Numerical investigation of soil nail wall during construction

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ABSTRACT
This paper presents a numerical investigation on the behaviour of a soil nail wall during the different stages of construction. Soil nailing is an effective reinforcing system for top-down construction of retaining structures. A well-known case in Germany is used in this study. By comparing the nail load development and distribution with field measurement, it is found that the two-dimensional finite element method can provide a reliable modeling of three-dimensional soil nailing construction in the field.

RÉSUMÉ
Ce document présente une recherche numérique sur le comportement d'un mur d'ongle de sol pendant les différentes étapes de l'excavation. Le clouement de sol est un système de renfort efficace pour la construction de haut en bas de maintenir des structures. Un cas bien connu en Allemagne est employé dans cette étude. En comparant le développement et la distribution de charge d'ongle à la mesure sur le terrain, on le constate que la méthode d'élément fini bidimensionnelle peut fournir une modélisation fiable du sol tridimensionnel clouant la construction dans le domaine.

1 INTRODUCTION

Over the past few decades, applications of soil nailing walls have been greatly increased in retaining structure construction. The main advantages of using soil nailing walls include, but not limited to, allowing in-situ strengthening of existing slopes, excellent working space in front of the excavation face, and requiring only light machinery and equipment for construction. It can be used for strengthening either natural slopes or man-made cuts. For the mentioned reasons the use of soil nailing walls in construction projects has increased substantially over the last three decades.

Soil nail walls are constructed in-situ and built in stages from the top down without excavating soil behind. Compared to ground anchors and other alternative top-down construction techniques, soil nail walls are relatively flexible and can accommodate relatively large total and differential settlements. It is more economical than conventional concrete gravity walls and is more cost-effective than or at least equivalent in cost to ground anchor wall system.

In addition, soil nail walls exhibit numerous features ideal for highway construction:

- less right-of-way and underground easement requirement;
- installation of soil nail walls is relatively fast and uses less construction materials than ground anchor walls;
- the system can be installed underneath an existing structure, thus saving the lateral space usually required by other sheeting and shoring methods;
- Overhead construction requirements are smaller than those for ground anchor walls because soil nail walls do not require the installation of soldier beams, which is particularly important when construction occurs under a bridge.

The development of soil nail walls can be traced back to a support system in sequential tunneling, where a passive steel reinforcement is installed in the rock followed by reinforced shotcrete. When applied to soil, this technique is termed soil nailing. One of its first applications was in 1972 for a railroad widening project near Versailles in France, where an 18 m high cut-slope in sand was stabilized using soil nails (Lazarte *et al.* 2003). Because of its cost-effectiveness and faster construction speed, the use of soil nail walls was increased thereafter in France and other areas in Europe. Its applications were further promoted by two major research programs: one in Germany from 1975 through 1981 by the University of Karlsruhe and the Bauer Group; the other is the Clouterre research program from 1986 through 1991 in France (Plumelle et al. 1990; Lazarte *et al.* 2003).

The pioneering applications of soil nail walls in North America were for temporary excavation support in the late 1960s and early 1970s. More widespread use of soil nail walls today is due in large part to the efforts of the U.S. Department of Transportation Federal Highway Administration (FHWA) (Byrne et al. 1998; Elias and Juran 1991; Lazarte *et al.* 2003). In 1994, FHWA launched the Demonstration Project 103 to disseminate further the use of soil nail walls among state highway agencies.

The finite element method (FEM) has been used widely by many researchers in soil nail wall modelling because of its powerful modelling capacity of existing FEM software (Briaud and Lim 1997; Zhou *et al.* 2009). Its applications have also increased due to the high cost and safety concerns in field testing.

Nowadays, with more powerful personal computers, three-dimensional (3-D) finite element method (FEM) is applied in analysing and designing of soil nail walls. However, because of time and cost efficiency, two-dimensional (2-D) FEM is still the most popular method in practice. This paper presents a 2-D FEM analysis of a well-known soil nail wall in Germany and verifies the reliability of 2-D FEM for this 3-D problem.

