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New innovative material for vibro replacement columns

Nouveau et innovant matériau pour le Renforcement de sol par colonnes ballastées

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ABSTRACT: Ground improvement enables construction work in places where the load-bearing capacity of the ground is insufficient by nature. Particularly for fine grained material and mixed soils, self-compaction is nearly impossible. The vibro replacement is a popular method for ground improvement. In this research, an innovative gravel-grout mixture for vibro replacement on the basis of polymers was developed. The mechanical parameters of the gravel-grout mixture can be controlled in a targeted manner, which ensures an individual and optimized matching to the ground in situ. The load-bearing capacity of the gravel-grout mixture can be increased to a magnitude comparable to that of concrete, while maintaining high permeability. Especially in case of compressible and poorly permeable soils, the drainage effect of the material proves to be a great advantage. This research contains an extensive laboratory testing program on a gravel-grout mixture for vibro replacement. Due to the high load-bearing capacity and permeability of the material, the soil mechanical laboratory tests in this research had to be modified and even expanded by rock mechanical laboratory tests. Based on the studies the importance of this innovative material for the practical application, is emphasized by numerical simulations.

RÉSUMÉ : L'amélioration du sol permet de réaliser des travaux de construction dans des endroits où la capacité portante du sol est par nature insuffisante. En particulier dans les sols à grains fins et mixtes, l'autocompactage est presque impossible. Le Renforcement de sol par colonnes ballastées est une méthode populaire d'amélioration du sol. Dans cette thèse, un mélange innovant de gravier et de liant à base de polymères pour le Renforcement de sol par colonnes ballastées a été développé. Les paramètres mécaniques du mélange gravier-liant peuvent être contrôlés de manière ciblée, ce qui garantit une adaptation individuelle et optimale au sol sur le site. La capacité portante du mélange gravier/liant peut être augmentée à un niveau comparable à celui du béton, tout en maintenant un haut niveau de perméabilité. Les propriétés de drainage du matériau s'avèrent être un grand avantage, en particulier dans les sols compressibles et peu perméables. Cette recherche comprend un vaste programme de laboratoire sur un mélange sol-liant pour le Renforcement de sol par colonnes ballastées. En raison de la grande capacité de charge et de la perméabilité du matériau, les essais de laboratoire de mécanique du sol ont dû être adaptés à ce travail de recherche et complétés par des essais de laboratoire de mécanique des roches. Sur la base du travail de recherche, l'importance de ce matériau innovant pour l'application pratique, est mise en évidence par des simulations numériques.

KEYWORDS: Ground improvement, vibro replacement columns, grouting, polymers

1 INTRODUCTION

Vibro replacement is a widely used method of soil improvement. In particular in fine grained material and mixed soils, whose self-compaction is nearly impossible, or for backfills, the potential for use is great. A grid-like arrangement of the vibro replacement Columns increases the load-bearing capacity and reduces the settlement of the soil, thereby improving the stability of the construction above it (Filz et al. 2012). Due to their high permeability, the columns act as a vertical drain and accelerate the consolidation. Usually, gravel with a grain size of 8/32, 16/32, or 4/32 is added as column material for the flexible stone columns. However, they generally have a relatively low load-bearing capacity and shear strength (Zheng et al. 2009). A modification of the column material by hydraulic binders is meanwhile also widespread, for example in the form of concrete columns. The concrete columns have a significantly higher load-bearing capacity and rigidity than flexible stone columns, but are almost impermeable to water. Columns between these extremes are semi-rigid (Han 2015). This also includes the novel gravel-grout mixture presented in this research. Although the gravel-grout mixture has a high load-bearing capacity, the drainage properties of the material still remain. Another advantage of the innovative material is the targeted and especially reliable controllability of mechanical properties.

