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Research Paper

Two- and three-dimensional analyses of excavation support with rows of dry deep mixing columns

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ABSTRACT

In this study, a 2D model of an excavation with a tied back sheet pile wall in interaction with perpendicular rows of deep dry mixed overlapping columns was compared to a 3D model. A method to take into consideration the effect of the overlap zones between columns in a 2D model, where the improved soil was modeled as a composite material, was investigated and the results between the 2D and 3D analyses were compared with focus on predicted failure load, failure mechanism and deformations. The results of this numerical study show that both the area improvement ratio of the improved soil and the quality of the overlap zone has a significant influence on how well a 2D model that incorporates the overlap zone between columns, performs compared to the 3D model.

1. Introduction

Dry deep mixing with lime-cement columns has been used extensively since the mid 1970s mainly to reduce settlement and to some extent to improve stability of road and railway embankments. Deep mixing has been used as reinforced retaining structures [1–5], but one relatively new application is to install columns on the passive side in an interaction with sheet pile walls. Columns are installed in rows or blocks inside the sheet pile wall and thereby increase the passive resistance and after excavation act as a ground improvement of the excavation bottom and foundation of the construction.

Laterally loaded columns have been investigated theoretically, numerically and experimentally by means of model tests by many researchers [6–32]. These studies have mainly considered laterally loaded columns due to embankment loading. The main conclusions are that single columns have limited effect on the improvement of stability and that overlapping columns should be installed in rows perpendicular to the embankment, in order to improve the moment capacity and the interaction with the surrounding soft clay.

A few case studies and numerical analyses of the deep mixing column type of ground improvement in deep excavations have been published [33–38]. In the majority of the numerical analyses that have been made, 2D "plane strain" models or 3D analyses where the improved soil is modeled as a composite material have been used. A study by Yang et al. [39] investigated the behavior of embedded improved soil raft to help restrain the movements of a retaining wall by conducting numerical analyses of a hypothetical case and simulation of a reported case history. An embedded improved soil raft is short soil cement columns that overlap with each other to form a continuously improved composite ground that acts like a strut below the excavated ground level. The authors examined the mechanisms of how the mass properties of the improved soil are mobilized, and how application of different material properties in the horizontal direction within a column and the geometrical arrangement of the columns, affects the degree of mobilization of the mass properties for the raft compared to the elemental properties. Based on these results, Yang et al. suggest that soil–cement columns used to improve the stability of excavations should be constructed with overlap rather than just in contact with each other. The results and conclusions presented by Yang et al. explains how the properties within the columns and how different arrangement of the columns influences the degree of mobilization of the material elemental properties, but when the soil improvement consists of column rows, even the distance between the column rows and the interaction between the columns and the soft soil between the column rows will have a significant effect on the overall behavior of the structure and the type of failure mechanism that will be obtained.

The system of a retaining structure where the soil is improved by deep mixing columns is a complex three-dimensional mechanical system in which the retaining structure, the columns and the soft

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soil between the columns interact. It has not been investigated how well a 2D plane strain model, where the improved soil is modeled as a composite material, can reflect the interaction between the column rows and the soil between the rows with respect to stress distribution, shear stresses, and relative movements between the columns and the soft soil that is free to move relative to the rows. Due to computational costs there is a great need for 2D analyses that can simulate the mechanical system sufficiently reasonable.

The aim of this study is to investigate if a 2D model can predict the ultimate limit state behavior regarding failure load, failure mechanism, stress–strain relationship, and deformations up to failure load, compared to a 3D model when the columns are subjected to lateral forces. Because several previous studies have shown that the strength properties of the overlapping zone are often lower than the strength of the columns, [26,40–41] the effect of a weak overlapping zone has been included. The paper investigates a method to model the vertical overlap between the columns in a 2D plane strain model compared to a 3D model. The results of the study are intended to provide an insight into the ability of a simplified 2D model to reflect the behavior of a 3D mechanical system consisting of rows of overlapping dry deep mixing columns subjected to lateral loading.

2. Finite element analyses

2.1. General

The finite element program PLAXIS 3D 2012 was used in this study. The soil and the columns were modeled with 10-node tetrahedral elements. Both the 3D model with rows of columns and the 2D plane strain model with a composite soil volume were modeled with PLAXIS 3D in order to eliminate possible sources of uncertainty related to the two principal geometrical problems.

