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Discrete element modeling for the study of the effect of soft inclusions on the behavior of soil mix material

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ABSTRACT

The influence of soil inclusions on the mechanical behavior of deep soil mix material was studied by discrete element simulations in combination with some laboratory tests. The innovative aspect of the simulations was that individual fracturing in the heterogeneous material was modeled. It was observed that the reduction of strength and stiffness did not correspond to the weighted average of the UCS and Young's modulus, taking into account the volumes of the strong and weak material. The actual reduction was considerably larger, e.g., on average the strength was reduced by 13% and 50% for 1% and 10% of inclusions, respectively. Moreover, other parameters, such as the shape, number, and relative position of inclusions, also have an important influence on the strength and stiffness. First, sharp-ended inclusions have a more negative impact on the strength and stiffness than rounded inclusions. Second, one large inclusion reduces strength and stiffness more than three smaller inclusions with the same shape and accounting for the same total volume percentage. Finally, diagonally-located and more-concentrated inclusions have a more negative impact on the mechanical behavior than vertically-aligned and widely-spread inclusions. The results of the numerical simulations showed good agreement with the results of laboratory tests with regard to the effect on strength and stiffness as well as the observed fracture patterns.

1. Introduction

1.1. Deep soil mixing technique

The deep soil-mixing technique has been used for ground improvement applications for several decades [1]. Currently, it is being used increasingly for the construction of soil- and water-retaining structures because of its economical and environmental advantages compared with classical techniques, such as concrete secant pile walls, diaphragm walls, and king post walls (i.e., soldier pile walls).

The soil-mixing technique is based on an in situ mechanical mixing of the soil with an injected binder (e.g., cement). By executing overlapping rectangular panels or cylindrical columns, a continuous wall is obtained. As soon as the panel or column has been mixed, steel H or I profiles are inserted into the fresh soil mix material to increase the shear and bending resistance of the wall. Depths up to 20 m have been reached.

Because of the specific mixing procedure of the soil-mixing technique and since a natural material is directly used as building material, the presence of soil inclusions (i.e., unmixed and thus weaker parts) is inevitable. The volume percentage varies between 0% and 3.5% in sandy soils up to 35% and more in stiff clays [2]. Apart from this, soil inclusions can be very small (a few millimeters), but large inclusions (up to 100–200 mm) also are found. This is illustrated by the two soil-mix cores of Fig. 1a, originating from the same soil-mix panel executed in a sandy soil (with a length of about 550 mm). In the upper core, a large inclusion, with a diameter of about 50 mm, was observed, while the sizes of the inclusions in the lower core were limited to a few millimeters. Note that both the inclusions, the execution parameters (e.g., amount of binder injected, water/cement ratio), and the type of soil influence the Uniaxial Compressive Strength (UCS) value. All of these factors can lead to a wide range of UCS values on one construction site, as illustrated by Fig. 1b, which shows the histogram of 31 UCS values for a Belgian construction site in a loamy soil.

1.2. Need for alternative design rules

The heterogeneous nature of soil-mix material precludes the application of classical design rules because they are valid only for homogeneous building materials. Moreover, the statistical

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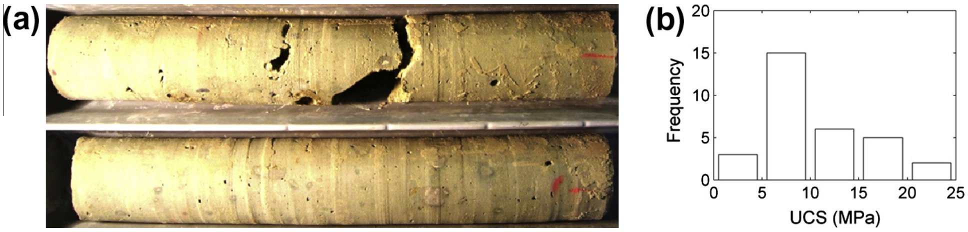

Fig. 1. (a) Two cores with a length of about 550 mm from the same soil-mix panel. The soil in the inclusions was washed out during coring. (b) Histogram of 31 UCS values of soil-mix samples from a construction site in Belgium (loam).

distribution of the UCS values of the soil-mix data is often strongly negatively or positively skewed, instead of being distributed symmetrically, as is assumed by classical design rules (e.g., the histogram in Fig. 1b clearly has a positively-skewed distribution). Classical design rules usually are defined as the mean value minus the standard deviation multiplied by a factor that corresponds to a certain confidence interval. However, this approach often leads to unrealistic characteristic values (i.e., even less than zero), while, in practice, the soil-mix material performs sufficiently well [3].