2 EXPERIMENTAL INVESTIGATION OF THE PROPERTIES OF THE GRAVEL-GROUT-MIXTURE

2.1 *Sample material and experimental laboratory tests*

The sample material consists of a uniformly sized gravel and a polymer-based grouting material. The grouting material is dispensed into the gravel, so that a homogeneous mixture of gravel and grout is created. The effective pore content is not completely saturated with grout. At the grain-to-grain contact points, grout menisci are formed and the grain surface is wetted with grout, see Figure 1. If the proportion of grout in the sample is increased, the binder menisci enlarge up to the point where the pores are completely filled.

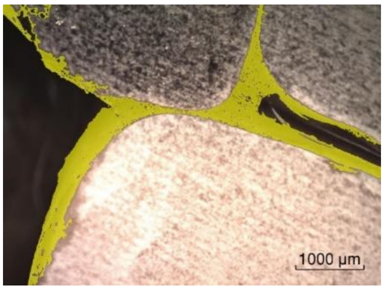

Figure 1. Microscopic analysis of the grout distribution (highlighted).

During the curing time of seven days, the test samples are stored at constant room temperature. After complete curing of the test specimens uniaxial compression and tensile tests, triaxial tests, and permeability tests were carried out. Due to the strength of the test specimens, which is comparable to rock, the rock mechanical testing equipment had to be used. For the triaxial tests, a loading rate of 0.1 mm/min was set and cell pressures 0.6 to 3.2 MPa were chosen. Similar pressures occur in ground engineering, tunneling, or mining projects. All laboratory tests were carried out taking into account the current standardization and valid recommendations.

2.2 *Evaluation of the laboratory tests*

The results of the uniaxial compression tests and permeability tests are shown in Figure 2 as an example for a low and high mass fraction of grout. The figure shows the essential mechanical and hydraulic material properties. With the increase in the mass fraction of grout, the strength and the load-bearing capacity of the gravel-grout mixture increases respectively (Shi, Wang & Luo 2010). As a consequence, the permeability of the material is reduced, since more pores are now filled with grout and less effective pore content is available for flow processes (Anagnostopoulos 2005). Although the permeability is reduced, the gravel-grout mixture, with a load-bearing capacity of the order of magnitude of concrete (16.0 MPa), still has a high permeability of 2.9E-03 m/s. Compared to gravel, the addition of grout has reduced the permeability by a power of ten.

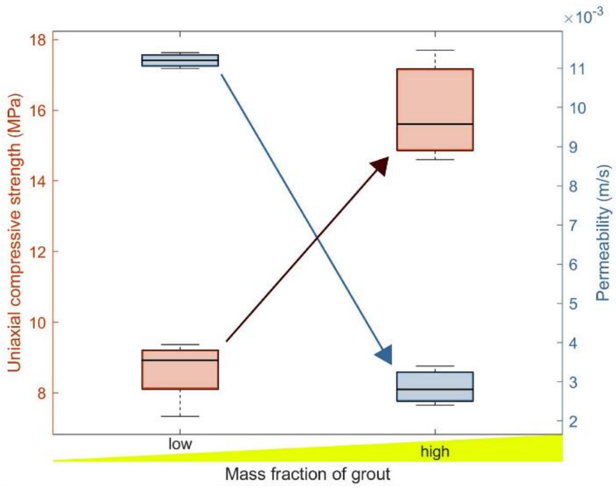

Figure 2. Mechanical and hydraulic material properties depending on the mass fraction of grout.

The ratio of uniaxial compressive strength to tensile strength of concrete is approximately $f_c = 8 - 15 \cdot f_t$. Compared to concrete, the gravel-grout mixture with $f_c = 5 - 6 \cdot f_t$ has smaller ratio values and consequently a higher tensile strength than comparable concrete. The fracture surface of the gravel-grout specimens lies in the load plane and runs along the grain surface (detached grout) as well as through individual grains. For this reason, not only the adhesive strength of the binder on the grain surface but also the tensile strength of the grains is crucial.

Figure 3. Tensile test: Failure along the grain surface and through the grains.

