A NEW APPROACH TO DETERMINE THE DIAMETER OF A JET GROUTED COLUMN USING SEISMIC METHODS

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Abstract

Jet grouting is a geotechnical method of ground improvement to increase shear strength and stiffness of soils. The method is typically used to construct in-situ geometries of grouted soil such as panels or columns. The diameter of grouted columns and its material strength depend on various process parameters and the subsurface soil properties. It is only vaguely possible to predict the final column diameter. Therefore, it is a general practice to excavate a test column and perform a visual examination. However, an excavation to control the in situ diameter is often impossible, especially under complex site conditions, such as a high ground water table. Therefore, as part of a research project, borehole seismic measurements (crosshole, downhole and tomography) were tested as a quality control to verify the extent of the column and to monitor the influence of the jet grout injection on the soil over time. The field surveys were conducted before and after the jet grouting process at different time intervals. The acquired seismic data show clear traveltime differences which allow the determination of the specific column depth and diameter. The tomogram measured in the natural soil and the tomograms of the measurements after the injection process were used to visualize the time dependent effects of the jet grout injection on the soil.

Introduction

Some of the most common jet grouting applications are foundation restoration, excavation support and sealing. The jet grouting process works with a high kinetic energy jet of fluid to loosen and mix the in-situ soil with a cement suspension. Typical jet grouted structures are panels, full columns or anything in between (partial columns) with designed strength and permeability. Columns are generated by rotating the drill stem and raising it. The purpose of the research project is to develop a method for quality control which is needed to verify the grouting process and to define the diameter of a grouted column. In order to perform a seismic field survey four boreholes have been drilled at the BAM testing site in Berlin (Germany). Three columns have been installed by the jet grouting technique using predefined process parameters. Seismic measurements have been conducted before and after the jet grouting process at various time intervals. Different seismic methods were combined in order to determine the diameter of the grouted columns and to assess the influence of the jet grout injection on the soil after specific time periods.

Test site

Within the frame of the research project a test site has been prepared on the BAM testing site about 60 km south of Berlin. It is a general validation facility for various investigation purposes and techniques. Geologically, the site belongs to the northern German Basin and consists of various sediments with a thickness of several thousand meters affected by salt tectonics. The surface of the test site is dominated by post glacial sediments consisting mainly of sandy layers of varying grain size and admixtures of silt and organic material. The groundwater table is about 3 ± 1 m below surface and varies seasonally (Niederleithinger et al., 2013).

Four boreholes have been drilled at the BAM test site (Figure 1), with one center borehole and three surrounding boreholes in 120° intervals. The distance between the boreholes and the center borehole is about 3 m and the borehole depths are about 15 m. Three grouted columns have been installed under controlled conditions in September 2014. The columns were placed half way from the center borehole BH1 to the three outer boreholes. Based on the experiences of the jet grouting contractor, the local soil conditions and the technological parameters of the grouting process the general diameter of the columns is estimated to be around 1.2 m.

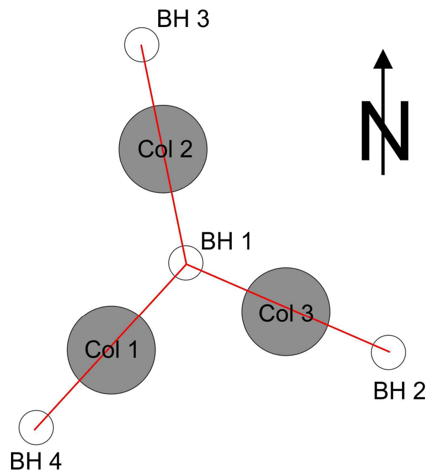

Figure 1: Sketch of the borehole locations (BH = borehole) and columns (Col = column). Measured seismic sections are shown in red.

Field survey

The seismic measurements were carried out between approximate depths of 15 and 1 m b.g.l. A first survey was carried out in late June 2014 to acquire field data for the reference state. Additional surveys followed directly after the jet grouting process as well as 7 and 28 days after. The location of the seismic sections can be taken from Figure 1 (red lines). In order to generate high frequency P-wave signals an electromechanical impulse source type BIS-SH (Geotomographie brand) was used. A string of 24 hydrophones type BHC4 (Geotomographie brand) with a sensor spacing of 0.5 m was used as a receiver to carry out seismic tomography measurements. The measurement interval was set to 0.5 m to reach a sufficient resolution. Data were recorded by a DMT Summit seismograph. The signal data quality was improved by signal stacking. In order to perform the downhole testing (ASTM D 7400, 2008) pipes were installed in the middle of each column shortly after grouting. The deviations of all boreholes were measured to determine the exact position of the seismic sensors and source installed in the boreholes.