2 IDEALIZING A SOIL NAIL WALL SYSTEM

There are many modelling methods developed to simulate 3-D soil nailing problem using 2-D FEM. Each method poses advantages and limitations in approximating the true behaviour of soil nails. These methods may be categorized into three methods described below:

A. Using composite material to combine the soil and reinforcement into one material;
B. Plane strain assumption by simulating discrete reinforcements with a continuous plate; and
C. Simulation of nail as an external connection to continues soil as a connector.

The Method B was proposed by Al-Hussaini and Johnson (1978) where the discrete reinforcement was smeared into continues plate across the spacing. This is achieved by factoring the Young's modules of the plate, E_p, using area ratio factors such as the axial stiffness (EA). This method is adopted in this study.

The interface elements also were used in this study to accurately model the interaction between soil nail and surrounding soil. It is clear that when the nail is idealized as a plate, the surface area in contact with the soil is significantly increased. It would also mean that the transfer of stresses from the soil mass to reinforcement by friction across the increased area would be magnified if no reduction was taken on the interface friction.

A factor of equivalent surface area is considered in the interface friction and nail stiffness in this study, a similar method was also used by Al-Hussaini and Johnson (1978) for numerical analysis of a reinforced earth wall. The idealized 2-D plate for a 3-D nail is schematically shown in Figure 1.

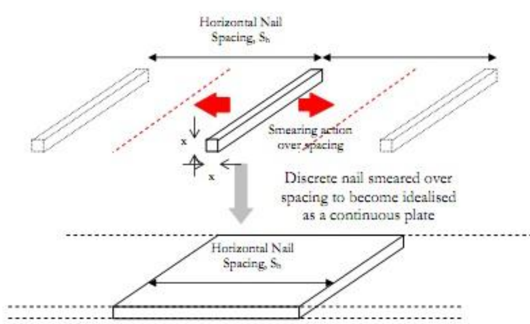

Figure 1: Smearing nail into continues plate (Al-Hussaini and Johnson, 1978)

3 A SOIL NAILING CASE IN GERMANY

3.1 Engineering Background

A large number of soil nailed walls have been constructed during the last two decades, both for permanent and temporary structures. However, only a few of them have thorough field measurement over an extensive period of time.

The case used in this study is reported by Stocker and Riedinger (1990). This nearly 15 m deep excavation was designed in a sloping terrain in Stuttgart, Germany in 1979. One side of excavation is bordered directly upon a city street, another side upon private houses. No anchor was allowed to be driven under the neighbouring buildings.

The excavation was carried out in steps of 1 or 1.1 m cover the whole length of the wall. The nails consisted of deformed steel bars with diameters of 25 mm and 28 mm, yield strength of 420 MPA, and failure strength of 500 MPA.

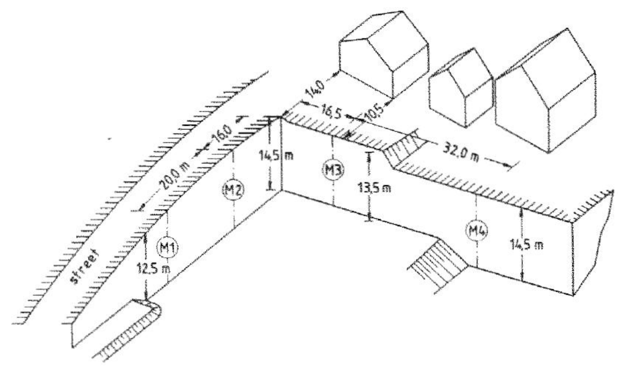

Figure 2: Site and layout of walls (Stocker and Riedinger, 1990)