In the triaxial tests, a cohesion of 4.6 MPa was determined for a high mass fraction of grout, using a nonlinear failure criterion, see Figure 4. Previous work with grouting material has shown, that the shear behavior of grouted bodies can be correctly described using the nonlinear failure criterion according to Hoek-Brown (Boley et al. 2019). In addition to the principal stresses, the Hoek-Brown failure criterion uses the uniaxial compressive strength σ_{ci} and the parameters s, a, and m_b. For compact and intact rock, the parameters are chosen to s = 1 and a = 0.5. The laboratory tests have shown that these values can also be used for the grouted body. The Hoek-Brown constant m_b of the gravel-grout mixture is determined by curve fitting from the data of the uniaxial compression tests and triaxial tests. For a high mass fraction of grout, m_b was determined to 4.61 (R^2 0.99).

$$\sigma_1' = \sigma_3' + 16.0(\text{MPa}) \cdot \left\{ \left(\frac{4.61 \cdot \sigma_3'}{16.0(\text{MPa})} \right) + 1 \right\}^{0.5} \quad (1)$$

The high value of the cohesion of the gravel-grout mixture can be verified by analyzing the microstructure of the gravel-grout mixture. The gravel grains are held together by the grout, because the entire surface of the gravel grains, except for the grain to grain contact point, is wetted with grout. Next to the contact points of the grains, concave grout menisci are formed, clearly seen in the microscopic analysis in Figure 1.

In contrast to cohesion, the addition of binder causes a reduction in the angle of friction. In the example, the angle of friction is reduced from 39° to 31°. The decline is due to the full-surface wetting of the grains with binder and the associated loss of grain roughness. The angle of friction and the cohesion were evaluated in the example for a stress range (σ_n) around 5.0 MPa.

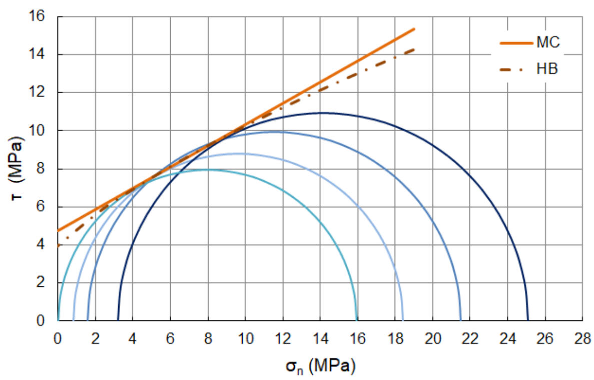

Figure 4. Fractional envelope according to Mohr-Coulomb (MC) and Hoek-Brown (HB) for a high mass fraction of grout.

3 NUMERICAL SIMULATION WITH PLAXIS 3D

The application potential of the new gravel-grout material is presented using an example from building practice and compared to conventional methods such as stone columns or concrete columns. This numerical simulation is carried out by using Plaxis 3D.

3.1 *Description of the numerical model*

In the calculation example, the spread foundation of an office building is modeled. The foundation loads are 150 kPa and are transferred into the ground via a 0.5 m thick layer of gravel. Below the gravel layer, there is a 6.0 m thick loess clay that has an extremely low load-bearing capacity. To reduce the settlement, a columnar soil improvement with a diameter of 0.6 m and an arrangement in a 1.50 m triangular grid ($A/A_C = 7.0$) is created. The 6.0 m long columns stand on a load-bearing loess stone. Since it is a symmetrical foundation, only 1/4 of the total model is calculated (Jiang et al. 2013), see Figure 5.

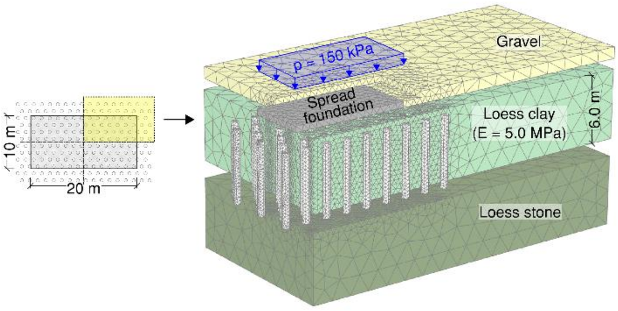

Figure 5. Model geometry and numerical grid (exploded view).

