

## Quality Assurance of Jet Grout Columns with Borehole Seismic Measurements

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### Abstract

Sealing and strengthening of the subsoil by injection is a major issue in the field of geotechnical engineering. One commonly applied method is jet grouting, which allows creating columns of grouted soil by eroding and mixing the in-situ soil with a thin cement suspension. A general difficulty linked with this method is to predict the resulting column diameter and its material strength. In this paper we illustrate the application of a newly developed non-destructive quality assurance testing tool used to determine the diameter of jet grout columns. This approach incorporates standard crosshole and downhole seismic measurements. To demonstrate its effectiveness, we tested the new approach within two-dimensional finite-difference numerical simulations. Additional field tests showed that this tool is also applicable in real site conditions. For this purpose, three jet grout columns were produced with different process parameters in a depth between 3.0 and 10 m. The evaluated diameters were within 1.0 and 1.5 m, slightly deviating from the previously predicted range by the jet grouting contractor. Moreover, we were able to detect the base of the columns at 10 m depth with no significant difficulties. On the other hand, unsaturated, partly unconsolidated sands between ground water level and surface considerably affected the seismic data, hence complicating the detection of the top of the columns.

### Keywords

Jet Grout, Seismics, Crosshole, Downhole

### Introduction

Jet grouting is a commonly applied method in civil engineering to improve the mechanical characteristics of soil by producing grouted columns. This method is carried out by rotating and pulling up a drill stem while injecting a cement suspension into the ground with a pressure up to 600 bar. During this process the in-situ soil is eroded and mixed with a thin cement suspension. The method is described in international standards as [1] and in [2]. The results are columns of grouted soil with diameters reaching up to 3 m. This procedure constructs panels, full columns or anything in between (partial columns) with designed strength and permeability. It is also used to reinforce existing foundations, to construct excavation support walls and slabs to seal the bottom of future excavation sites, etc.

Jet grout columns are produced below the surface in construction areas often characterized by heterogeneous geotechnical properties (e.g. shear strength) and high water table. Therefore, it is challenging to adapt the process parameters to reach the intended column shape and hence to predict the final jet grout column diameter and its material strength. Both are dependent on various process parameters, e.g. injection pressure and suspension density.

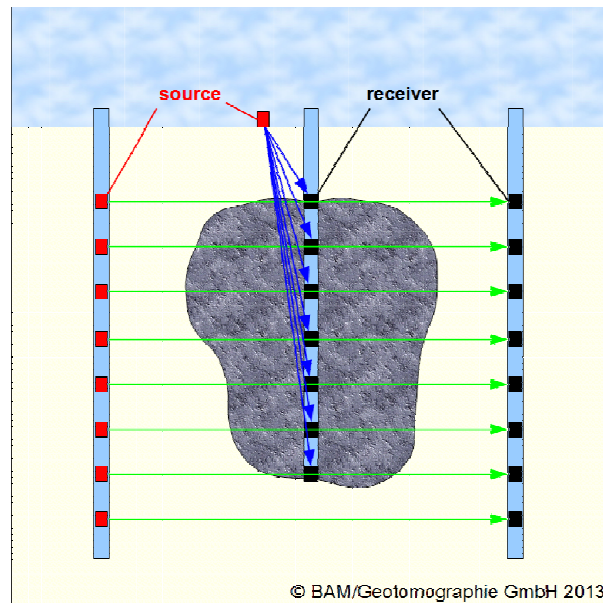
Even after approximately 35 years of application the most reliable method to determine the diameter of jet grout columns remains excavation and experience based values. However, excavation needs considerable time and monetary budgets. Relying just on experience based values may lead to quality issues. For this reason, the demand for fast and cost-effective non-destructive quality assurance tools has been increasing, inducing investigation in various research areas (e.g. [3] [4], [5]). Some of these methods require accurate information about

the soil and the suspension. Furthermore, their application may be limited to a short time frame after production.

We propose in this paper a new approach to determine the diameter of jet grout columns based on a combination of standard crosshole and downhole seismic measurements. In comparison to other methods, reliable data can be already obtained after 6 hours expecting enhanced detectability of the column. This is related to the increasing velocity contrast between soil and the hardening column with time. The presented approach requires, as shown in Fig. 1, two boreholes around the target column and one borehole in the column itself.