Results

Subsequently, one representative column (Col 2) has been chosen as an example. In order to calculate the diameter of the jet grouted columns the tomography dataset was reduced to the horizontal ray paths. During seismic data processing first arrival traveltimes of the P-waves have been picked for each parallel source-receiver position of the reference state dataset and for the dataset gathered 28 days after the injection process when the cement suspension had reached the expected final strength (e.g. Wesche, 1993). Figure 2 shows the traveltime curves of the cross ray paths for each parallel source-receiver pair without (black line) and with the grouted column in between (red line). After 28 days a substantial decrease of traveltimes between 4 m and 11 m can be observed (Figure 2, left) indicating the specific boundaries of the column.

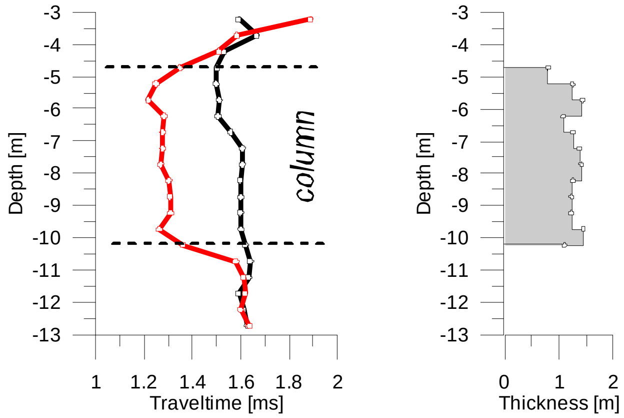

Figure 2: Left: Measured traveltime curves of the reference state (black line) and 28 days after the injection process (red line) for Col 2. Right: Calculated diameter of the grouted column (Col 2).

The calculation of the diameter D_{col} is based on the assumption that the traveltime of the seismic wave propagating from one borehole to the other is the sum of the traveltime in the column and in the natural soil on both sides of the column. The calculation requires the knowledge of the distance between the boreholes d_{BH}, the velocity of the natural soil without the column v_{soil}, the average velocity of the soil with the column in place v_{mean} and the velocity of the grout column itself v_{col}. The distance between the boreholes is known from borehole deviation measurements. The velocity v_{soil} is taken from the measurement of the reference state before the injection process. The average velocity can be measured after the injection process and the wave velocity of the column v_{col} using a downhole test. The velocity of the grouted material was determined to be 3.3 km/s verified by laboratory ultrasonic experiments. The diameter can be calculated by the following equation (Eq.1):

$$D_{col} = \frac{d_{BH} \cdot v_{col}}{v_{soil} - v_{col}} \cdot \left(\frac{v_{soil}}{v_{mean}} - 1\right) \qquad \text{Eq.1}$$

The determined diameter varies between 1.1 and 1.4 m and the depth extent between 4.5 and 10.5 m for column 2 (Figure 2, right). The general depth and the mean diameter of the column can be used to set boundary conditions to perform the tomographic inversion, described in the following.

In order to visualize velocity changes of the soil after the injection process the complete tomography dataset was used. The tomographic software GeotomCG was used to calculate the tomogram of the reference state using the Simultaneous Iterative Reconstruction Technique (Lehmann, 2007). The reference model was taken as the starting model to calculate the tomograms 3.5 hours, 7 days and 28 days after the injection (Figure 3). In general, the tomography method performed with the given source and receiver configurations does not provide sufficient resolution for vertical structures. Therefore, it was unavoidable to set boundary conditions during the inversion procedure using all available information to obtain a better resolution to image the inner structure of the vertical column. The application of constraints enables the user to define cells in which seismic velocities remain constant and cells in which seismic velocities can vary (Santamarina & Fratta, 1998). Based on the previous determination of the column depth and the calculated diameter the boundary conditions were set as shown in Figure 3. The velocities of the center cells where the column is supposed to be installed can be freely adjusted (Figure 3, light blue). The width of this area was set to 1.6 m, one cell size larger than the maximum calculated diameter of 1.4 m. The velocities of the cells directly next to the expected column are not completely unconstrained but allow a larger influence of the previous velocities. The seismic velocities of the cells surrounding the source and receiver boreholes and below the expected column, which are assumed to be not influenced by the injection, remain unaltered from the starting model (Figure 3, dark blue).

