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Effect of Grout Bleed Capacity on the Engineering Properties of Cement Grouted Sands

Effet de la capacité de ressuage de coulis de ciment sur les propriétés mécaniques des sables injectés

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ABSTRACT: Grouts of three different cement types, each at four different cement gradations, with W/C ratios ranging from 0.6 to 3.0 and bleed capacities ranging up to 70% were injected into two different sands. Permeability, unconfined and triaxial compression and resonant column tests were conducted to investigate the influence of grout bleed capacity on the engineering properties of cement grouted sands. Cement grouting resulted in (a) permeability coefficient values as low as 10^{-8} cm/s, (b) unconfined compressive strength in the range of 1MPa to 35MPa, (c) cohesion in the range of 100kPa to 1400kPa, (d) improvement of the internal friction angle by up to 5° , (e) higher shear modulus by up to 25 times and (f) improved damping ratio by up to 10 times. Bleed capacity is an indicator of sand void volume filled with solidified grout but its degree of correlation with the static and dynamic properties of the grouted sands ranges from very good to negligible.

RÉSUMÉ : On a injecté des coulis de trois types de ciments différents, chacun avec quatre dosages en ciment différents, avec un rapport eau/ciment variant de 0.6 à 3.0, et une capacité de ressuage se situant jusqu'à 70% lorsque injectés, dans deux sables différents. On a effectué des essais de perméabilité, de compression simple et triaxiale et de colonne résonnante pour étudier l'influence de la capacité de ressuage des coulis sur les propriétés mécaniques des sables injectés. L'injection du ciment a résulté en: a) des valeurs de coefficients de perméabilité aussi faible que 10^{-8} cm/s, b) une compression simple de 1MPa à 35MPa, c) une cohésion de 100kPa à 1400kPa, d) une augmentation de l'angle de frottement jusqu'à 5° , e) un module de cisaillement jusqu'à 25 fois plus élevé, f) une augmentation du coefficient d'amortissement jusqu'à 10 fois plus élevé. Le ressuage des coulis est un indicateur du volume des vides du sable remplis de coulis solidifié mais son degré de corrélation avec les propriétés statiques et dynamiques des sables cimentés varie de très bonnes à négligeables.

KEYWORDS: cement grout, bleed capacity, permeability, strength, shear modulus, damping ratio

1 INTRODUCTION

Improvement of the mechanical properties and behavior of soils by permeation grouting using cement suspensions is frequently required in order to assure the safe construction and operation of many structures. The grout water-to-cement ratio (W/C) and the maximum cement grain size (d_{max}) are two important parameters controlling the cement grout bleed capacity and, consequently, the effectiveness of cement grouts in terms of the percentage of soil voids volume filled by grouting. Although the bleed capacity of cement grouts has been frequently quantified, its correlation with the engineering properties of the grouted sand has not been investigated so far.

Scope of this presentation is to provide some insights on the effect of grout bleed capacity on permeability, unconfined compressive strength, shear strength parameters and dynamic properties of ordinary and microfine cement grouted sands, in conjunction with the effect of the grout W/C ratio.

2 MATERIALS AND PROCEDURES

For the purposes of this investigation, a Portland, a Portland-composite and a pozzolanic cement (CEM I, CEM II/B-M and CEM IV/B according to Standard EN 197-1) were used. Each cement was pulverized to produce three additional cements with nominal maximum grain sizes (d_{max}) of 40 μ m, 20 μ m and 10 μ m and average Blain specific surface values of 567, 720 and 928 m^2/kg , respectively. Cements with $d_{max}=10\mu$ m can be considered as "microfine" according to Standard EN 12715 ($d_{95}<20\mu$ m and specific surface over 800 m^2/kg). Also, cements with $d_{max}=20\mu$ m have adequately small characteristic grain sizes to be considered, marginally, as "microfine". Typical gradations of these cements are presented in Figure 1.