Therefore, in 2009, the Belgian Building Research Institute (BBRI), the Belgian Association of Foundation Contractors (ABEF), and KU Leuven applied for a project subsidized by the Flemish Government Agency for Innovation by Science and Technology (IWT). The aim of the project was to reformulate the classical design rules to the fundamental behavior of soil-mix material, taking into account the heterogeneous character, soil inclusions, scale effect, and time effects, such as curing time and creep. During the project, attention was paid mainly to the compressive strength of the soil-mix material, the adherence between the soil-mix material and steel reinforcement, and the sustainability and permeability of the material.

Within the scope of this project, a large number of laboratory tests were conducted, but numerical simulations also were conducted, allowing the study of the occurrence and growth of individual fractures in the heterogeneous material during loading. By approximating the failure process of fracture initiation and growth as realistically as possible, the simulations can be used for prediction of new situations, e.g., more or less heterogeneities, larger or smaller heterogeneities, and the scale effect. Apart from the UCS tests on core samples, large soil-mix blocks (600 × 1200 mm) were tested to study the scale effect [4]. The main focus of this article is the results of the numerical simulations.

2. Discrete element modeling

2.1. Simulation of fracturing

The failure of rock is determined mainly by the initiation and propagation of fractures in the rock material. At relatively low loads, fracturing can be initiated by micro-fractures that develop into macro-fractures at higher loads. The approximations provided by the classical elasto-plastic continuum models are, for the most part, sufficiently accurate to simulate global deformation behavior [5]. However, simulation of fracture initiation and growth is still necessary, e.g., to allow a correct distinction between shear and tensile fractures, but also to understand and quantify the effect of heterogeneities in the material. Several numerical approaches have been developed during the past few decades to simulate crack propagation.

The finite element method (FEM) is a tool that is used extensively in structural analysis [6]. Since it is based on the theory of continuum mechanics, it is not well suited for the analysis of crack propagation. However, discrete as well as continuum numerical approaches have been developed for modeling discontinuities [7]. In the discrete approach, a crack is represented by a real mesh discontinuity [8]. This implementation requires remeshing to cater to crack propagation, which makes the modeling of arbitrary crack growth in FEM very difficult. Several finite element based methods have been proposed without the need of remeshing. However, some of the methods, such as the Element-Free Galerkin (EFG) method [9] and the Element-Free Galerkin Particle (EFG-P) method [10], have encountered difficulties in enforcing essential boundary conditions and numerical integration. In addition, they have high computational expense. More recently, methods referred to as 'partition of unity' (PU) methods have been developed extensively (e.g., the Extended Finite Element Method (XFEM), which incorporates enrichment functions to simulate simple crack propagation [11]). Nevertheless, to deal with more complicated configurations (e.g., the growth of multiple cracks) all these methods still must be improved.

Apart from these and other methods, such as the Finite Difference Method (FDM) and the Displacement Discontinuity Boundary Element Method (DD-BEM) that allow the simulation of fracture growth, the Distinct Element Method (DEM) is a very valuable alternative [12]. The studied domain was divided into a mesh of separate (rigid or deformable) elements, bonded together by contacts. Several DEM codes have been developed. In the Particle Flow Code (PFC), for example, materials are modeled as a dense packing of rigid spherical elements, bonded together at their contact points [13]. For this study, the Universal Distinct Element Code (UDEC) was chosen because it is a familiar, efficient, and reliable software package. Originally, it was developed for the simulation of the behavior of a fractured rock mass, e.g., its slope stability [14]. However, in the past, it has been used successfully for the numerical modeling of fracture initiation and growth in rock [15,16]. The fact that our research group at KU Leuven already had experience with this code certainly was a significant factor in the selection of this particular code.

2.2. Global approach

UDEC is a 2D numerical program that is based on the discrete element method [17]. The discrete elements model consists of discrete blocks that are mutually connected by contacts. Tensile and shear failure criteria are defined for these contacts, allowing them to open and deform upon activation. The UDEC solution scheme is based on a (dynamic) explicit finite-difference method, which also is used in continuum analysis [18]. UDEC was developed to study various phenomena, such as rock fall and slope instability, which depend on the activation of existing fractures. The philosophy followed in this study is that by dividing a medium in multiple discrete small blocks (tightly bound together), their boundaries can act as potential fracture paths when an external load is applied [5,15]. In other words, a contact between two adjacent blocks does not represent a physical crack as long as it is not activated. An example of a mesh of triangles for a rectangular medium is shown