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Experimental investigation of pressure grouting in sand

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Abstract

Pressure grouting technology has been widely adopted in ground improvement and soil stabilization. To better understand the grout evolution and diffusion process upon pressure grouting injection in sand, laboratory-scale tests were carried out on loose sand under confined boundary conditions, with different grout water/cement (*w*/*c*) ratios (0.5 and 1) and soil degrees of saturation (ranging from 5% to 60%) taken into account. By comparing the injected grout volume, the grout bulb volume and density, and the characteristics of the grouted bulbs (dimension and shape) obtained at increasing grouting pressure, the main features of the pressure grouting process were revealed. The injected grout volume increased almost linearly with the grouting pressure, and a lower volume of grout could be injected for a lower *w*/*c* ratio at the same grouting pressure, representing a lower injectability. An increase in the grouting pressure leads to an enlarged grout bulb dimension for both *w*/*c* ratios, and this increase shifts the grout diffusion process from being dominated by compaction to one involving a fracture-like pattern. Generally, a spherical grout bulb is obtained at a lower *w*/*c* ratio of 0.5; however, at the higher *w*/*c* ratio of 1, fracture starts to occur even at a low grouting pressure of 100 kPa and continues to propagate as the grouting pressure increases. The influence of the degree of saturation of the soil was significant on both the injectability and the characteristics of the grout bulbs, since the cohesion of the unsaturated sand changed along with it. When *Sr* exceeds 5%, the volume of the injected grout decreases, but then increases after a threshold value of approximately 40%. Conversely, compaction grouting seems to be dominant at the threshold *Sr* value, while fractures tend to appear at both lower and higher degrees of saturation. A considerable amount of bleeding occurred with the two main diffusion processes during pressure grouting. The *w*/*c* ratio seems to be the most significant factor contributing to this behavior in sand samples.
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Keywords: Grouting pressure; *w*/*c* ratio; Degree of saturation; Injectability; Grout diffusion characteristic

1. Introduction

Pressure grouting is a ground improvement or soil stabilization technique that involves injecting a fluid-like material under controlled pressure at strategic locations, via single or multiple ports, into soil or rock strata to improve their mechanical properties. It is a term used widely with meanings which vary depending on the application. For instance, the grout can be pressurized into the soil through holes or pipes drilled, jetted, or driven to the desired location and may take the form of permeation grouting, jet grouting, compaction grouting or fracture grouting (Dayakar et al., 2012; Wang et al., 2009, 2013).

Of these techniques, compaction grouting and fracture grouting are often used to implement compensation grouting (or displacement grouting), which aims to control the ground settlement caused by underground construction or deep excavation (Jafari et al., 2004) or to densify the soil to improve its characteristics (Hamderi and Gallagher, 2015). Two reasons have been suggested in recent studies (Yin et al., 2009; Hossain and Yin, 2012; Hong et al., 2013) for the increased

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pull-out resistance of grouted soil nails common in compaction and fracture grouting: (i) the grouting pressure may compact and densify the surrounding soil, improving the confining effect on the grouted nail; and (ii) these techniques induce fractures in the surrounding soil, enhancing the bond strength and interface roughness of the soil nail. In practice, it is known qualitatively that a higher grouting pressure provides higher compensation efficiency for ground settlements (Bezuijen et al., 2007), enhances the pull-out resistance of soil nails (Seo et al., 2012) and raises the lateral resistance of grouted piles (Rollins et al., 2009).

Until recently, however, this method has been predominantly empirical, with grout being injected and the heave of the ground being monitored or, in the case of reinforcement construction, its effectiveness verified by a field pull-out test (Chu, 2003; Pradhan et al., 2006). During pressure grouting, the characteristics of the grout bulb created underground are generally unknown, even though it determines the efficiency and safety of the process. The empirical nature of the procedure can lead to uncertainties, such as a shortfall in compensation or compensation occurring at a different location from where the grout was injected (Paans, 2002). It can also result in accidental ground cracking under high pressure. These issues may cause the grout to propagate in an uncontrolled manner and lead to damage of surrounding buildings (Kolymbas, 2005; Gafar et al., 2008), and thus provide the motivation for this study of the propagation process during pressure grouting in sand. In this paper, changes in the grout bulb characteristics and grout diffusion patterns are investigated by checking the bulbs exposed at increasing pressure levels from identical soil samples.