All suspensions tested during this investigation were prepared using potable water since it is considered appropriate for

preparing cement-based suspension grouts. The W/C ratio of the suspensions was set equal to 0.6, 0.8, 1.0, 2.0 and 3.0 by weight, in order to test both stable and unstable suspensions in terms of bleed capacity. A superplasticizer (patented new generation of admixture based on polycarboxylate chemistry) at a dosage of 1.4 % by weight of dry cement was used to improve grout properties. All suspensions were prepared using high speed mixers. As recommended by the superplasticizer producer,

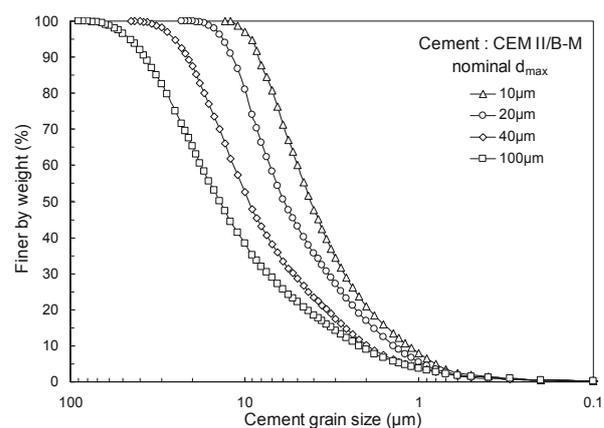


Figure 1. Typical cement gradations.

Table 1. Bleed capacity values (%) of all cement grouts

d _{max}	W/C				
	0.6	0.8	1.0	2.0	3.0
100µm	5-10	17-19	16-39	44-60	60-70
40µm	5-7	11-15	10-26	42-55	56-68
20µm	N/T	N/T	0-4	25-37	43-49
10µm	N/T	N/T	0-2	7-26	38-42

N/T: Not tested

the total amount of cement, 70 % of the water and the superplasticizer dosage were mixed for 5 min. Then, the rest of the water was added and mixing continued for another 5 min. Bleed capacity measurements were conducted for all cement suspensions used and the results are summarized in Table 1.

According to Standard EN 12715, a suspension is stable when it has a bleed capacity of not more than 5 % after 120 min from preparation. It can be observed that a W/C ratio of about 0.6 was required to obtain stable suspension of the coarse cements (d_{max}=100µm and 40µm) while microfine cement suspensions were stable for a W/C ratio of 1.0

The soils used were clean, uniform, limestone sands with angular grains and were grouted at a dense (relative density approximately 90%) and dry state. Two different sand gradations were used with grain sizes limited between sieve sizes (ASTM E11) Nos. 10-14 and 14-25 (d₁₅ size of 1.5mm and 0.8mm, respectively) in order to allow grouting by both the coarse- and fine-grained suspensions. The angle of internal friction of the sands was 42.2° and 42.6°, respectively.

Laboratory equipment, similar to the arrangement described in ASTM D4320-84, was used to produce small-size grouted sand specimens, with a height of 112mm and a diameter of 50mm, ready for testing (Pantazopoulos et al. 2012). Injection was stopped when the volume of the injected grout was equal to two void volumes of the sand in the molds. After 24 h, the specimens were extracted from the split molds and cured in a humid room for 28 days before testing.

Grouted specimens were tested in unconfined compression at a displacement rate equal to 0.1%/min. Hydraulic conductivity tests were performed according to the procedure described by Head (1986) for permeability testing in a triaxial cell with two back-pressure systems. Drained triaxial compression tests were conducted under confining pressures of 100, 200 and 400kPa and axial strain rate equal to 0.1%/min, without initial saturation and consolidation. The dynamic properties of the grouted sands were investigated at confining pressures up to 400kPa by conducting torsional resonant column tests for a shear strain range, γ, of approximately 5*10⁻⁵ % to 5*10⁻² %. Testing procedures and interpretation of raw data complied with well established methods (Pantazopoulos and Atmatzidis 2012). For comparison, similar tests were conducted on clean sands.

3 COEFFICIENT OF PERMEABILITY

The coefficient of permeability values of all grouted sands tested are presented in Figure 2 with respect to W/C ratio, bleed capacity and maximum cement grain size of the suspensions. The coefficient of permeability decreases considerably (by about 5 orders of magnitude) as the W/C ratio decreases from 3 to 0.6 and attains a value of about 10⁻⁷ to 10⁻⁸cm/s indicating practically impermeable materials. The permeability of the grouted sands appears not to be affected by the cement grain size. Evaluation of the permeability of the grouted sands in terms of grout bleed capacity indicates a similar trend as with the W/C, but allows some observations to be made in terms of the effect of cement grain size. For cement grouts with d_{max} equal to 100µm and 40µm, the coefficient of permeability of the grouted sands attained values in the range of 10⁻⁷ to 10⁻⁸cm/s and 10⁻³ to 10⁻⁴cm/s, for grout bleed capacity ranging from 6%