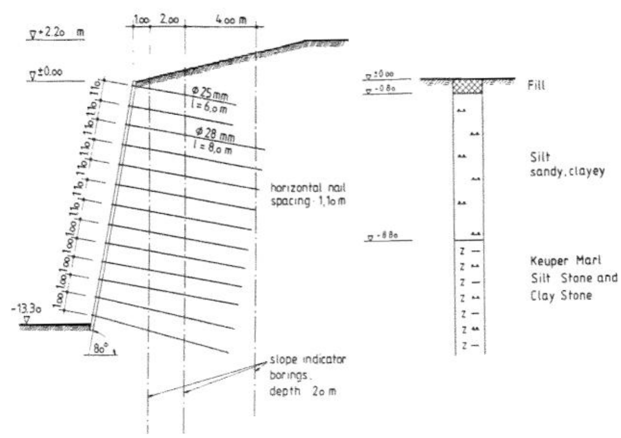

Figure 3: Typical layout of nailed walls (Stocker and Riedinger, 1990)

3.2 Site Soil Conditions

The soils at the site consisted of 0.8 to 1.8 m thick upper layer of fill material, underlain by layers of stiff to medium consistency sandy silt. Bellow these layers are a layer of claystone. The soil strata are schematically shown in Figure 3. The soil parameters obtained in the laboratory (Stocker and Riedinger, 1990) are shown in Table 1.

Table1 Typical geotechnical parameters of soil layers

	Density	Friction	Cohesion	E

	(KN/m2)		(KN/m2)	(KN/m2)
Fill	19	30	-	1000
Sandy silt	20	27.5	7	20000
Claystone	21	23	50	60000

The 2-D plane strain continueous plate method is used in this analysis. The most important factor in this method is to idealize the 3-D soil nail into a 2-D plain strain shell element with equivalent axial capacity and stiffness. To do so, two equations should be met:

$$(EA)_{plate} = (EA)_{Nails} \quad (1)$$
$$(EI)_{plate} = (EI)_{Nails} \quad (2)$$

Where E is the modulus of elasticity, A is the correction sectional area of plate or nail, I is the moment of inertia of plate or nail.

Based on these equations the thickness of the plate can be calculated from this equation:

$$T_{plate} = \sqrt{12(\frac{EI}{EA})} \text{ Nail} \quad (3)$$

$$E_{eq}=(A_{nail}/A)\ E_{nail}+(A_{grout}/A)\ E_{grout} \quad (4)$$

Where A is total gross section of nail and grout.

According to the assumptions above, the input parameters for 2-D FEM are shown in Table 2.

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Table 2. Input parameters of the nail plate in 2-D FEM

$E_{nail\ (Kn/m^2)}$	$200e^6$	$E_{eq\ (kn/m^2)}$	$37e^6$
$E_{grout\ (Kn/m^2)}$	$30e^6$	$EI_{eq\ (kn.m2/m)}$	181
$D_{nail\ (cm)}$	2	$EA_{eq\ (kn/m)}$	$2.89e^5$
$D_{grout\ (cm)}$	10	$T_{plate\ (cm)}$	8.7

The Mohr–Coulomb failure criterion is used in soil modeling. The soil properties are shown in Table 3.

Table 3: Soil properties for 2-D FEM

Soil Type	Density (kN/m^3)	Friction (Degree)	Cohesion (kN/m^2)	Module of elasticity (MN/m^2)
Fill	19	30	-	1
Sandy Silt	20	27	7	20
claystone	21	23	50	60

Based on the geometry of excavation and soil stratum conditions, a 2-D FEM model is built, as shown in Figure 4, where nails are modelled as 2-D shell elements with the same lengths as the case in the field.

4 FEM RESULT ANALYSES

A total of four nails were equipped with strain gages applied to the steel at the intervals of 0.5 to 1.5 meter (Stocker and Riedinger 1990). Thus, stresses could be measured along the axial of the nail during excavation. The distribution of nail force and its increase with the depth of excavation is shown in Figure 5. The nail force increases significantly as excavation goes deeper. The distribution of other force nails at the final excavation level is shown in Figure 6. More detailed about the measurement for long-term performance and temperature influence can be found in Stocker and Riedinger (1990).

