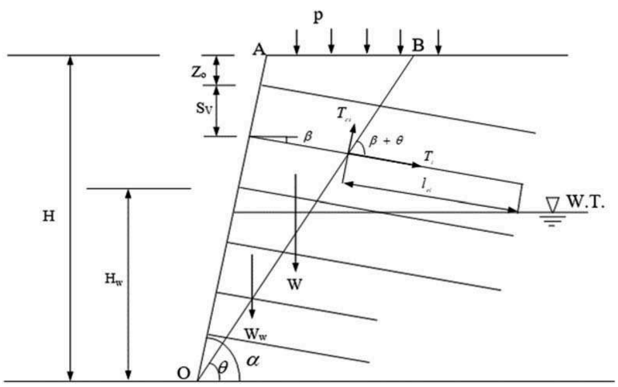

Figure 11. Potential failure surface of a reinforced slope, (after Luo 2001).

$$FS = \frac{\frac{c'H}{\sin\theta} + [(W - W_w)\cos\theta + T_c\cos(\beta+\theta) + T\sin(\beta+\theta)]\tan\varphi'}{W\sin\theta - T_c\sin(\beta+\theta) - T\cos(\beta+\theta)} \quad (7)$$

In PLAXIS, the factor of safety is evaluated using the strength reduction method, e.g. phi-c reduction, where the strength of the soil is reduced in a bid to trigger the ultimate failure, and the factor of safety is calculated in correspondence to the failure mechanism.

The factor of safety and the corresponding ultimate failure predicted by PLAXIS 2D and 3D are presented in Figure 12 & Figure 13, respectively.

For comparison against LEM, the failure mechanism predicted by PLAXIS, e.g. in this case the wedge mechanism, is visually measured for its dimension, for the input to Eq. (7) to evaluate the factor of safety in the LEM way.

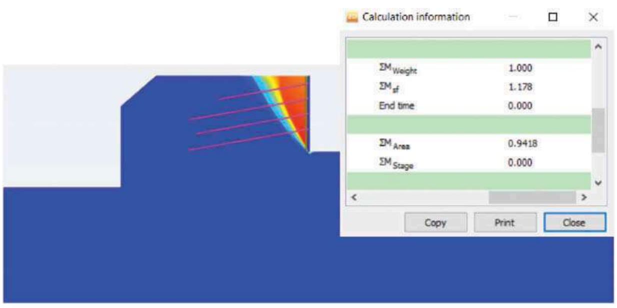

Figure 12. Failure mechanisms & FOS by PLAXIS 2D.

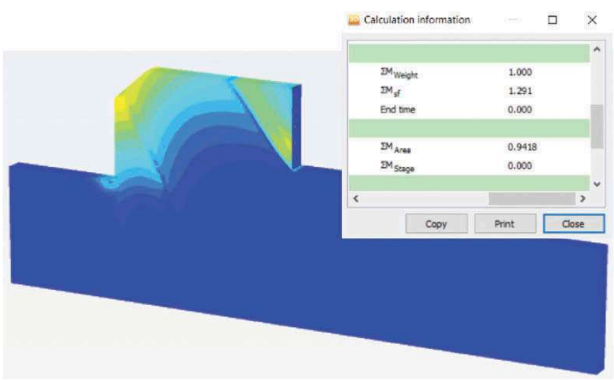

Figure 13. Failure mechanisms & FOS by PLAXIS 3D.

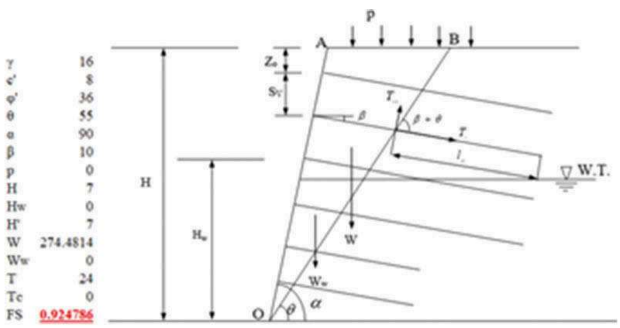

Figure 14. LEM prediction of FOS based on 2D wedge.

