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Stochastic assessment for the behaviour of systems of dry soil mix columns

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ABSTRACT

The mechanical properties of dry soil mix (DSM) columns can be highly variable. Variability can be accounted for in the construction specification for deterministic design and directly in reliability based design. Design methods and specifications to date adopt simplifications that do not take the variability of the columns fully into account. This paper uses both simple and advanced probabilistic methods to assess the performance/failure and system redundancy of dry soil mix columns. Reliability-based design methods and examples are given for the design of column strength and the adjustment of the column spacing to achieve a target probability of unacceptable performance or failure. An acceptance criteria chart is developed. The pull-out resistance tests on the DSM columns constructed for the Ballina Bypass motorway construction project in NSW Australia are compared to the chart to provide guidance with respect to acceptance criteria required to achieve the desired performance.

1. Introduction

The dry soil mixing (DSM) technique is a method of ground improvement used to strengthen and stiffen soft to firm cohesive soils having an undrained shear strength of about 50 kPa or less. For a road embankment the columns are installed individually below the crest of the embankment to control settlement and in panels or grids below the batters to provide stability [20,12]. The method is cost-effective in situations where the settlement of an embankment needs to be limited and long consolidation times are not possible in the construction programme.

The process of constructing the columns involves screwing the mixing tool into the ground to the target depth, then pumping dry cement powder through the Kelly bar using high air pressure and, finally, withdrawing the mixing tool while rotating it at high speed. The process is computer controlled with the rate of withdrawal from the ground being a function of the rate of cement input. The type of soils and in-situ conditions affect the undrained shear strength (referred to as strength hereafter) and Young's modulus (referred to as stiffness hereafter) of the columns. To achieve the assumed design strength and stiffness, the ratio of the natural water content of the soil to the cement content and the Blade Rotation Number (BRN) are usually controlled (e.g., [12]). Experience shows however, that adjacent DSM columns can have very different strengths and stiffnesses even though they are installed in the same ground using nearly identical methods (e.g., [12]). Indeed, they do not have uniform strength within a single column or between columns. Many factors contribute to the variability of column strength and stiffness. These include the inherent variability of the ground, the moisture content, non-uniform feed rates and mixing of the cement, the soil mineralogy (clay content, clay mineralogy, sulphate content), the cation exchange capacity, the specific surface area of the soil and the type of cement used. The coefficient of variation of strength is reported to range between 0.3 and 0.8 [2,16,5,10] in contrast to natural soil which is reported to have a variance ranging between 0.1 and 0.4 [4].

Design for capacity and serviceability is generally performed using deterministic calculations [9]; SGF Report 495E 1997; [13,1,19,12]. The entire soil mass can be considered as having improved properties even though the columns are installed at discrete intervals. This leads to design methods where uniform equivalent strength and stiffness parameters for the improved ground are computed. These methods are usually referred to as weighted average approaches (e.g., EuroSoilStab, SGF4:95E, [12]). To account for the variability of the soil properties, conservative values are chosen according to the degree of uncertainty. Quality assurance procedures are utilized in the construction specification to control performance.

A feature of the weighted average approach is that the same capacity and settlement can be achieved by combinations of high strength/stiffness columns spaced far apart or by low strength/stiffness columns spaced close together. A designer will choose

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Nomenclature

A	cross sectional area of the columns
C_0	original design column strength
C_{col}	column strength
C_d	design column strength
D	spacing of columns
E	column stiffness
E_0	original design column stiffness
H	thickness of embankment
L	length of columns
S	settlement
$V_{C_{col}}$	coefficient of variation of column strength
V_{C_s}	coefficient of variation of measured strength
V_E	coefficient of variation of column stiffness
W	weight of embankment applied on a column
γ	unit weight of embankment
μ_E	mean column stiffness
$\mu_{C_{col}}$	mean column strength
$\mu_{\ln E}$	mean of $\ln E$
$\mu_{\ln C_{col}}$	mean of $\ln C_{col}$
μ_{C_s}	specified mean strength
Φ	cumulative standard normal distribution function
σ	standard deviation
$\sigma_{\ln E}$	standard deviation of $\ln E$
$\sigma_{\ln C_{col}}$	standard deviation of $\ln C_{col}$

the combination that results in the lowest cost, which is most commonly high strength columns spaced as far apart as the adopted design methodology allows. This is because the cost of equipment per day that contractors charge is much higher than the cost of materials so the low cost solution is the one that minimises equipment use. While constructing fewer columns is cost effective, it is possible that a sparse system of columns has a different probability of failure than a dense system of columns. The differences between dense and sparse systems of columns can be assessed by application of three-dimensional probabilistic finite element methods (PFEM) but, to the author's knowledge, no examples of such methods for arrays of dry soil mix columns exist in the literature.