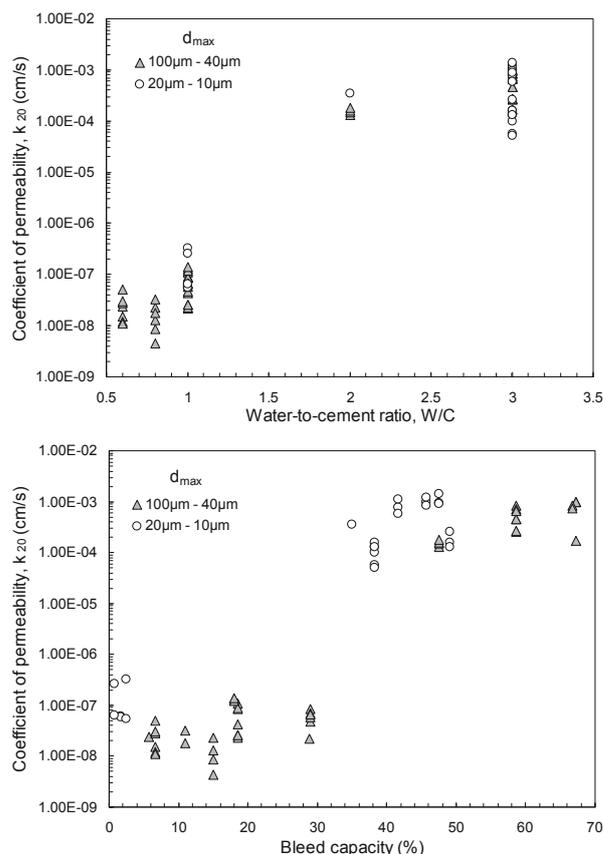


Figure 2. Effect of grout W/C ratio and bleed capacity on the permeability of cement grouted sands.

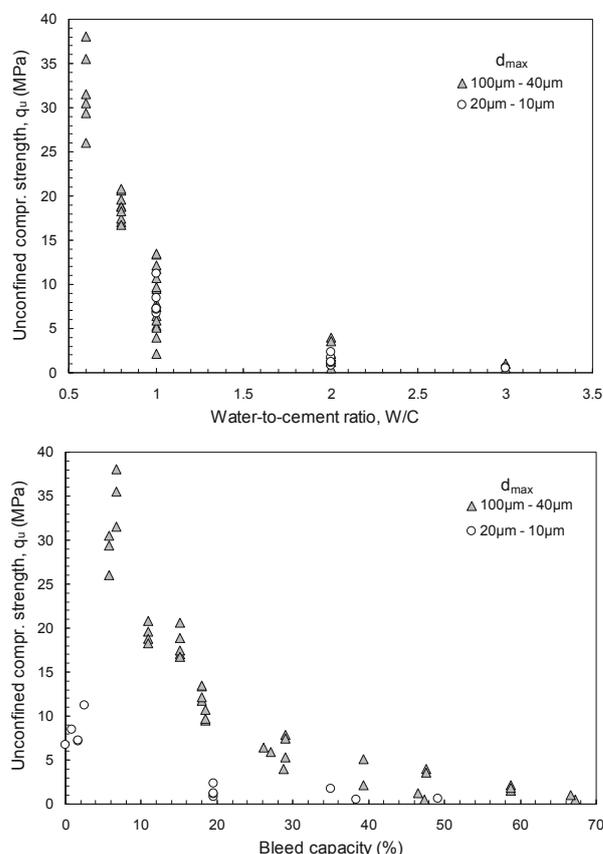


Figure 3. Effect of grout W/C ratio and bleed capacity on the unconfined compression strength of cement grouted sands.

to 30% and from 48% to 68%, respectively. Sands injected with microfine cement grouts ($d_{max}=20\mu\text{m}$ and $10\mu\text{m}$) obtained, generally, higher coefficients of permeability, by half to one order of magnitude, compared to sands grouted with the coarser cement suspensions, for similar bleed capacities. This is reasonable and can be attributed to the increased amount of coarse-grained cement needed to obtain the same bleed capacity with suspensions of microfine cements. It should also be noted that (a) similar coefficient of permeability values (10^{-7} to 10^{-8} cm/s) are obtained when injecting with stable or unstable suspensions for bleed capacity values up to 30% and (b) for higher bleed capacity values, the coefficient of permeability of the grouted sand decreases dramatically but remains in the range of 10^{-4} to 10^{-3} cm/s.