To highlight the effects of soil improvement by the innovative gravel-grout material, four calculation variants are considered. The natural soil is compared with a ground improvement with flexible stone columns, semi-rigid gravel-grout columns, and rigid concrete columns. The corresponding soil and material parameters are shown in Tables 1, 2. These tables also contain information on the material model. Based on previous research on the modeling of ground improvements with stone columns (Killeen & McCabe 2014, Al-Ani & Wanatowski 2017), the material model hardening soil is used for the stone columns, gravel, and loess clay. The gravel-grout columns and the loess stone take into account the material model Hoek-Brown. A linear elastic material model is selected for the spread foundation and the concrete columns.

Table 1. Literature values of the soil/rock.

Soil/rock	Gravel	Loess clay	Loess stone
γ (kN/m²)	19	19	19
$E/E_{50}^{ref}/E_{oed}^{ref}$ (MPa)	50	5	60
E_{ur}^{ref} (MPa)	150	15	-
Power m (-)	0.5	1.0	-
ν (-)	-	-	0.25
ψ (°)	7.5	0	0
MC: φ'/c' (°)/(kN/m²)	37.5/0	25/10	-
HB: σ_{ci}/m_b (MPa)/(-)	-	-	37.5/0.23
Material model	Hardening soil	Hardening soil	Hoek-Brown

Table 2. Literature values and results of the laboratory tests with gravel-grout mixture for the column material.

Column material	Gravel	Gravel-grout	Concrete
γ (kN/m³)	20	20	24
$E/E_{50}^{ref}/E_{oed}^{ref}$ (MPa)	100	1800	30000
E_{ur}^{ref} (MPa)	300	-	-
Power m (-)	0.5	-	-
ν (-)	-	0.25	0.20
ψ (°)	10	-	-
MC: φ'/c' (°)/(kN/m²)	40/0	-	-
HB: σ_{ci}/m_b (MPa)/(-)	-	16.0/4.61	-
Material model	Hardening soil	Hoek-Brown	Linear elastic

3.2 *Simulation results and evaluation*

The necessity and effectiveness of ground improvement can be assessed using Figure 6. The figure shows the vertical displacements. The foundation settlement of 0.9 m is not compatible. As a consequence, ground improvement is necessary. The soil improvement with stone columns reduces the settlement to 0.08 m. Smaller settlement differences can only be achieved with the columns made of gravel-grout or concrete. The vertical displacements are then only 0.02 m.

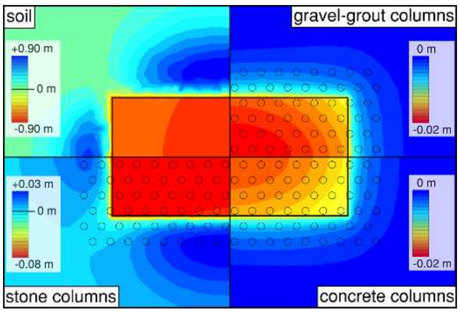

Figure 6. Comparison of the vertical displacements u_z in the four calculation variants.

In all column variants, the greatest vertical displacements occur in the middle of the column group and decrease towards the edge. The vertical deformations are often greatest on top of the column and decrease in depth. In the group of stone columns, the columns in the center of the group are predominantly aligned vertically, while the columns in the edge area are bend (Shahu & Reddy 2011). This is the main difference to the gravel-grout or concrete columns, which are predominantly aligned vertically and are hardly compressed. Figure 7 shows the lateral displacements of a column from the edge area of the column group, which is still below the spread foundation. Due to the high shear strength capacity of the concrete columns, the lateral displacements are significantly lesser compared to stone columns (Rashma et al. 2020). Lateral displacements of just a few millimeters also occur on the semi-rigid gravel-grout columns. These displacements are, however, larger than the rigid concrete columns. Peak values of lateral displacement occur in the upper area of the column, approximately between 1.0 - 2.0 m, which corresponds to approximately 2-3 times the column diameter (Han 2015). The overall load-bearing behavior of the stone columns is mainly determined by the interaction between column, floor, and load application and is expressed by the bulging of the columns, especially at a depth of approx. 1/3 of the column length (Kirsch 2004).

