NUMERICAL ANALYSIS OF SOIL NAIL WALLS COMBINED WITH PRESTRESSED ANCHORS

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KEYWORDS

Soil nails, prestressed anchors, mass displacement, ultimate limit state, failure mechanisms, numerical modelling, combining practice and theory

ABSTRACT

Soil nail walls typically consist of a shotcrete wall and soil nails and are often used for excavations and measures to ensure safety of slopes. The wall system requires a degree of deformation in the subsoil in order to activate nail forces. Soil nail walls are often combined with prestressed anchors to limit soil deformation and settlements to adjacent structures. Such combined systems might not fulfil the design requirements when the required forces in the soil nails cannot be mobilised due to limited soil-deformation in the presence of prestressed anchors. Furthermore, the prestressed anchors might influence the shape and size of failure mechanisms compared to failure mechanisms of soil nail walls without the combination with prestressed anchors. This contribution outlines first results of a numerical simulation of combined wall-systems consisting of soil nails and prestressed anchors using the 2D FE-code "Optum G2". Full-scale tests on soil nail walls are used to calibrate the numerical model. Subsequently, the results of the full-scale tests and the numerical model are compared and discussed. Furthermore, a row of soil nails is replaced by prestressed anchors in the numerical model in order to investigate differences in load-bearing behaviour between combined and ordinary systems.

1. INTRODUCTION

Soil nail walls have been utilised for many years to enable excavations and as measures to enhance the safety of slopes. Deformations of the supported structure as well as the adjacent soil are needed to activate soil nail forces. Such deformations in the soil, however, might cause damage to surrounding

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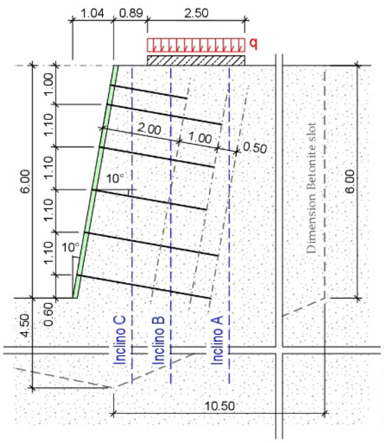
structures. Therefore, soil nail walls are often supplemented with prestressed anchors. The use of prestressed anchors influences the load bearing behaviour of soil nail walls. The basic analytical model for the dimensioning of soil nail walls (Figure 1 right) assumes that the deformations of the whole system are sufficient to fully mobilise the required nail forces in the soil. Hence, the approach does not take any strain dependent development of nail forces due to the presence of prestressed anchors into account. The interaction of soil nails and prestressed anchors has been investigated at ultimate limit state in the framework of a bachelor's thesis at the Lucerne University of Applied Sciences and Arts or *Hochschule Luzern* (HSLU) [3]. The investigation was based on finite element modelling and was calibrated using a practical example provided by Gässler [1]. Gässler investigated the load bearing behaviour of soil nail walls in large-scale tests (Figure 1 left). The results and conclusions of the investigation still represents the state of the art in the dimensioning of soil nail walls.



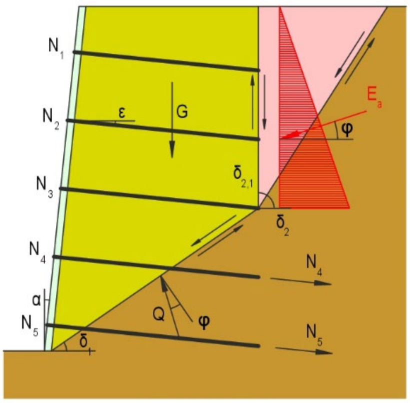


Figure 1 left: Large-scale test by Gässler (1987) [1]; right: Analytical model for the dimensioning of soil nail walls (newly drawn after Rüegger [5])

2. NUMERICAL MODELLING IN OPTUM G2

The finite element program OPTUM G2 (version 2021 2.2.20, build date 2022.08.19) with the advanced constitutive soil model HMC (Hardening Mohr-Coulomb; Krabbenhoft, 2019 [4]) was used. Gässler [1] analysed the soil present in the large-scale tests, however, the soil stiffness was not considered. Inverse calculations with different soil stiffness parameters were conducted for densely packed sand-soil. The boundary conditions and the parameter set of the numerical model are provided in Figure 2 and Table 1. The parameter-set of "hostun sand" [2] provided the most plausible results in terms of the inverse calculations and comparison to the test results of Gässler [1] (Table 1). The goal of the numerical analysis was to reproduce the large-scale tests given in [1], where the surcharge load q was stepwise increasd until failure. In accordance with this procedure, an elastoplastic analysis was carried out in OPTUM G2 with step-by-step excavation and installation of the soil nail layers. Subsequently, the load q at ultimate limit state was determined in an elastoplastic multiplier analysis.

