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Centrifuge model tests on soil nail walls combined with prestressed anchors

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ABSTRACT: Soil nail walls are often used for excavations and measures ensuring safer slopes. They consist of a shotcrete wall fixed with a certain pattern of soil nails. The wall system requires a degree of deformation in the contained soil in order to activate the nail tensile capacity. Soil nail walls are therefore often combined with prestressed anchors that limit soil deformation and settlements on adjacent structures. Nevertheless, such combined systems might not fulfil the design requirements if the nail tension cannot be mobilised due to limited soil deformations by the presence of prestressed anchors. Furthermore, the activation of prestressed anchors might influence the shape and size of the expected failure mechanisms. This work addresses this effect by means of centrifuge modelling, exploring the contribution of single-row prestressed anchors at variable heights, comparing them with a control model with no prestressed anchors. The test setup and model results provide an insight into the governing failure mechanisms.

1 INTRODUCTION

Soil nails walls are being used as supporting structures for excavations since decades. They usually consist of a shotcrete wall and several rows of soil nails. The method is well established and allows usually for low-cost excavation pits. However, nails need a certain amount of deformation in the soil to mobilise their tensile capacity. This behaviour gives some limits to its use in terms of serviceability limit state (*SLS*). To reduce the wall-deformation at *SLS,* prestressed anchors are more often used in combination with soil nails.

Gässler (1987) investigated the load-bearing behaviour of soil nail walls in terms of analytical models as well as with model- and large-scale tests. He concluded that the dimensioning of soil nail walls using limit equilibrium methods (e.g. Atkinson, 2007) is sufficient in terms of the studied load-bearing behaviour. There might be certain limits with the use of limit-equilibrium methods in terms of force mobilization of the nails with the use of prestressed anchors as the prestressed anchors tend to constrain the mobilization of tensile forces in the nails. The strain-stress conditions of the soil as well as the deformation-dependent behaviour of soil nails play a crucial role at ultimate limit state (*ULS*). Therefore, the question rises as to whether the full nail resistance can be assumed to be mobilised at *ULS*. Dietrich & Arnold (2024) investigated the load-bearing behaviour of nail forces in combined soil nail systems numerically. However, the validity of their observations remains to be confirmed. In this work a centrifuge model is used to compare the results already gained and gain further insight into the load-bearing-behaviour of soil nail walls combined with prestressed anchors.

2 PHYSICAL MODELLING

A scale model of a simplified soil nail wall is tested at TU Delft's geotechnical centrifuge (Allersma 1994). A stepwise load increase above the soil nail wall is applied to study the load-bearing behaviour at *ULS*. The tests are conducted at 60*g* with a model scaled by 1:60 compared to its prototype (Schofield, 1980).

2.1 Model scaling & preparation

Prior to the centrifuge modelling a prototype of a soil nail wall combined with one row of prestressed anchors as given in Fig. 1 was analysed in detail using the Finite Element Method (*FEM*) code OPTUM G2 (Krabbenhoft et al. 2016). The supporting structure was dimensioned in terms of nail length and prestress force according to the Swiss design code SIA 267 (SIA, 2013).

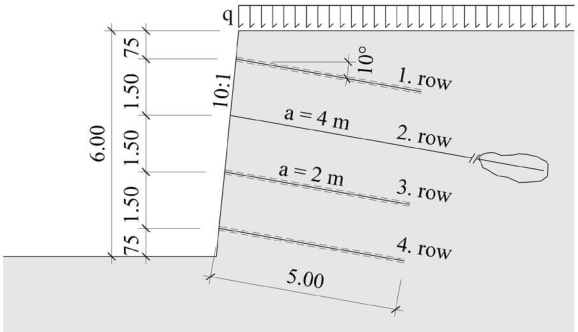

Figure 1: Prototype of a soil nail wall combined with prestressed anchors. All units in m.

