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LOAD TRANSFER IN SOIL ANCHORS – FINITE ELEMENT ANALYSIS OF PULL-OUT TESTS

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Abstract: Soil anchors are widely used to stabilise soils and provide additional support to earth retaining structures. They are found in critical civil infrastructure such as transportation networks like highways and railways. Understanding their behaviour is important for the safety of these structures and the public. Therefore, careful design with appropriate soil parameters is required to ensure their efficiency.

Finite element (FE) analysis is a powerful engineering tool that is able to predict the response of soil anchors. Various types of FE models are used, such as 2D axisymmetric or full 3D solid continuum and the more practical load-transfer FE analysis. Usually relevant field or laboratory tests are required in order to define the model parameters. Field pull-out tests are one of the most common and reliable type of such tests.

This study presents field data from such field tests that were carried out on in-situ ground anchor systems, using strain gauges to evaluate the changes in the variations of axial load and skin friction along the nail during the tests. The results of these field tests provide details about the development of skin friction with induced displacements, thus offering the opportunity to perform load-transfer finite element analyses of the soil anchor.

A FE model based on the load-transfer approach is developed to analyse this soil-structure interaction problem. A number of FE analyses using parameters derived from the field tests are run to validate the finite element load-transfer models which are compared with the field test results and exhibit an excellent agreement.

Keywords: soil anchors; soil-structure interaction; pull-out tests; finite element analysis

1. Introduction

Soil anchors are widely used to control displacements of retaining walls by resisting the movement and via utilising the available pre-stress. The pre-stress can originate from enhancing the shear resistance of soil and the skin friction at the interface between the grout material and soil mass. An important aspect of soil anchor design is the interface shear strength between the grout and the surrounding soil (Tagaya et al., 1988; Powell & Watkins, 1990, Kumar & Kouzel, 2008). Various laboratory experiments and field tests may be performed to define the shear behaviour between the grout and the surrounding soil, and one of the most reliable is the so called field pull-out test (Merrifield & Sloan, 2006; White et al., 2008; Seo et al., 2011a, 2017).

The interface behaviour between a soil-nail and the surrounding nail is very complex in nature because the governing mechanism involves shear banding development at the nail-soil interface, hoop stresses around the circumference of the nail and increase of confining pressure with the depth (Seo et al., 2012, 2014a, b). The problem becomes even more complicated when there is a hybrid soil-nail and compression anchor system (Seo et al., 2010, 2011b) where the behaviour is governed by a combined action of nail compression and anchor tension. Detailed experimental and numerical studies (Seo et al., 2016) are required to obtain an adequate understanding of the problem.

This paper presents an approach to defining load-transfer curves for soil anchors using instrumented anchor pull-out field tests. This approach has been used before to a certain extend in distributed fibre optic sensing (Soga et al., 2015, 2017; Kechavarzi et al., 2016; Di Murro et al., 2016; Acikgoz et al., 2016, 2017) and was applied to monitoring axially loaded piles (Ouyang et al., 15; Pelecanos et al., 2016, 2017a,b) and geothermal energy piles (Ouyang et al., 2018a,b,c).

The paper is arranged as follows: it first introduces the problem and then presents the monitoring data from a field test along with the developed load-transfer curves. Finally, it applies these curves to a finite element analysis of the field test as verification and shows that indeed load-transfer curves are a reliable approach to modelling the deformation behaviour of soil anchors.

2. Field tests

2.1 Problem statement

Pull-out tests of soil anchors are performed in order to assess their ultimate capacity and also obtain some relevant geotechnical parameters for anchor design and soil-structure interaction studies. In particular, for performance-based design, where one is interested not only in the ultimate limit state but also in the pre-yield performance (e.g. magnitude of expected displacements and deformations) field pull-out tests are useful in defining the load-transfer response of soil-anchor systems.

The problem is described graphically in Figure 1: (a) an anchor pull-out test in carried out in the field by pulling the strands within the anchor, which are attached at the bottom of the anchor. This effectively results in a force load acting at the bottom of the anchor with an upward direction; (b) if one is interested in modelling this numerically, a possible practical approach would be to use a finite element beam-spring model that requires nonlinear load transfer curves to define the soil springs. So, the issue here is how one can define reliably the parameters for those nonlinear soil springs.