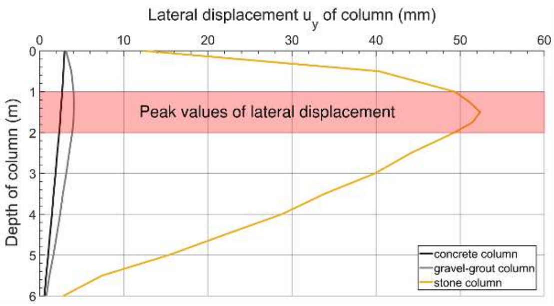

Figure 7. Lateral displacement of a concrete/gravel-grout/stone column from the edge area below the spread foundation.

Figure 8 shows the different deformation behavior of the entire group of columns of stone and gravel-grout, from which the load-bearing behavior of the columns can be seen. In contrast to the stone columns, the gravel-grout and concrete columns act as vertical support elements, while they mainly absorb the loads from the building. The interaction between the ground and the column is characterized by negative skin friction in the upper area of the column. Depending on the separation between the spread foundation and the column, as well as the compressibility of the soil (loess clay). This leads to a reduction of the load in the soil over the depth and an increase of the force in the columns until the depth where the differential settlement between soil and column is equal to zero. Below this neutral plane, the force in the column is transferred to the loess clay through positive skin friction and to the loess stone through tip resistance, like for usual deep foundations (Katzenbach et al. 2013). The material parameters of the gravel-grout columns attest to a more flexible load-bearing behavior than the concrete columns, see Table 2. These differences are not very pronounced in the present example, but are basically recognizable.

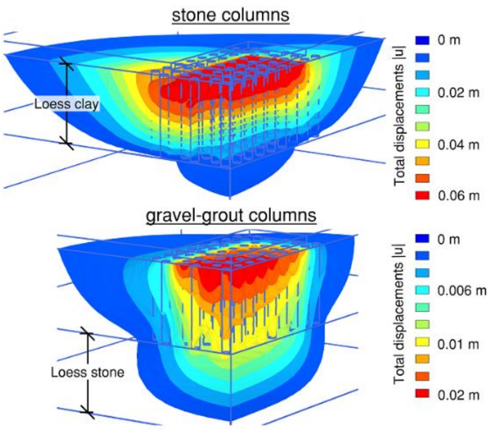

Figure 8. Comparison of the total displacements |u| of stone and gravel-grout columns based on the iso surfaces.

4 CONCLUSIONS

The results of the experimental and numerical research are summarized below. Further investigations are required for the use of the gravel-grout mixture for vibro replacement, in particular concerning the construction process for ground improvement and geotechnical analysis.

- Adding grout increases the strength of the gravel-grout mixture to 16.0 MPa, up to the order of magnitude of concrete.
- The addition of grout reduces the effective pore content and consequently the permeability of the gravel-grout mixture. In the range of the load-bearing capacity of concrete, the permeability is still 2.9E-03 m/s.
- The tensile strength of the gravel-grout mixture depends on the adhesive strength of the material on the grains and the tensile strength of the rock. The material mixture basically has a higher tensile strength than comparable concretes.
- Material behavior can be described as being well approximated by the Hoek-Brown failure criterion.
- The microanalysis of the material shows, that the increase in cohesion is due to the increase in the size of the grout menisci.
- In contrast to cohesion, the addition of binder causes a reduction in the angle of friction.
- Numerical comparative calculations show, that the gravel-grout mixture works as a vertical support element and can be used for ground improvement solutions like vibro replacement.
- The example from building practice shows the strengths of the gravel-grout columns compared to conventional stone columns. The office building can thus be founded on the gravel-grout columns, whereas the area ratio of a foundation with stone columns would have to be adapted since subsidence of 0.08 m would occur.
- The load-bearing behavior of the gravel-grout columns is more flexible than the concrete columns.

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