4 UNCONFINED COMPRESSION STRENGTH

The results presented in Figure 3 indicate that the unconfined compression strength of the grouted sands increases significantly with decreasing W/C ratio of the grouts, as verified by other research efforts (i.e. Dano et al. 2004) and seems not to be affected by cement grain size. However, the effect of cement grain size can be clearly demonstrated in terms of grout bleed capacity. The unconfined compression strength of the grouted sands is very well correlated with grout bleed capacity of both the coarse-grained cements ($d_{max}=100$ and $40\mu\text{m}$) and the microfine cements ($d_{max}=20$ and $10\mu\text{m}$) but, definitely, microfine cement grouts with the same bleed capacity as cement grouts yield significantly lower grouted sand strength. As with permeability, this can be attributed to the increased amount of coarse-grained cement needed to obtain the same bleed capacity as microfine cement suspensions.

5 SHEAR STRENGTH

The shear strength of the grouted sand specimens is expressed in terms of internal friction angle and cohesion, by applying the Mohr-Coulomb failure criterion. As indicated in Figure 4, the internal friction angle ranged from 40° to 50° and the effect of W/C ratio, bleed capacity and cement grain size appear to be insignificant. In general, the internal friction angle of the grouted sands was up to 5° higher than the value obtained for clean sands. The cohesion of the grouted sands is strongly affected both by the W/C ratio and by the bleed capacity of the grouts. As shown in Figure 5, the cohesion values of the grouted sands ranged from 600kPa to 1450kPa, from 300kPa to 500kPa and from 50kPa to 250kPa, for W/C ratios equal to 1, 2 and 3, respectively. Furthermore, grouted sands injected with stable grouts (bleed capacity values less than 5%) obtained the highest cohesion values ranging from 1200kPa to 1450kPa. Increased bleed capacity values (unstable suspensions) in the range of 15% to 65%, leads to an almost linear decrease of the cohesion values from 800kPa to 100kPa. The effect of cement grain size on grouted sand cohesion, as shown in Figure 5, where the microfine cements exhibit higher values of cohesion than the coarse-grained cements, by 40% to 150%, is misleading since the suspensions used had different bleed capacities for the same W/C ratio. For example, at W/C ratio equal to 1, the microfine cement suspensions are stable (bleed capacity $< 4\%$) and fill the sand voids with cement more completely and uniformly than the coarse cement suspensions with W/C=1 (bleed capacity $> 16\%$).

6 SHEAR MODULUS

Presented in Figure 6 are typical results obtained for the shear modulus, G , of grouted sands at a confining pressure equal to 50kPa and shear strain equal to $10^{-5}\%$. The effect of confining pressure is not pronounced for the grouted sands tested (Pantazopoulos and Atmatzidis 2012). As shown in Figure 6, the shear modulus values decrease, from 4.1GPa to