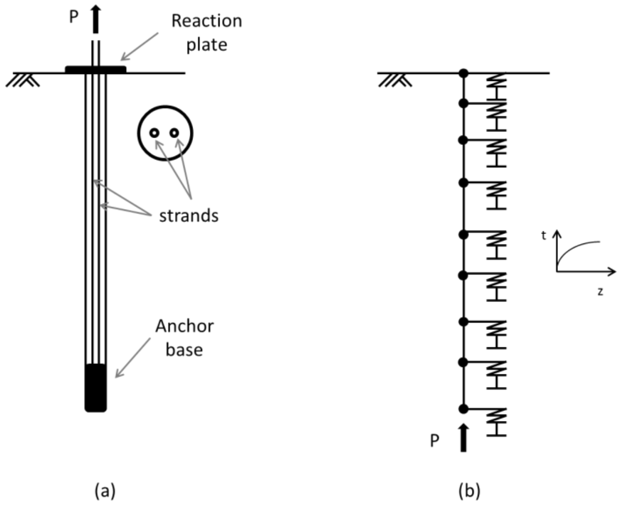


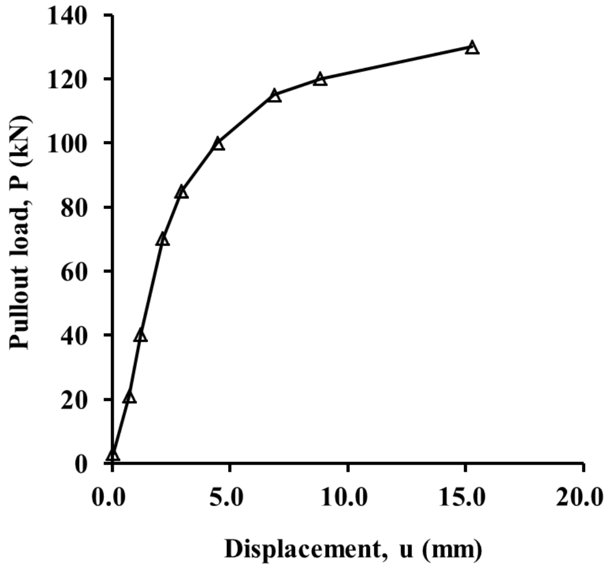
Figure 1: Problem definition: (a) an anchor pull-out field test and (b) a relevant finite element beam-spring model.

2.2 Pull-out tests

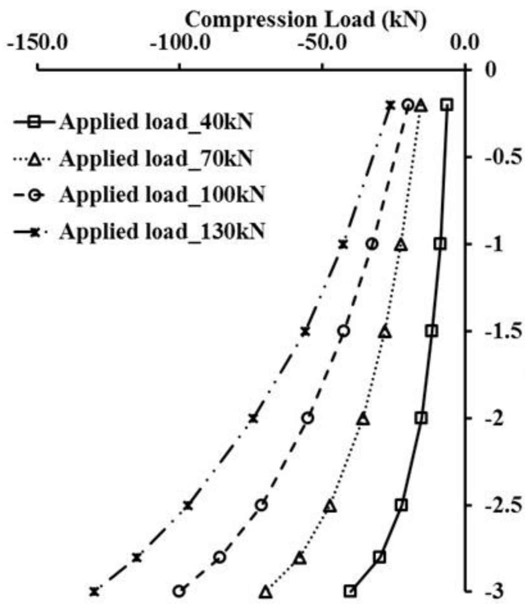
An anchor pull-out field test was performed in Seoul, Korea. The tested PC strands were made of steel with a diameter of 12.7 mm and it is 3 m long. The ground anchor consisted of two PC strands within the plastic pipes, and an anchor body. The maximum yield load of two PC strands was 318 kN. The PC strands were located in a plastic pipe which was filled with oil so that friction was not generated between two PC strands and plastic pipes when PC strands were pulled out. Therefore, applied pull-out load was transferred directly to the anchor body, and then the anchor body could push the grouting material. To measure this load propagation within the grouting, vibrating wire strain gauges (VWSGs) (SG4150 manufactured by GTC cooperation) were installed by using steel wires to fix beside a steel bar. A total of seven VWSG were installed along the bar with some intervals.

The anchor pull-out load was increased progressively and strain values from the VWSGs at 4 load steps (40, 70, 100, 130kN) were recorded. Figure 2 shows the results of the pull-out test. Figure 2 (a) shows the soil anchor top lop-displacement curve, (b) shows the profiles of axial force, whereas (c) shows the profiles of anchor skin friction. Axial force was calculated by multiplying the monitored axial strains with the axial rigidity, EA, (E is the anchor's Young's modulus and A is anchor cross-sectional area). The values of skin friction were calculated by differentiating the values of axial strain with the depth.

It is shown that the soil anchor reaches an ultimate load capacity at just above 130kN and that the values of axial force and skin friction increase progressively as the applied load increases. As expected, larger values of both axial force and skin friction occur at the bottom of the anchor, which is closer to the point of action of the load.