To demonstrate the effectiveness of the new approach, we conducted two-dimensional finite-difference numerical simulations and ray tracing [6]. Within these models we simulated jet grout columns located below surface and calculated the seismic wavefields for crosshole and downhole measurements. Field experiments showed that this tool is also applicable in almost real site conditions.

This study is organized as follows. In the next section the methodology of the new approach is presented, followed by field tests, results and the discussion of the results.



**Fig. 1** Schematic representation of the presented approach: Combination of crosshole (green) and downhole (blue) seismic measurements.

## Methodology

### Borehole Seismics: Crosshole and Downhole

Crosshole seismic measurements are conducted for dynamic soil testing in depths down to 100 - 150 m. The aim of this method is to measure P- and S-wave travel times  $T$  between parallel source and receiver boreholes at equal depths (Fig. 1 in green). After every single measurement the source and the receiver are simultaneously moved along the boreholes in suitable depth intervals  $\Delta z$  scanning the area in between. The calculated wave velocities can be used to estimate the elastic properties of the soil. Within this study crosshole measurements were conducted before and after jet grouting to determine the direct effect of the grouted column on the soil properties. The application of the crosshole method is described in [7] and [8].

On the other side, downhole seismic measurements, in geophysics known as vertical seismic profiling (VSP), use the recorded travel times usually between a surface source and borehole receivers to calculate the interval velocities  $c_{int}$  between the vertically distributed receivers (Fig. 1 in blue). In our case, a source (P- and S-wave) is used on the surface close to the wellbore located almost directly above a single receiver (zero-offset VSP). Due to the lateral proximity of the source to the receiver the recorded data provide reliable information about the material properties close to the borehole at the receiver depth. After recording the first shot, the single receiver is moved vertically along the borehole in a predefined interval  $\Delta z$ . The interval velocity  $c_{int}$  is calculated according to Eq. (1):

$$c_{int} = (L_{R2} - L_{R1}) / (T_{R2} - T_{R1}), \quad (1)$$

whereby  $L_{R2}, L_{R1}$  are the distances and  $T_{R2}, T_{R1}$  the travel times from source to receiver at deeper (R2) and shallower (R1) locations. The application of the downhole method is described in [7] and [9].

After recording the crosshole travel times  $T_i$  and calculating the interval velocities  $c_{int(i)}$  from bottom  $i = 1$  to top  $i = end$  the diameter  $D_i$  of the jet grout column is calculated according to Eq. (2):

$$D_{(i)} = (T_{soil} - T_{(i)}) * c_{int(i)} * c_{soil} / (c_{int(i)} - c_{soil}), \quad (2)$$

with  $T_{soil}$  and  $c_{soil}$  as the mean soil travel time and the mean soil velocity, respectively.

## Field Survey

The field experiments were performed at the NDT-CE Test and Validation Center at BAM-TTS in Horstwalde located about 60 km south of Berlin. The area is situated in the northern German Basin and dominated by salt tectonics. As a former glacial valley, the local geology of the near surface is characterized by post glacial sediments incorporating sandy layers of various grain sizes. Soil profiles show that admixtures of silt and organic material are also included [10].

## Jet Grouting and Borehole Seismic Measurements

Jet Grouting was performed from 3 to 10 m depth in between of four PVC-cased boreholes (BH1-BH4), which were arranged in 120° intervals from each other with borehole BH1 located in the center. Production errors were incorporated in the jet grout columns by varying the injection parameters pressure  $P = 400$  bar and density  $\rho = 1.5$  g/cm<sup>3</sup>. Table 1 shows the production parameters for the three jet grout columns.

**Table 1** Jet grouting parameters of three columns.

	<b>Column 1</b> (BH1-BH4)	<b>Column 2</b> (BH1-BH3)	<b>Column 3</b> (BH1-BH2)
$P$ (bar)	400	300 (3 – 6.5 m depth) 400 (6.5 – 10 m depth)	400
$\rho$ (g/cm <sup>3</sup> )	1.5	1.5	1.3 (3 – 6 m depth) 1.5 (6 – 10 m depth)

Before jet grouting was performed, a priori crosshole measurements were carried out in a depth between 1 and 14.5 m below surface in 0.5 m intervals. These measurements served as reference data. The downhole measurements were recorded between 1.5 m and 9.5 m below surface in 1 m intervals. These settings were maintained for all measurements.