The shape of a grout body and the subsequent soil fracturing are affected by various parameters such as the specific properties of the grout (water/cement ratio, grouting pressure etc.), the ground properties (density, water content, permeability etc.) and the boundary conditions (e.g., Mori et al., 1990, 1992). This study considers different grout water/cement (*w*/*c*) ratios (0.5 and 1) and degrees of soil saturation (ranging from 5% to 60%) in a series of laboratory-scale injection tests that were performed at the same dry density under confined conditions. This boundary was chosen to simulate the effects (Lee et al., 2012) for large numbers of grout injections (Au et al., 2003; Soga et al., 2004). By comparing the injected grout volume (injectability), the grout bulb volume and density, and the shape of the grouted bulbs obtained at increasing pressures, the evolution and diffusion during the process are revealed. The results improve the understanding of the grouting injection process in sand and help define the key parameters that control the grout diffusion modes.

2. Experimental materials

2.1. Sand

The soil studied is silica sand obtained from Stockton Beach, Newcastle, Australia. This sand consists of 98.82% quartz, 0.8% rock fragments, 0.21% Zircon, 0.11% Ilmenite and 0.06% Rutile (Ajalloeian et al., 1996). Fig. 1 shows the sand grain size distribution curve determined by dry sieving (ASTM D 421&D422). The curve

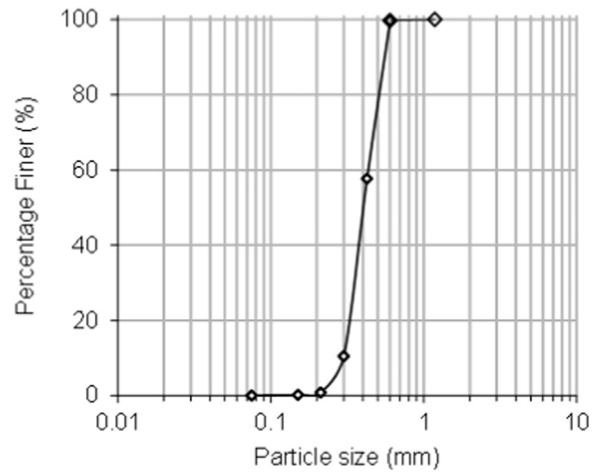

Fig. 1. Particle size distribution of the Stockton sand.

is characterized by a uniformity coefficient C_u of 3.56 and a D_{50} of close to 0.9 mm.

The specific gravity of the sand grains was measured by a Gas Pycnometer (ASTM D 5550-00), and three measurements gave an average value of 2.67 mg/m^3. The maximum and minimum densities of the sand were determined following the ASTM standards D 4252-00 and D 4253-00 and values of 1.71 mg/m^3 and 1.46 mg/m^3, respectively, were obtained.

2.2. Cement grout

The cement used in this study is a locally available Portland cement with a soundness of 1.0 mm, a fineness of 330–410 m^2/kg and a specific gravity of 3.14 mg/m^3. The grout was prepared by mixing a certain mass of water and cement powder using a blender at water/cement (*w*/*c*) ratios of 0.5 or 1. The density of the prepared grout was measured to be 1.80 mg/m^3 for $w/c = 0.5$ and 1.46 mg/m^3 for $w/c = 1$. After an initial setting time of 1.5–3 h and a final setting time of 2.5–4 h, the grout then developed a compressive strength of 6.6 MPa for $w/c = 0.5$ and 2 MPa for $w/c = 1$ in 24 h, which continued to increase over time. The final strength reached 37 MPa and 12 MPa for $w/c = 0.5$ and $w//c = 1$, respectively, after curing for 28 days (see Fig. 2).

The grout bleeding in a static system (where cement particles in the grout move only due to gravitation and inter-particle potential) were measured using a method recommended by Widmann (1996). The bleeding ratios (dV/V, defined as the volume of clear water segregated on the top divided by the original grout volume following Kong (2005)) were recorded and are presented in Fig. 3. For the *w*/*c* of 0.5, a bleeding ratio of only 1.5% was obtained at equilibrium after approximately 4 h; however, much larger bleeding occurred for the *w*/*c* of 1.0, which was 10% after only 1 h and reached 28.6% at equilibrium after 4 h.

3. Experimental methods

3.1. Grout injection

The setup used for the grout injection test is depicted in Fig. 4. A steel cylindrical chamber with a 200 mm inner

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