(a)



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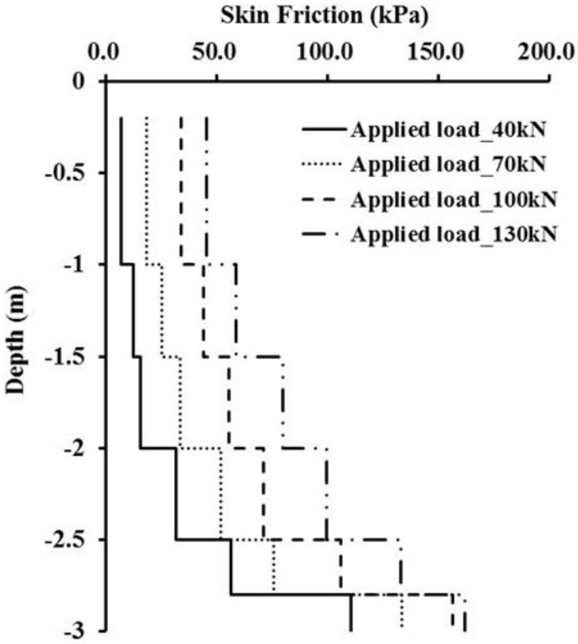


(c)

Figure 2: Field test results: (a) anchor top load-displacement curve, (b) profiles of axial anchor force and (c) profiles of anchor skin friction.

2.2 Observed load-transfer curves

Further post-processing of the monitoring field data can provide values for the skin friction and the vertical displacements of the soil anchor. Skin friction values can be obtained by direct (numerical) differentiation of the axial force values with the depth. Vertical displacement values can be obtained by numerical integration of the axial strain values, with the depth. Integration can provide the values of relative displacement, not total displacement. To get total displacement, one needs to add the integrated values to absolute values from readings at a fixed point. In this case, the fixed point was at the top of the anchor, as shown in the top load-displacement curve. Plotting together skin friction and vertical displacement at different depths along the soil anchor, one can get the load-displacement (t-z) curves at those depths. These are shown in Figure 3.

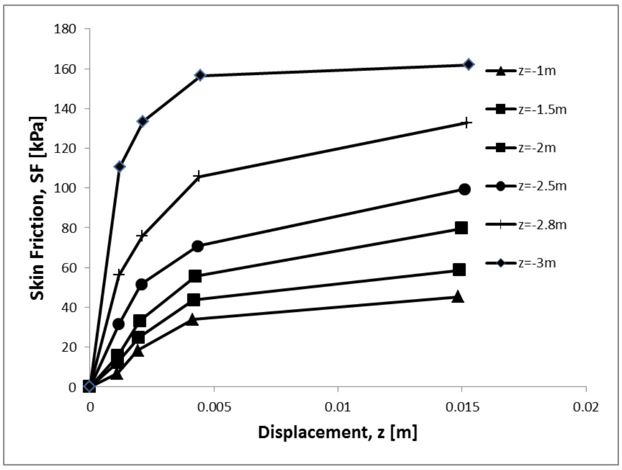


Figure 3: Developed load-transfer curves from the field test at different depths along the anchor length.

3 Finite element analysis

3.1. Numerical model

The monitored data from the field tests described above were used to develop a numerical model of the field test. The computational model is based on a finite element beam-spring formulation where the soil anchor is modelled with two-noded beam elements with axial displacement degrees-of-freedom, whereas the surrounding soil is modelled with nonlinear springs. The governing finite element equation (Eq. 1) satisfies global equilibrium and the global stiffness matrix consists of the anchor stiffness matrix, K_a, and the soil stiffness matrix, K_s. Applied loads are applied at the bottom of the anchor and define the load vector, P, and the solution of the equation provides the vector of vertical nodal anchor displacements, u.

$$([K_a] + [K_s]) \cdot \{u\} = \{P\} \qquad (1)$$

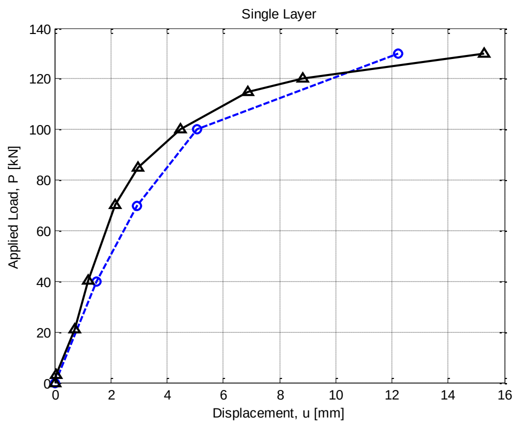
The soil springs follow a nonlinear load-transfer curve (t-z) described by a hyperbolic-type relation, given in Eq. 2. This equation relates shaft friction, t, with local nodal displacement, z. It is a 4-parameter relation in which tm and km define the ultimate friction and maximum soil stiffness respectively. Finally, dimensionless parameters d and h describe stiffness degradation and hardening/softening respectively (Pelecanos & Soga, 2017a,b, 2018).