The prototype was then transformed to a model according to the scaling principles (Garnier et al. 2007; Madabhushi, 2014) for length, bending stiffness, axial stiffness and force. The prototype soil nail wall is simplified into four horizontal nail rows, separated 25 mm from center-to-center (see Figs. 2 and 3). The load plate was dimensioned to minimize its effect on the expected failure mechanism in the soil.

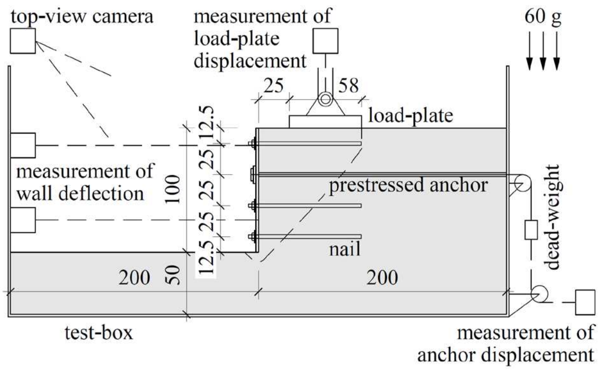

Figure 2: Sketch of the centrifuge model of the soil nail wall combined with prestressed anchors

The shotcrete wall, with a prototype thickness of 150 mm, was scaled according to the bending stiffness *EI* to an aluminium plate of 2 mm thickness. The model nails consist of 3 mm in diameter and 83 mm long PMMA rods, matching the scaling of the axial stiffness *EA*. These model nails are coated with mortar to realistically model the interface between nail-injection and surrounding soil (see Fig. 3).

Figure 3: construction of the soil nail wall model using coated PMMA model nails

The prestressed anchors consist of Dyneema SK78 (FibrXL, 2020) cords, routed through a Teflon-casing and fixed in one end to the retaining wall and on the other to a counterweight. In this modelling approach, the anchoring with the surrounding soil, where the prestress-force is usually mobilised, was not modelled. Instead, the prestress force was applied through a dead weight situated outside the box (see Fig. 4). This setup allows for a constant anchoring force, scaled by the *g*-level. An anchor force of 260 kN was applied by using a dead weight of 125 g at 60*g*.

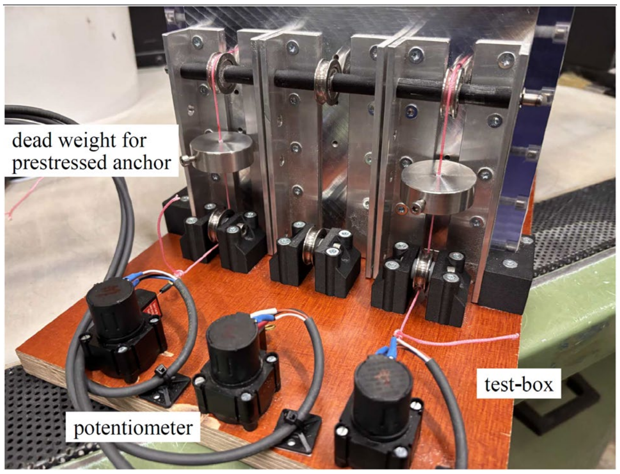

Figure 4: back-view of the model box. Dead weight and Dyneema cord connected with potentiometers to measure the displacement of the anchor-cord

For simplicity, dry Geba Sand (Quinten et al., 2025) air pluviated into the strongbox at a soil relative density of $I_D \approx 40\%$ was used as the soil model.

Pull-out tests have been conducted on the model nails at 1*g* to narrow down the load-bearing behaviour of the nails in the centrifuge model, according to Milligan and Tei (1998) and the SIA codes 267 and 267/1 (SIA, 2013). The pull-out tests were conducted under dead-weight surcharges to have realistic stress conditions at the nail-soil interface (see Fig. 5) and agreed well with typical values obtained in practice.