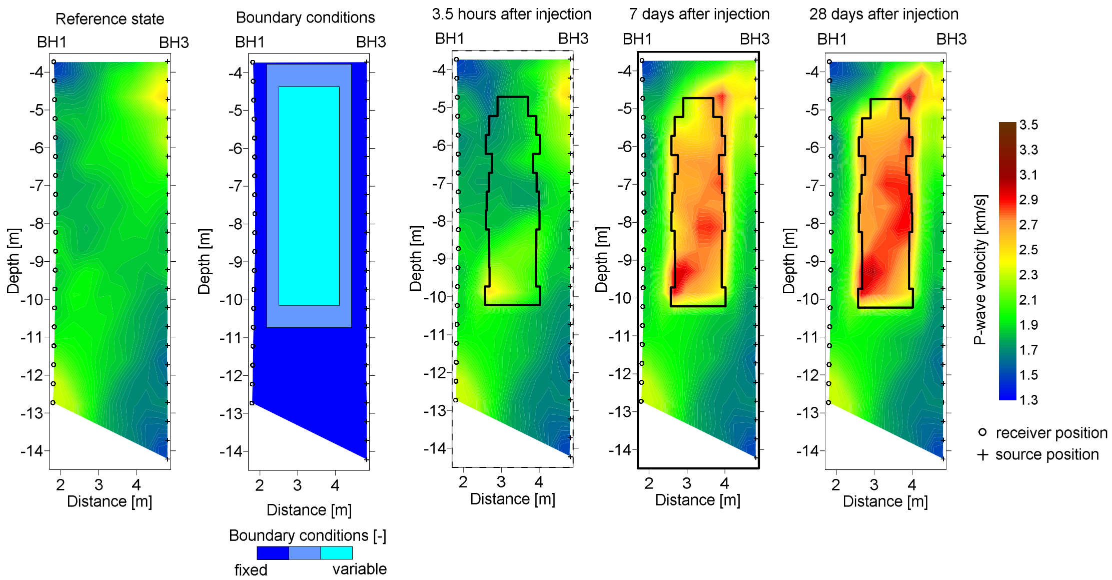

Figure 3: Reference state tomogram, boundary conditions and tomograms after the injection process. The black lines indicate the calculated column boundaries.

The tomograms show the time dependent effects of the jet grouting on the seismic velocity of the soil (Figure 3). After 3.5 hours the injection leads to a slight decrease of seismic velocities close to the surface in a depth between around 5 and 8 m in the center area where the column is supposed to be installed. The velocities are around 1.6 km/s while the reference state shows velocities of around 1.9 km/s. It is expected that the soil loses strength directly after the injection process due to the mixed cement suspension. Between 8 and 10.5 m the velocities increase to a maximum of 2.5 km/s at the bottom. The reason for the velocity differences inside the column after 3.5 hours may likely be caused by different setting times of the cement because the injection process started at the bottom. After 7 days the velocity increase inside the column is substantial and reaches values between 2.7 and 3 km/s. The velocity difference between the tomogram after 7 and 28 days are only marginal. This suggests that a sufficient strength of the cement is certainly reached after a maximum of 7 days. According to different literature (e.g. Wesche, 1993) it is confirmed that the development of the cement strength depends primarily on time. It is known that within the first 1-2 days the strength increases rapidly. The increase of strength afterwards is less significant and after 28 days almost no additional increase in strength can be noticed. Small differences between the diameter approximated by geometric assumptions using horizontal ray paths and the diameter received from tomographic inversion can be noticed. It might be caused by the velocity of the grouted material which was assumed to be constant for the calculation although the velocities inside the column vary as shown in Figure 3.

Conclusions

A new quality control method has been proposed to verify the diameter of jet grouted columns using borehole seismics. The surveys were carried out before and after the injection process at a test site in Berlin (BAM testing site) prepared with three jet grouted columns using specific pressure and grout density parameters. A downhole test was used to determine the acoustic velocity of the grouted material. By relatively simple geometric assumptions the approximate diameter of jet grouted columns can be calculated using the horizontal rays of the dataset. The calculated specific depth and diameter of the column can be used to set boundary conditions to perform the tomographic inversion. Tomography results show the time dependent effects of grouted injections on the soil velocity and thus on the stiffness. Within the first 4 hours too many effects seem to prevent a reliable result. Hence, the results obtained so far suggest that a reliable seismic testing can be made in a time frame of 1 to 7 days after the injection process.

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