$$t = \frac{k_m \cdot z}{\sqrt[d]{\left[1 + \left(\frac{k_m}{t_m} \cdot z\right)^{(h \cdot d)}\right]}} \qquad (2)$$

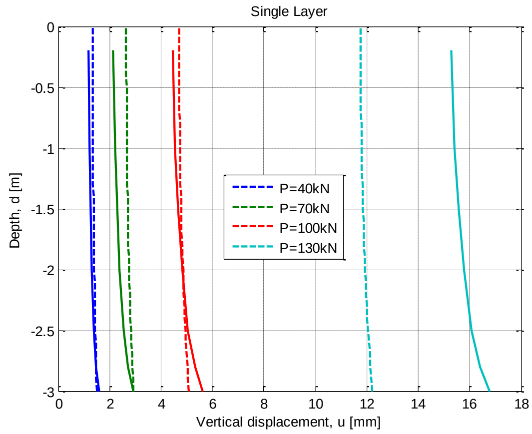
3.2. Analysis of field test

The results of the finite element analysis are shown in Figure 4 along with the field monitored data. Figure 4 (a) shows the anchor top load-displacement curve, (b) shows the profiles of vertical anchor displacement, (c) profiles of the axial anchor force whereas (d) profiles of the anchor skin friction. It is shown that there is a very good match between the field observed data and the numerically predicted values from the finite element model. This suggests that the derived load-transfer curves are adequate for modelling displacements, deformations and ultimate response of soil anchors.

It may also observed that there is a small mismatch between the numerically predicted values of axial anchor force and those of the field test, especially close to the top of the anchor. More specifically, it is observed that the numerical model predicts zero values of axial force at the top boundary. The zero values from the model are expected, as the boundary condition at the top of the anchor is free. It is anticipated that the non-zero values of axial force from the field data are due to the presence of the reaction plate at the top of the anchor which has resulted in some plate-soil-anchor interaction. This difference however is rather small and therefore can be ignored.



(a)



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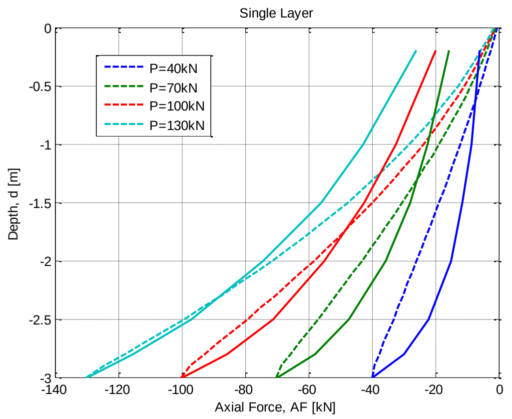

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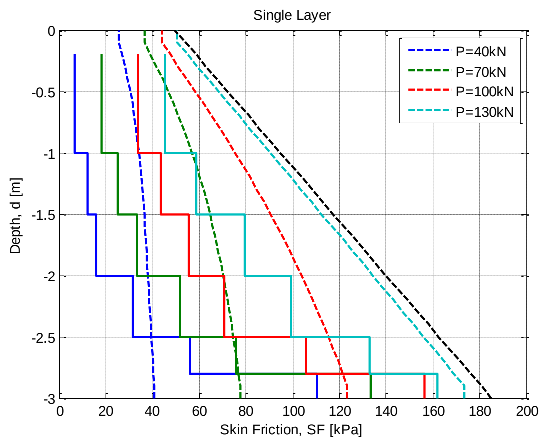

(d)

Figure 4: Results of finite element analysis: (a) anchor top load-displacement curve, (b) profiles of vertical displacement, (c) profiles of axial force and (d) profiles of skin friction.

4 Conclusions

The complex interaction behaviour between soil nails and the surrounding soil is an outstanding engineering problem. Issues related to the confining pressure, the hoop stresses around the circumference of the nail and the shear banding behaviour need to be understood.

This paper presents an approach to determine load transfer curves in soil anchors. It uses field pull-out tests to determine the skin friction and vertical displacement values which when plotted together can show the load-transfer development.

The results of a recent field test in Seoul, Korea are presented, processed and discussed. Subsequently, load transfer curves are developed and relevant finite element analyses are performed which compare reasonably well with the field data. This serves as verification for the proposed method which suggests that this procedure may be used to define the deformation response of soil anchors.

It is shown that soil nails exhibit load-transfer behaviour similar to axially-loaded foundation piles. In particular there is an observed consistency in developed skin friction with the induced displacements. Therefore, the use of a 1D finite element beam-spring formulation with relevant t-z curves appears to be an appropriate method to numerically analyse the deformation and displacement behaviour of soil nails.

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