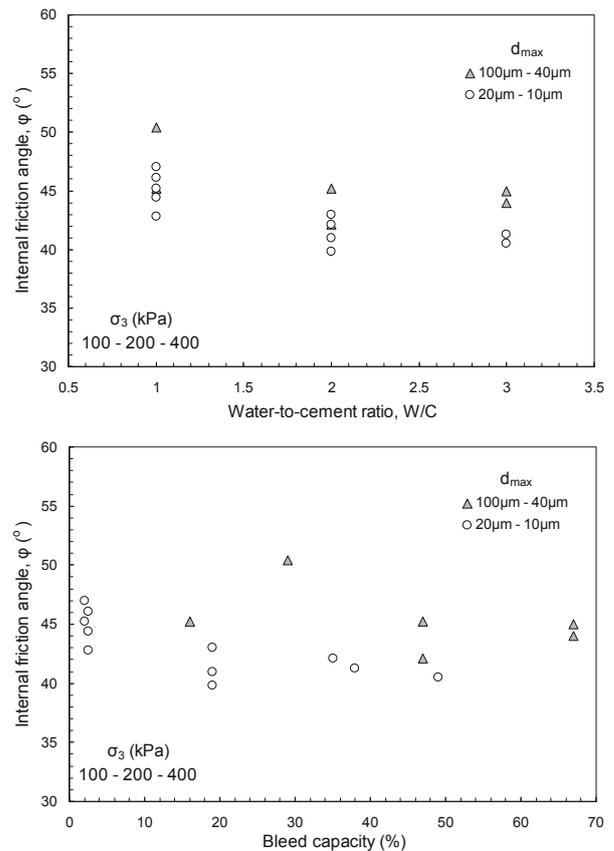


Figure 4. Effect of grout W/C ratio and bleed capacity on the internal friction angle of cement grouted sands.

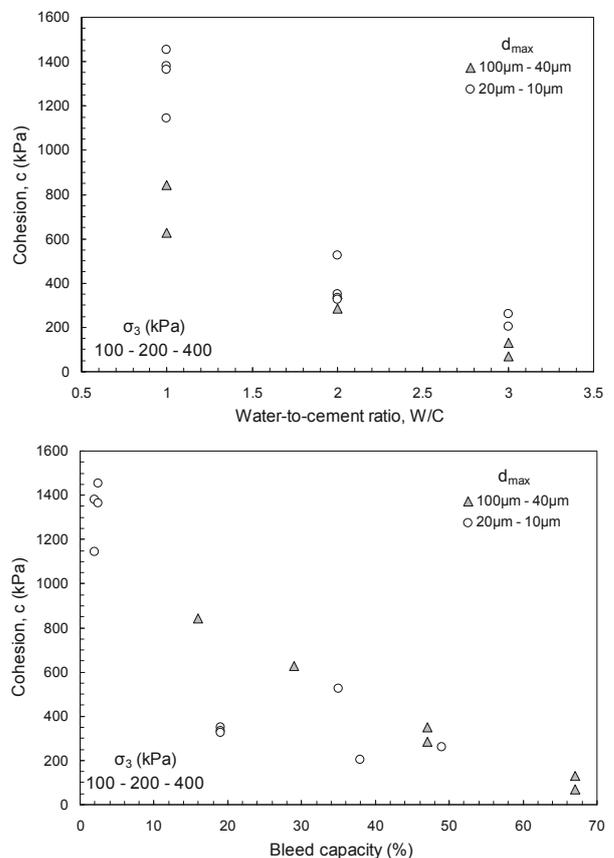


Figure 5. Effect of grout W/C ratio and bleed capacity on the cohesion of cement grouted sands.

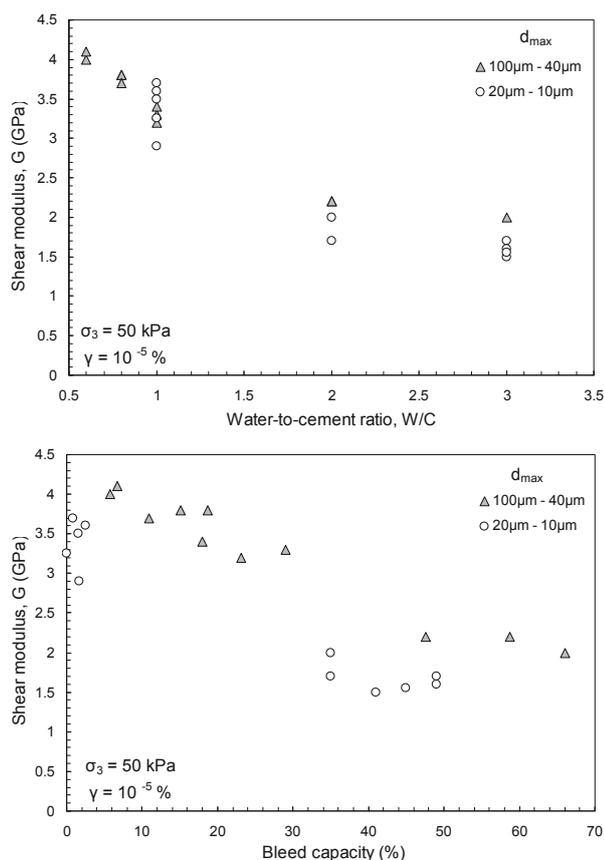


Figure 6. Effect of grout W/C ratio and bleed capacity on the shear modulus of cement grouted sands.