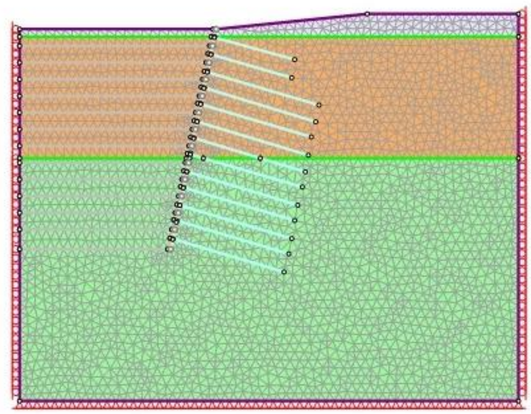

Figure 4: 2-D FEM model of soil nail wall

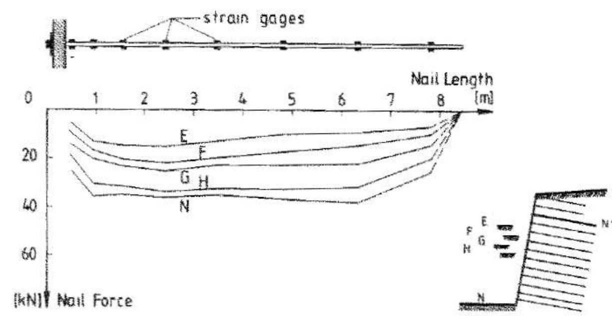

Figure 5: Distribution and change of the nail force with proceeding excavation (Stocker and Riedinger 1990)

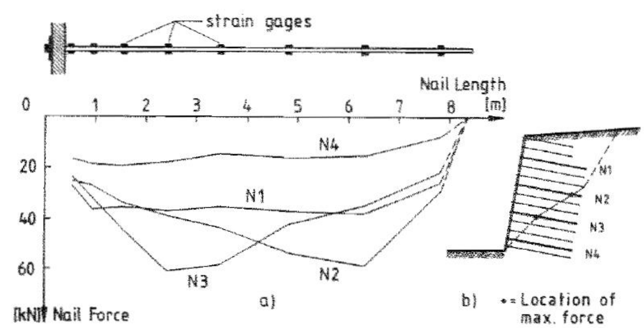

Figure 6: Distribution of nail force at final excavation level (Stocker and Riedinger 1990)

The horizontal movement of soil during construction was also monitored through slope indicators. The movement of soil during excavation is shown in Figure 7.

The displacement results are almost the same as measurements in the field and the maximum displacement occurs at the top of the wall, 60 mm. The horizontal displacement field from 2-D FEM is shown in Figure 8.

The comparison of the horizontal displacement from 2-D FEM with those of field measurement at the final excavation is shown in Figure 9, where it can be found that the 2-D FEM can provide very reliable analysis results of soil movement during construction.

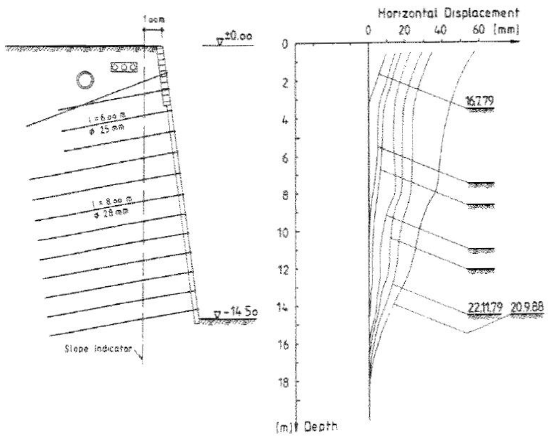

Figure- 7: Horizontal wall deformation base on different excavation level (Stocker and Riedinger 1990)