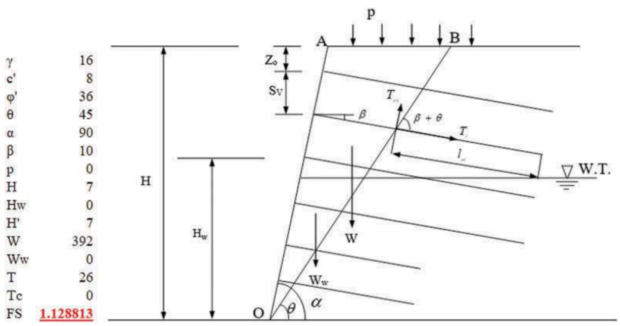

Figure 15. LEM prediction of FOS based on 3D wedge.

Table 4. Summary of FOS by FEM and LEM.

Description.	θ	*FOS*
PLAXIS 2D	55°	1.18
Limit Equilibrium	55°	0.92
PLAXIS 3D	45°	1.29
Limit Equilibrium	45°	1.13

The LEM predictions are presented in Figure 14 & Figure 15, which adapt to the wedge dimension from PLAXIS 2D and 3D, respectively. As it turns out, 2D and 3D predicts slight difference in the factor of safety, due to the different size of wedge mechanisms and the nail length in the passive zone. Comparison in factor of safety by PLAXIS and Limit Equilibrium Method is summarized in Table 4.

PLAXIS 3D predicts slightly higher factor of safety than 2D due to a smaller wedge mechanism considered. Limit Equilibrium predicted FOS is in general slightly lower, but sufficiently close to PLAXIS predictions, considering the tolerance effects going into a naked-eye inspection of the wedge size from PLAXIS, given the fact that there is no functionality in PLAXIS to output the dimension of the failure wedge in exact number; after all, the FOS by PLAXIS is based on the amount of soil strength that can be reduced, while maintaining the global equilibrium, rather than the geometric details of the failure mechanism develops as a result of the strength reduction during the safety calculation.

4 CONCLUSIONS

With *Embedded Beam Row* element for soil nail, PLAXIS 2D analysis closely yields the deformation of the reinforced slope, as well as the structural response of the soil nails, that is comparable to the result of PLAXIS 3D analysis and field measurement.

In addition, the 2D and 3D FEM prediction of FOS fluctuates mildly around the LEM based FOS of unity, that the experimental project was based off. It is further affirmed that, in the absence of a 3D program, 2D *Embedded Beam Row* model can handle a group of soil nails or piles in the planestrain condition. Owing to the merit of 2D *Embedded Beam Row*, the analysis of soil-nails or piles in group, is free from numerical artefacts as found in the cases of using alternative structural elements.

It is worth to note that the bearing capacity is an input for the *Embedded Beam Row* element, thus it is essential to validate the numerical pull-out response against field test data, to ensure that the available skin resistance is not exceeded in the analysis at all time; the mobilization of skin resistance is however the result of the constitutive model response, as well as the soil-structure interaction realized through the special line interface; the latter and its Interface Stiffness Factor (ISF), has subtle influence on the load-displacement behavior of geo-structure modelled, and requires calibration on a case-by-case basis just to be rigorous. The default set of ISF, based on the load-displacement behavior, of bored piles founded in sand according to the Dutch Annex of Eurocode, is found to be appropriate for the case of CLOUTERRE-1, due to the similarity in the sub-soil characteristics.

The discrepancies in the prediction of axial force of soil nail close to the facing, could be due to the complex interaction or local failure at the connection, for which an elastic *Plate* element used in the analysis, cannot capture the behavior properly.

Partially the mismatch of numerical result and field measurement, can be attributed to the tolerance effects arising from the experimental setup, e.g. the soil-nailed structure was built without overdesign factor; and in one of the experiments, it failed purely due to water infiltration made on purpose, for the understanding of failure mechanisms; that said, the load-displacement behavior could be erratic when the problem is on the verge of failure, and that is beyond what a FEM numerical analysis at its tolerance could capture.

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