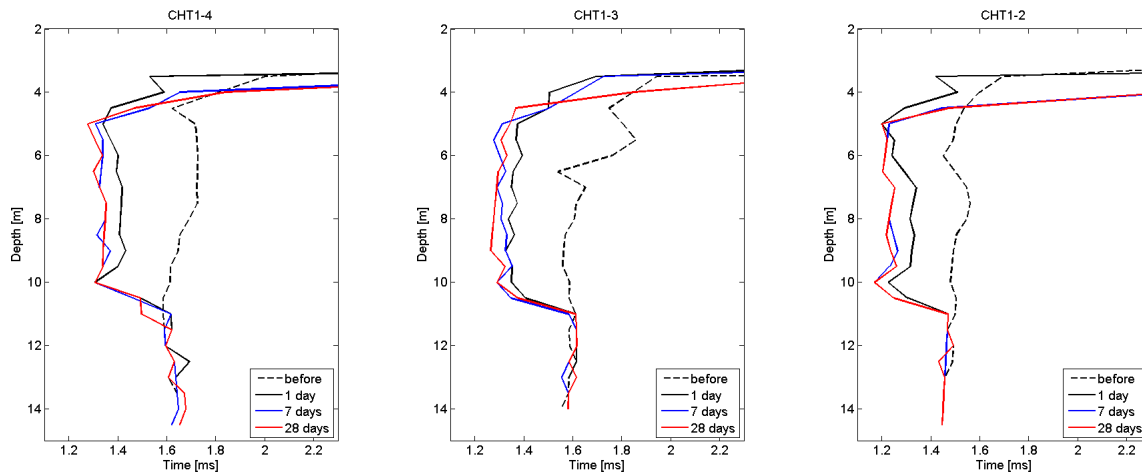
For detailed information concerning the measurement setup and equipment (developed by Geotomographie GmbH), the jet grouting process and the results, see [11].

## Results

Fig. 2 shows the determined travel times of the crosshole ray paths for each parallel source-receiver pair in depth for the respective borehole combination. Most first arrivals were picked by the AIC algorithm [12], except for data obtained at depths  $< 4$  m. Crosshole as well as downhole data showed close to the surface high noise, low frequencies and low velocities in comparison to deeper areas. This change is apparently caused by unsaturated, partly unconsolidated sands above groundwater level ( $\sim 3$  m). The picked first arrivals in Fig. 2 reveal significant travel time differences between the reference data (black dashed line) and the data acquired after jet grouting. They clearly indicate the column boundaries around 4 m and 10 m depth by means of substantial decrease of travel times. It can be seen that the greatest change in travel time occurred one day after jet grouting. Small differences among the data after jet grouting show that concrete hardening continued after one day but with a significantly reduced velocity.

On the other side, we obtained from the downhole tests the velocity of the columns.

Additional ultrasonic laboratory measurements of cubed grouted soil probes verified a velocity of  $c_{col} = 3.3$  km/s.



**Fig. 2** First arrivals for crosshole tests at column 1 (left), column 2 (mid), and column 3 (right) before (reference data) jet grouting and 1 day, 7 days and 28 days after jet grouting.

## Diameter Evaluation

Fig. 3 illustrates the evaluated diameters of the three jet grout columns after 4 weeks of hardening.

Due to the poor data quality close to the surface, picking of arrival times is less accurate compared to the area below groundwater level ( $\sim 3$  m). Hence, the transition from soil to column surface could not be resolved accurately. The crosshole data (see Fig. 2) indicate the column surface to be located in a depth of about 4 m. Nonetheless, the column top is located at 3 m depth, which was verified by drilling. In contrast to the top, the base of the jet grout