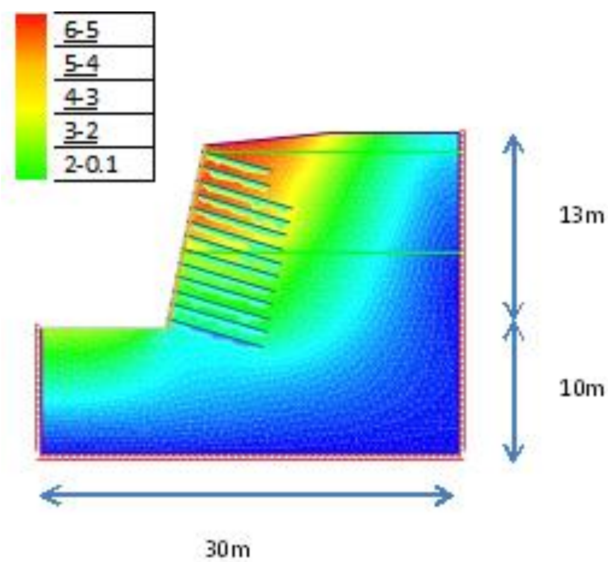

Figure 8: Horizontal displacement of soil at the end of construction (color scale in cm)

The distribution of nail load along its length is shown in Figure 10, where the maximum nail load occurred at some distance from the facing. This is similar to the field measurement. But the variation of soil nail load is much larger in FEM than field measurement. It seems the friction between nail and soil is more mobilized in the field than the one in FEM. Nails 3,7,9 and 12 are located approximately in the depth of 3,7,9 and 12 meter under earth.

The comparison between the maximum nail loads at different levels of nails is shown in Figure 11, where the FEM predicts much larger nail loads than the field measurement. However the trends from both cases are very similar. This shows that results from 2-D FEM are more conservative in predicting nail load.

The development of Nail 3 during excavation is shown in Figure 12, where the nail load increases as excavation goes deeper and deeper. This is similar to the field measurement, though there are discrepancies in the magnitude and the locus of maximum nail load.

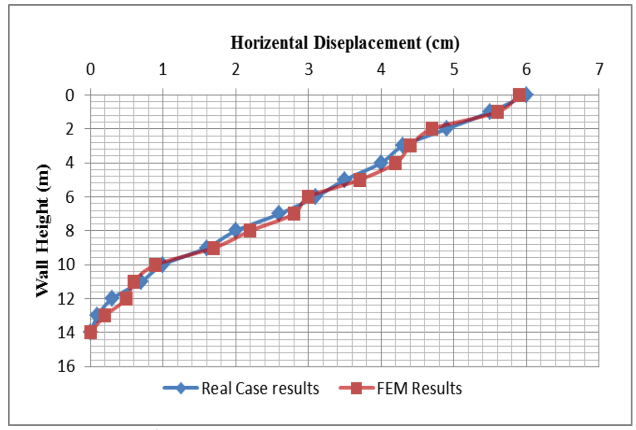

Figure 9: Comparison on horizontal displacement between FEM and field measurement