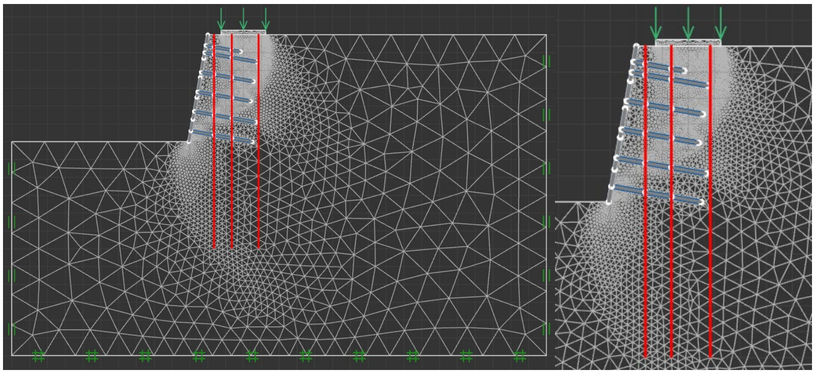


Figure 2 left: Overview of the model with boundary conditions, geometry and mesh of the numerical model for the inverse calculation of the large-scale tests by Gässler [1] right: Model details of the soil nail wall

3. RESULTS OF THE NUMERICAL ANALYSIS

Comparison with the large-scale test

The measured failure mechanisms in the large-scale test B of Gässler [1] compares favourably to the numerical analysis in terms of the failure mechanism shape as well as in terms of bearing capacity. However, the comparison of the numerical results to other large-scale tests documented by Gässler [1] does not show a good correlation. The details are shown in Figure 3. The bearing capacity of the large-scale test B reported by Gässler [1] of q = 150 kN/m^2 also compares favourably to the elastoplastic analysis with q = 134 kN/m^2. However, the nail forces obtained differ significantly.

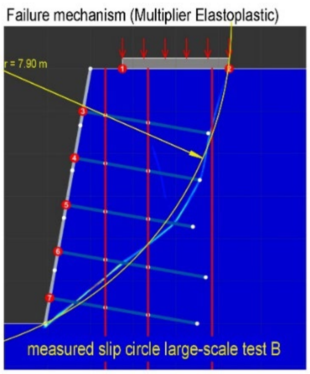


Figure 3 Comparison of failure mechanisms given by [1] to the numerical analysis

Table 1 Model explanations & input parameters

model explanations		**«Nail row» parameters**	
Width	30 m	*D*	6 cm
Height	18 m	E-Modulus	2E+05 MPa
Mesh	Adaptive net (6-n-Gauss-elem.)	Spacing	1.2 m
Boundaries	lower edge: non-displaceable	Axial strength	21.5 kN/m
	lateral edges: displaceable (vertical dir.) // non-displaceable (horizontal dir.)	Lateral strength	0 kN/m
Soil nails	Material model “nail row”	**«Plate» parameters**	
Shotcrete	Material model “plate”	*EA*	3.6E+06 kN/m
Prestressed anchor	Modelled with “Connector” and “Geogrid”	*EI*	4'320 kNm^2/m
«Geogrid» parameters		n_p	2'400 kN/m
EA	5.2E+04 kN/m	m_p	72 kNm/m
Yield force	496 kN/m	*w*	300 kg/m/m
«Connector» parameters			
E-Modulus	19.5E+05 MPa	Sectional area	4.0 cm^2
Yield strength	1'860 MPa	Spacing	1.50 m
Material parameters «hostun sand» *soil-model: HMC (Krabbenhoft, 2019) [4]*			
p_{ref}	100 kPa	φ’	42 °
m	0.55	ψ	13 °
$E_{50,ref}$	30 Mpa	*c*’	3 kPa
$E_{ur,ref}$	90 Mpa	γ_{dry}	15.6 kN/m^3
ν_{ur}	0.2	K_0	0.331

Comparison of nail forces when using prestressed anchors

The experimental setup B utilised by Gässler [1] is adopted in the numerical model illustrated in Figure 3. In the model, however, the second row of soil nails was replaced by prestressed anchors. The prestressed anchors were defined with a free anchor length of 7 m (according to Swisscode SIA 267 [6]), an anchorage length of 7 m and a fixation load of 335 kN. The free anchor length was set as «Connector» and the anchorage length as «Geogrid» ([4]; Table 1). The fixation load of the prestressed anchor was defined on the basis of a similar executed construction project with both soil nails and prestressed anchors. The relatively high fixation load was necessary to prevent excessive deformation of the supporting structure.

The results of the comparison are illustrated in Figure 4. The results indicate that the predicted nail forces in the numerical model are significantly lower with prestressed anchors compared to the numerical analysis without prestressed anchors for small surcharge loads. However, the results also show that the soil nails tend to have a similar load-bearing behaviour at ultimate limit state compared to the simulation without prestressed anchors.