To account for the variability of deep-mixed ground, Filz and Navin [5] discuss an alternative design methodology for embankment stability where a probability distribution of column properties is assumed and a design column strength is calculated to achieve an assumed factor of safety (FS) for an instability mechanism. This design value is then incorporated into a deterministic analysis and, presumably, the adopted probability distribution of the column properties forms the basis of the acceptance criteria in the construction specification. More recently, Al-Naqshabandy and Larsson [2], Bergman et al. [3] and Huang et al. [8] have applied reliability assessments to lime-cement columns and dry soil mix columns. Al-Naqshabandy and Larsson [2] showed that deterministic design is not appropriate when the variability of column strength is high. The needs for reliable assessments of different sources of uncertainties and the verification during construction were also highlighted. Bergman et al. [3] presented a reliability-based serviceability limit state design of lime-cement columns. Huang et al. [8] conducted a preliminary study of the system redundancy of dry soil mix columns. It is noted however simple reliability based design methods are still missing. In this paper, new methods for reliability-based and cost-effective design of dry soil mix columns are developed. How the interactions between columns affect the probability of failure of individual columns and column system have not been studied. In addition, no guidance is provided regarding how the acceptance criteria should be developed, and the development of acceptance criteria is generally left to the experience of the design engineer. In this paper, we use PFEM methods [6] to investigate the probability of failure for sparse and dense column systems for capacity and serviceability. We compare the results from the PFEM with those from 1D probabilistic calculations which stipulate the adopted probabilities of exceeding the serviceability and ultimate design criteria. We further discuss the implications of maintenance costs and the probability of unacceptable performance using the adopted design values for the mean column strength and spacing. This will give guidance for choosing the optimal spacing that is the most cost effective. Lastly, we use 1D probabilistic calculations to derive a chart that can be used to provide qualitative guidance for adopting acceptance criteria in deterministic or reliability-based design approaches. Column QA test data obtained for the Ballina Bypass motorway construction project in NSW Australia are compared with the chart to assess its effectiveness.

2. Baseline deterministic calculation

Here we calculate column spacing as a function of mean column strength and embankment height using conventional deterministic methods. The combinations of mean column strength and spacing are later compared to results from the PFEM.

The DSM columns (see Fig. 1) interact with the surrounding soil. However, for the purpose of our assessments we exclude the soil partly to facilitate analysis by 3D PFEM. The columns were modelled as elastic springs and the load is entirely supported by the columns. Because only the vertical capacity of the column system is investigated, the spring elements have only vertical degrees of freedom. The embankment is included in our model to distribute vertical loads between the columns. Including soil between the columns will certainly affect how the load is distributed. It is noted however, that these effects can be simulated to a large extent by increasing the stiffness of the embankment. It is assumed that the columns have a diameter of 0.8 m and a length of 10 m, the

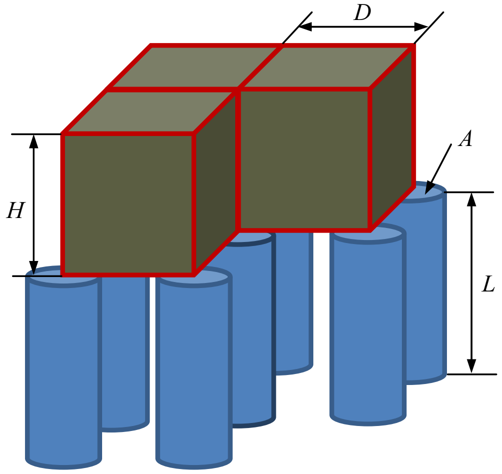

Fig. 1. Column system.