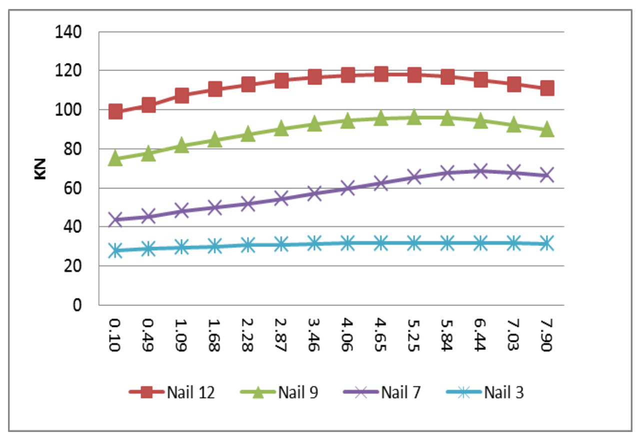

Figure 10: Load at different levels of nails at the end of excavation

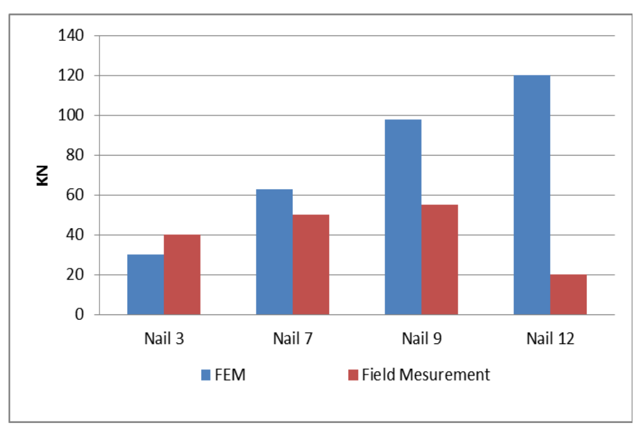

Figure: 11. Comparing nail force based on measurement and FEM

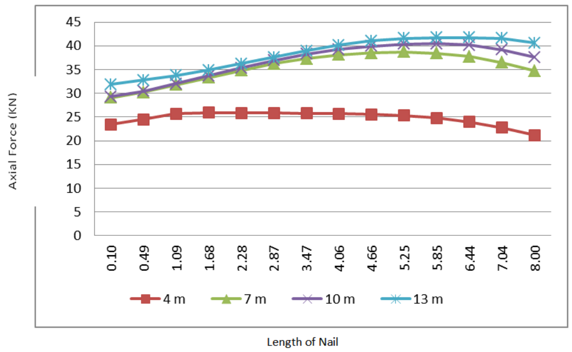

Figure 12: Development of nail load in Nail 3 with excavation

CONCLUSIONS AND DISCUSSIONS

A numerical investigation of a soil nail wall is presented in this paper. A well-known case in Germany is used in this study. A 2-D FEM is used to simplify this 3-D problem. The results show that 2-D FEM can provide reliable results, particularly in soil deformation during soil nail construction. For soil nail load, 2-D FEM tends to provide more conservative results. There are also some discrepancies for the locus of the maximum nail load compared with field measurement.

With the rapid improvements in computer technology, it is expected that more 3-D FEM analyses will be implemented with greater ease in the future. However, this study shows that a 2-D FEM can provide reliable results and will be still popular in practice due to its simplicity and easy implementation.

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REFERENCES

Al-Hussaini, M.M. and L.D. Johnson 1978. Numerical analysis of a reinforced earth wall. ASCE, Symposium on Earth Reinforcement, 98-126.

Briaud, J. L. and Y. Lim 1997. Soil-nailed wall under piled bridge abutment: Simulation and guidelines. *J. of Geotechnical and Geoenvironmental Engineering*, 123(11): 1043-1050.

Byrne, R.J., Cotton, D., Porterfield, J., Wolschlag, C., and Ueblacker, G. 1998. *Manual for design and construction monitoring of soil nail walls*. Report FHWA-DP-96-69R, Federal Highway Administration, Washington D.C.

Elias, V. and Juran, I. (1991). *Soil nailing for stabilization of highway slopes and excavations*. Publication FHWA-RD-89-198, Federal Highway Administration, Washington D.C.

Lazarte, C.A., Elias, V., et al. 2003. *Geotechnical engineering circular No. 7: Soil nail walls*. Publication FHWA0-IF-03-017, Federal Highway Administration, Washington D.C.

Plumelle, C., Schlosser, F., Delage, P., and Knochenmus, G. 1990. French national research project on soil nailing: Clouterre. *Design and Performance of Earth Retaining Structures.* ASCE, GSP 25. 660-675

Stocker, M., Riedinger, G. 1990. The bearing behaviour of nailed retaining structures. *Design and Performance of Earth Retaining Structures, ASCE GSP 25,* 612-628.

Zhou, Y. D., Cheuk, C.Y., *et al.* 2009. An embedded bond-slip model for finite element modelling of soil-nail interaction. *Computers and Geotechnics,* 36(6): 1090-1097.