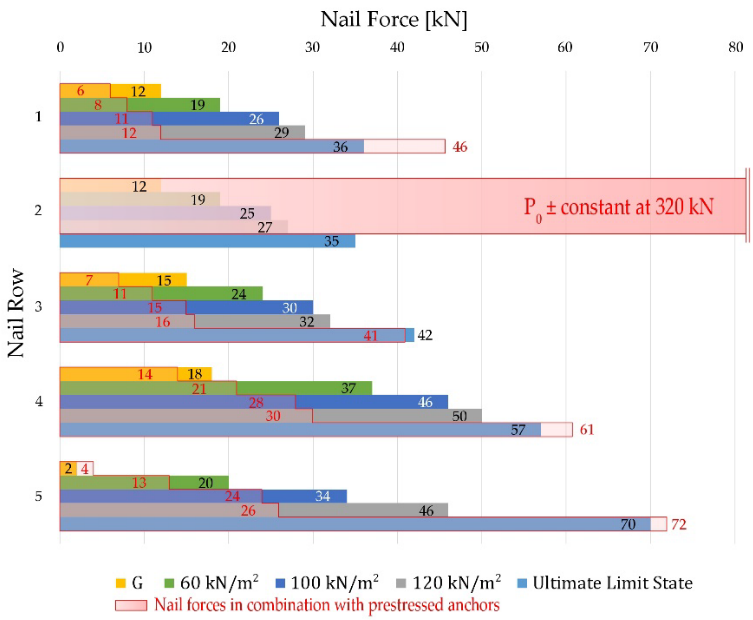


Figure 4 Mobilisation of nail forces at different levels of surcharge load q (Figure 1); G: situation without surcharge load q

The prestressed anchor row enables a surcharge load increase q = 134 kN/m^2 to 725 kN/m^2 at ultimate limit state. However, the soil nail forces remain approximately constant or with only small deviations for different values of the fixation load.

Further investigations on an idealised soil nail wall

An idealised model was created to investigate the influence of different construction stages on the mobilisation of soil nail forces (Figure 5). This model was initially defined as a soil nail system without prestressed anchors. The lengths of the soil nails were defined such as to fulfil the ultimate limit state without taking into account the dimensioning according to the design standards. An elastoplastic numerical analysis, using a φ'-c-reduction, resulted in a safety factor of 1.03. The focus was placed on the mobilisation of nail forces in the different construction stages. Details are provided in Figure 5. Subsequently, the second soil nail row was substituted with prestressed anchors to compare the mobilisation of forces. The fixation load was again set with a relatively high value as the variation of the fixation load did not significantly influence the mobilisation of soil nail forces, as portrayed in Figure 4.

The results in Figure 6 again indicate that the soil nail forces tend to decrease with the presence of prestressed anchors. Comparison of the results given in Figure 6 to the system described by Gässler [1] (Figure 4) shows that the mobilisation of additional soil nail forces over the various construction stages is clearer for the situation given in Figure 5. Figure 7 indicates the horizontal deformations of the soil nail wall at the final construction stage as well as the visualisation of a potential failure mechanism. These results show that a failure mechanism develops below the prestressed anchor row, which might explain the more pronounced mobilization of soil nail forces with continuing construction stages. The safety factor of the failure mechanism illustrated in Figure 7 using a φ'-c-reduction is 1.3.

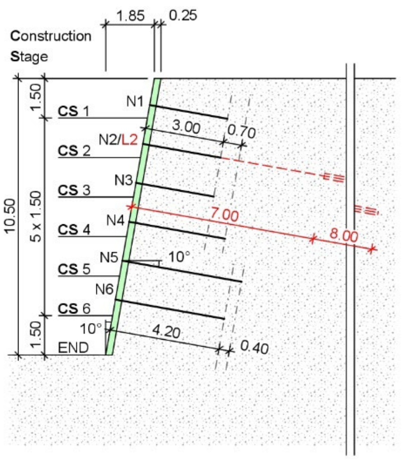


Figure 5 The idealised soil nail wall with the construction stages CS 1-CS 6 and the prestressed anchor row L2

The observed failure mechanism presents itself as a rigid body rotation around a point in the vicinity of the prestressed anchors, resulting in a potential pull-out failure of the soil nails in the layers below the prestressed anchors.

This might also be the cause for the more pronounced mobilisation of soil nail forces with ongoing construction stages. Therefore, the analytical model to investigate the safety of soil nail walls proposed by Gässler [1] and illustrated in

Figure 1 is not valid for the herein investigated situation because a different failure mechanism is seen to be mobilised at ultimate limit state. However, failure mechanisms affecting the entire soil nail wall system need to be analysed also.