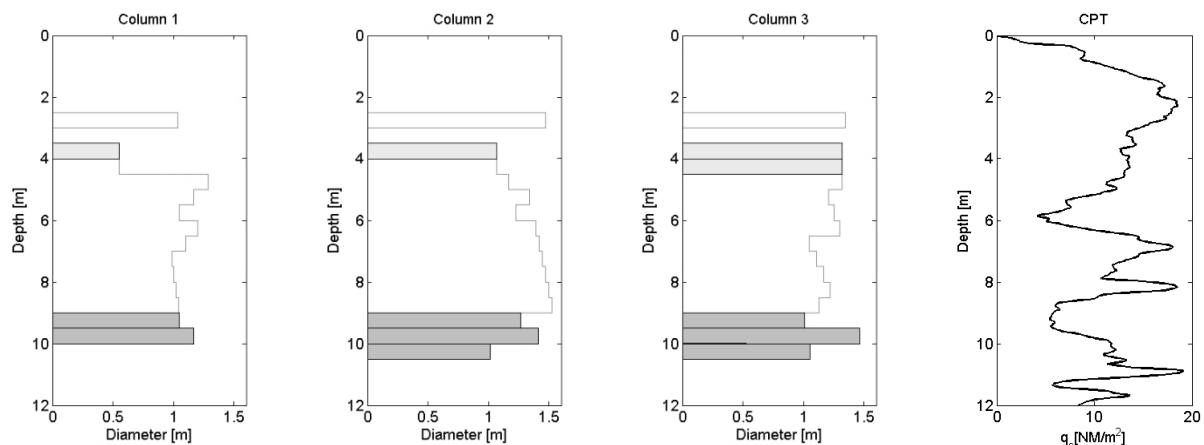
column is defined by a clear travel time increase of approximately 0.16 ms from 10 to 11 m. This matches the designed depth of 10 m.

In Fig. 3 light grey data are biased by groundwater level but corrected using information from deeper parts of the column, where downhole data showed typical jet grout column velocities. Dark grey areas in the bottom part of the columns highlight data with no downhole data coverage. Nevertheless, similar velocities can be assumed since crosshole travel times in these zones are similar to travel times recorded in shallower source-receiver pair depths.

The evaluated diameters are between 1.0 and 1.5 m. This range is slightly wider than what was predicted by the contractor (1.0 - 1.2 m). Due to the same injection pressure  $P = 400$  bar and suspension density  $\rho = 1.5 \text{ g/cm}^3$  applied during the production of column 1 and 2 (10 - 6.5 m depth) and column 1 and 3 (6 - 3 m depth), similar radii in these areas were expected. For column 1 and 2 it is not the case. Column 2 clearly reveals larger radii. On the other side, column 1 and 3 show similar diameters in the upper part. A similar trend of increasing diameter downwards is visible as well, including a sharp bend in a depth of approximately 7 m. The declining diameter trend of column 2 in a depth of 6.5 - 3 m could be interpreted as an effect of the reduced injection pressure  $P = 300$  bar in that zone. Remaining variations could be ascribed to local changes of soil properties (e.g. shear strength).

Bearce et al. developed a DC electrical resistivity push probe to estimate the geometry of jet grout columns [13]. This technique was applied on the same jet grout columns presented in this study. Since the push probe has to be placed into the columns during data acquisition, the measurements were carried out immediately after jet grouting. The evaluated diameters are consistent with the results obtained with our approach.

Some attempts have been made to correlate the evaluated column diameters with CPT data (Fig. 3 right). There is no obvious correlation in our data. This might be related to the fact, that many parameters influence the diameter evaluation of the jet grout columns in the first place. Jet grouting field experiments carried out in different soils showed that for example also the grain size has a considerable effect on the final column diameter [14]. Several CPTs were carried out approximately 20 m away from our test site. All data show significant variations.



**Fig. 3** Column diameters evaluated with data obtained after 4 weeks of hardening. Grey areas indicate manually corrected values. Right: Cone resistance data.

## Discussion and Conclusions

The presented approach for a quality control tool to assess jet grout columns integrates two commonly used techniques from geophysics, crosshole and downhole seismics. If these methods are applied separately from each other none is able to provide sufficiently accurate

information about the diameter of the studied object. As shown, our approach to combine both methods works reliably below ground water level. Determined diameters appear to be reasonable, slightly deviating from the contractor's prediction, which does not need necessarily to be fully correct. Unsaturated sands above groundwater level (~ 3 m) reduce the energy of the triggered source signal leading to poor data quality and hence increasing the uncertainty of travel time determination. It is known that additional noise in real construction sites would make data processing even more difficult. Hence, appropriate processing steps and modified automatic picking algorithms will be required to obtain more satisfying results, particularly for the depths between surface and groundwater level.

According to our numerical simulation results presented in [6], refracted waves do not significantly affect the data. To avoid wrong diameter evaluation, reasonable data handling and careful interpretation of the waveforms is essential.

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