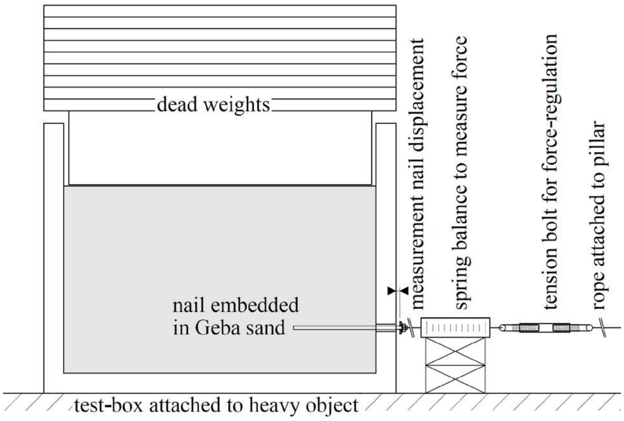

Figure 5: Test-setup for the pull-out tests of the model nails.

2.2 Test protocol & data acquisition

The soil-nail model (see Fig. 6) is brought to an equivalent acceleration of 60*g* and then loaded vertically at the top of the wall (see Fig. 2). The load is applied under displacement control, with a penetration velocity of 0.01 mm/s. During loading, the horizontal wall deflection is measured at the wall thirds via point laser measurements. The prestressed anchor displacement is measured using potentiometers, through the cord connection with the counterweights (see Fig. 4). The applied load and vertical displacement of the load-plate is recorded through a load cell connected to the vertical actuator and its corresponding displacement, respectively. Finally, the model side view is recorded with an action camera.

3 FIRST RESULTS

Preliminary tests showed that the nail length given in Fig. 1 was not feasible as the test setup could not be brought to failure. Therefore, the nails were shortened from 83 mm to 65 mm, at model scale, and only two instead of three prestressed anchors were built in one row. Results of two tests, one with soil nails only and one with one row of prestressed anchors is shown in Fig. 7.

3.1 Determination of failure

The overall wall deflection compared to the applied load is shown in Fig. 7. An acceleration of wall deflection can be seen and therefore the tangent method as described in Atkinson (2007) is applied to localise the potential failure of the soil nail wall. A similar approach has been used for the wall with prestressed anchors. There, the wall deflection rate fits the deflection of the anchor cord. Again, using the tangent method shows the potential failure of the combined system.

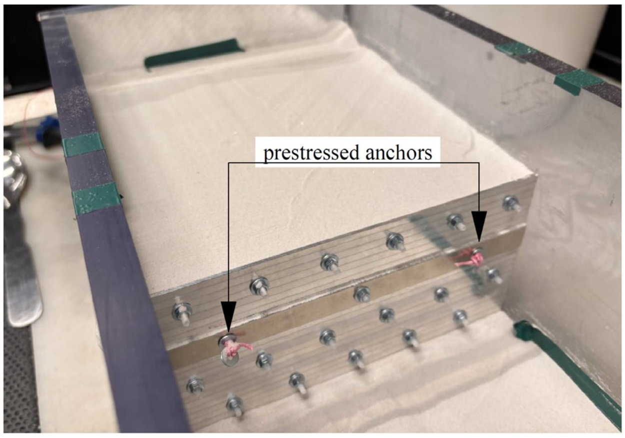

Figure 6: Typical test setup

Fig. 7 shows an increase of wall deflection at 550 N in model scale for the soil nail wall whereas the wall deflection increase starts at 1110 N at model scale for the soil nail wall with prestressed anchors. Furthermore, wall deflection measurements show that the wall with prestressed anchors has less displacements with increasing load compared to the wall without prestressed anchors.