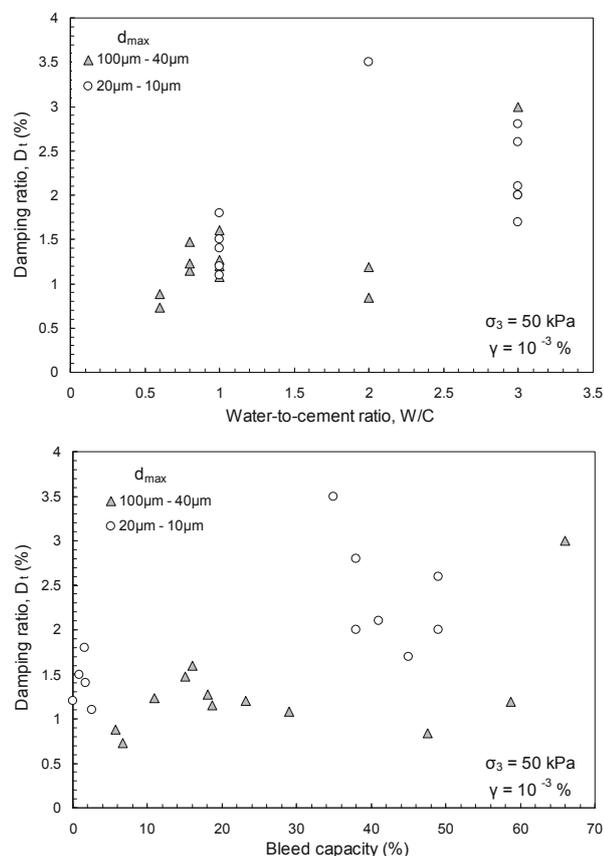


Figure 7. Effect of grout W/C ratio and bleed capacity on the damping ratio of cement grouted sands.

1.5 GPa, with increasing W/C ratio, from 0.6 to 3. The shear modulus values of the clean sands did not exceed 170MPa, indicating an improvement up to 25 times by grouting. The effect of grout bleed capacity on the shear modulus of grouted sand is clearly depicted in Figure 6, where it can be observed that above a bleed capacity value of about 30%, the shear modulus of the grouted sand decreases sharply by about 40%. Cement grain size seems to have a measurable effect on the shear modulus values of the grouted sands. For similar bleed capacity values, the sands grouted with microfine cement grouts have lower shear modulus values, by 15% to 30%, compared to sands grouted with coarse-grained cement grouts.

7 DAMPING RATIO

The damping ratio values of the grouted sands are presented in Figure 7 for a confining pressure equal to 50kPa and shear strain equal to 10^{-3} %. The effect of shear strain and confining pressure on the grouted sand damping ratio has been presented elsewhere (Pantazopoulos and Atmatzidis 2012). In general, the values obtained ranged from 0.5% to 8.0%, increased with increasing shear rate (from $5 \cdot 10^{-5}$ % to $5 \cdot 10^{-2}$ %) and decreased with increasing confining pressure (from 50kPa to 400kPa). The grout W/C ratio has a measurable effect on the damping ratio values of the grouted sands, which have a tendency to increase with increasing W/C ratio. The effect of grout bleed capacity on the damping ratio of the grouted sand appears to be less dominant, mainly for coarse-grained cements. For microfine cements there is a tendency for the damping ratio of the grouted sands to increase with increasing bleed capacity of the grouts. Even though the available data are limited, grouted sands injected with stable grouts (bleed capacity less than 5%) of microfine cements indicated damping ratios lower by 50% than those for grouting with unstable grouts. The damping ratios of the clean sands (for confining pressure and shear strain equal to 50kPa and 10^{-3} %, respectively) did not exceed 0.5%, indicating an improvement up to 10 times by grouting.

8 CONCLUSIONS

Based on the results obtained and the observations made, the following major conclusions may be advanced:

1. Bleed capacity is an indicator of grout effectiveness, since it is representative of the soil void volume filled by cement.
2. The distinction between stable and unstable grouts may not be an indicator of grout effectiveness since similar effects may be produced by both stable and unstable grouts.
3. Bleed capacity values correlate very well with some grouted sand properties (i.e. unconfined compression strength, cohesion) and not at all with other properties (i.e. damping ratio, internal friction angle).

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