2.2. General geometrical and geological model

The soil consists of 1 m of stiff dry crust overlaying 10.5 m of normally consolidated very soft clay over very stiff frictional soil. The stiff frictional soil was not included in the model. The vertical model boundaries parallel to the *yz*-plane are fixed in *x*-direction and free in *y*- and *z*-directions while vertical model boundaries parallel to *xz*-plane are fixed in *y*-direction and free in *x*- and *z*-directions. The model bottom condition was chosen fixed in all directions while the ground surface is free in all directions. The groundwater table was set at the top of the soft clay, 1 m below the ground surface. In order to avoid boundary effects, the length of the model was chosen to be 35 m and its width, due to symmetrical effects, to be 3 m, Fig. 1. The modeled retaining structure was a steel sheet pile wall with a length of 7 m. The length of the sheet pile wall was chosen such that a rotational stability failure governed the failure mechanism of the wall. The sheet pile wall was horizontally anchored backward with steel wire anchors 1 m below the ground surface with a center-to-center distance of 3 m. The anchors were fixed at the boundary and had a free length of 20 m. A steel whale beam, HEB 300, was modeled at the anchorage level. The adhesion between the soil and the sheet pile wall was taken into account by adding positive and negative interface elements between the sheet pile wall and the soil. The improved soil consists of dry deep mixing columns with a diameter of 0.6 m, installed as overlapping columns perpendicular to the sheet pile wall. The column rows had a width of 7.0–7.2 m and a length of 10 m starting from the upper edge of the soft soil. The simulated width of the excavation was chosen to be 15 m, while the unexcavated side was chosen to be 20 m from side boundary of the model.

2.3. Analyses set-up

In this study, excavation was performed in two steps to a final excavation depth of 4 m below the ground surface, before a uniformly distributed surface load, *q*, was applied from 0 to 5 m behind the sheet pile wall. In the first step, the ground was excavated to a depth of 2 m before the anchor was installed 1 m below the ground surface. The anchors were then prestressed with a force corresponding to 50% of the anchors yield load, 300 kN, before the next excavation step was performed. A prestress force was applied in the anchor element to prevent excessive horizontal deformations at the top of the sheet pile wall. After the second excavation stage, a uniform distributed load, *q*, was applied and increased in constant increments of 10 kPa until a failure collapse mechanism was reached. A dry excavation was assumed in the conducted analyses. In order to eliminate the effect of free water in the excavated region, the water conditions for the excavated soil volumes below the ground water table were set to dry. Due to the excavations, the earth pressure acting on the sheet pile wall increased and the column rows were subjected to an increasing lateral loading and a simultaneously decrease in overburden pressure on the passive side of the retaining structure. In this way, the development of the emerging failure mechanism and the stress–strain relationship

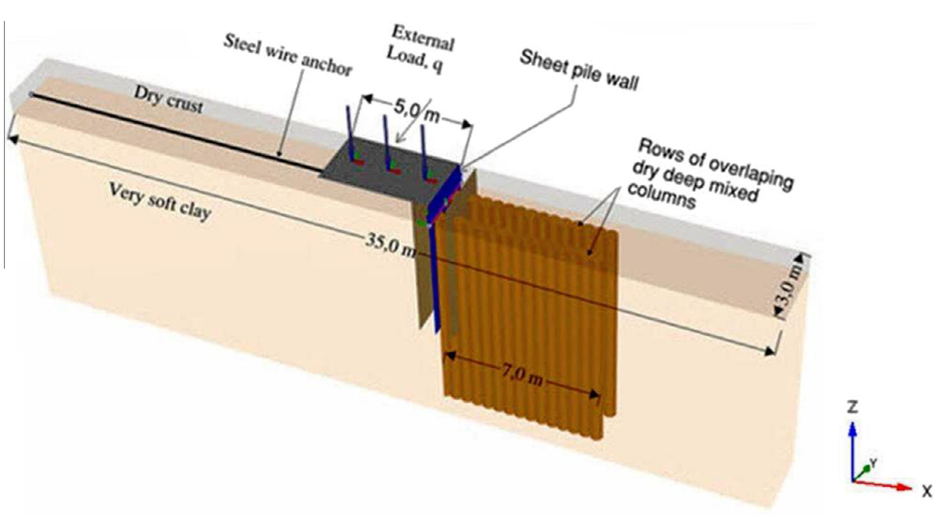

Fig. 1. Model geometry.