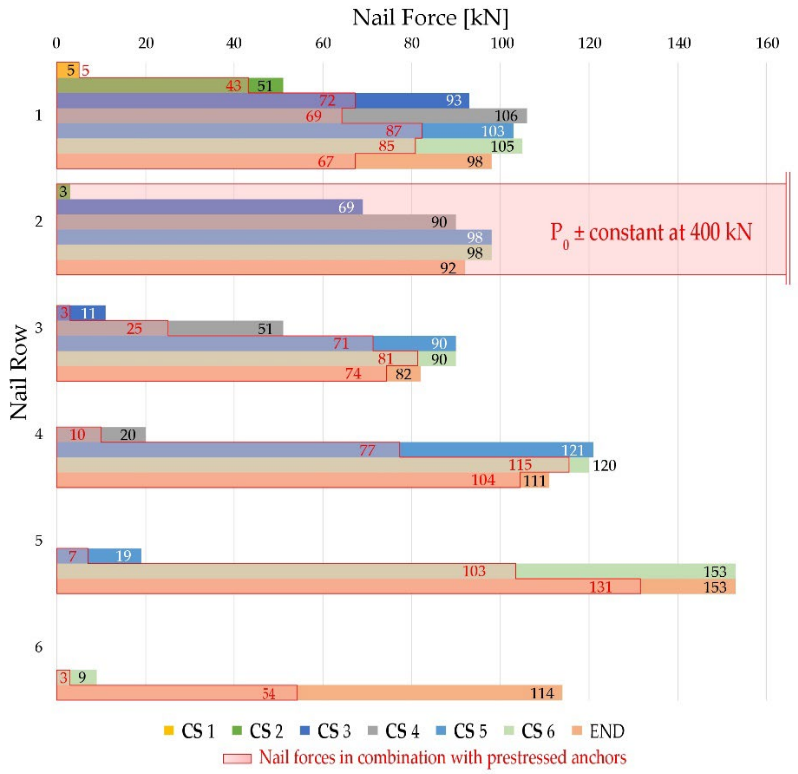


Figure 6 Soil nail forces of the idealised system for different construction stages

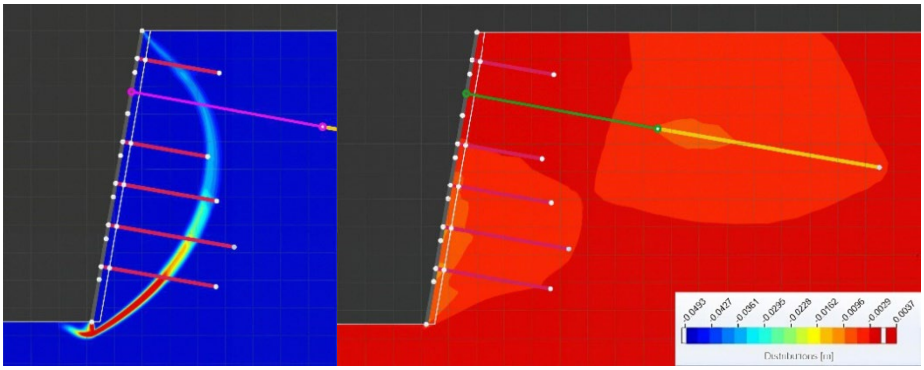


Figure 7 left: Possible failure mechanism (visualisation of shear dissipation) right: Horizontal deformations

CONCLUSIONS

The numerical investigations clearly show that the presence of prestressed anchors in a soil nail wall has a direct influence on the forces mobilised in the soil nails. All numerical simulations show decreasing soil nail forces due to the presence of prestressed anchors. The overall stability of the supporting structure at ultimate limit state was not decreased in comparison to ordinary soil nail walls. However, the fixation loads of the prestressed anchors were relatively high in order to prevent deformations of the supporting structure.

The investigation of various construction stages predicts a critical failure mechanism in the form of a rigid body rotation below the prestressed anchor row. Therefore, it is important to also investigate failure mechanisms which are not formed over the overall height of the soil nail wall but develop below prestressed anchor rows – especially for prestressed anchor rows located near the top of the wall. Consequently, the position of prestressed anchor rows in soil nail walls can lead to incorrect dimensioning of the wall if failure mechanisms tend to form below the prestressed anchor rows. The well-known analytical model given by Gässler [1] should hence be supplemented with failure mechanisms which are formed below the prestressed anchors with continuing construction states.

The numerical results are to be verified in terms of physical modelling to compare the development of failure mechanisms and to gain more information on the real behaviour of soil nail walls in combination with prestressed anchors.

ACKNOWLEDGEMENT

The authors would like to thank MSc ETH Jürg Nyfeler for his valuable input and the numerous discussions including his practical perspective as external examiner for the bachelor thesis.

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