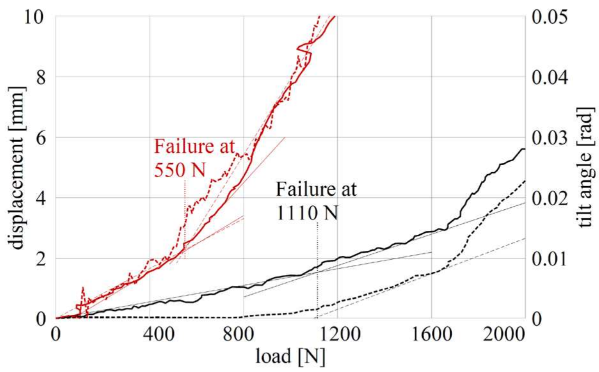

Figure 7: Wall deflection (red, solid line) and wall inclination (red, dashed line) versus applied load for the test with only nails. Wall deflection (black, solid line) and displacement of the prestressed anchor (black, dashed line) versus applied load for the test with prestressed anchors.

4 DISCUSSION AND OUTLOOK

The overturning of the soil nail wall during the centrifuge test shows a potential failure mechanism (see Fig. 8) and makes clear that the model shotcrete wall displaces horizontally as well as it rotates.

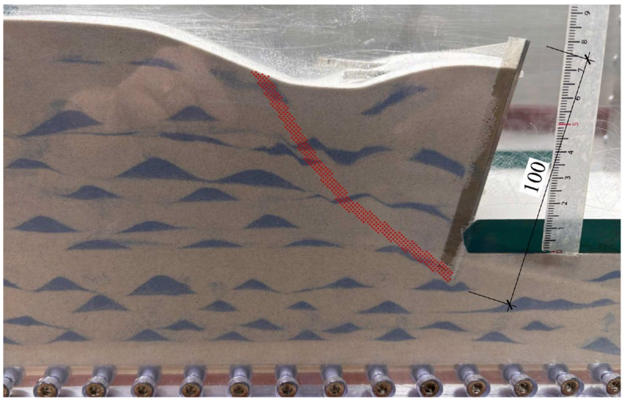

Figure 8: Soil nail wall at failure; thick line in red corresponds to the interpreted shear band

The soil nail wall with prestressed anchors in the second row shows a similar failure mechanism (see Fig. 9), but with a clear influence of the prestressed anchors limiting the horizontal displacements as well as showing less wall rotation. This results also in a higher surcharge load at *ULS* as given earlier (Fig. 7). The prestressed anchors (Fig. 7) show that with achieving *ULS* as defined earlier, the anchor cord starts to move.

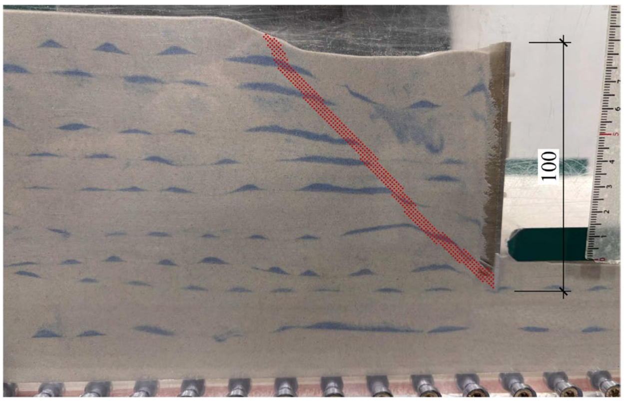

Figure 9: Soil nail wall with prestressed anchors in the second row at failure; thick line in red corresponds to the interpreted shear band

A corresponding prototype of the soil nail wall with prestressed anchors explored in this work is expected to experience an increase of supporting load on the prestressed anchors until reaching failure. However, this effect of load increase could not be modelled because the prestress-force was applied through dead weights which did not allow for a load increase. An increase of prestress-force would potentially give even more stiffness to the wall system.

The indication of first test results shows the expected differences in load-bearing behaviour of the two wall systems. However, a more detailed evaluation of the test results is needed. Nevertheless, the results here presented give the possibilities for a direct comparison with equivalent numerical models and a review of current design approaches.

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