New Aspects of Quality Control for Jet Grouting

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ABSTRACT: Jet grouting is applied worldwide for geotechnical solutions under challenging conditions. The execution parameters for jet grouted columns are presently verified on test columns. Once confirmed, they are repeated during construction on each column assuming that the ground conditions are comparable to those ground conditions at the location of the test column. A completely new approach is to geometrically control each column by vibration monitoring in combination with a built-in alignment control. The main aspect of this new approach is the recording and evaluation of vibration induced by the impact energy of a high pressure beam in hardened primary elements. The time acceleration profiles allow to conclude on the geometry of primary columns and to predict the quality of the overlap between primary and secondary columns. This goes along with a new type of drilling rod that is upgraded to transfer data online via the drilling rod.

Keywords: jet grouting;quality control;drilling alignement;vibration monitoring;acceleration profile

1.The application of jet grouting in geotechnical construction

Jet grouting was adapted from the mining industry and has experienced impressive growth in a wide range of application fields. The main characertistic of jet grouting is a powerful jet released from a small diameter drilling rod that erodes the soil and forms a column(see figure 1) .
The relation between the rod diameter, mostly between 10 to 15 cm, and the column diameter, between 150 cm to 350 cm, makes this construction method very effective under conditions with limited space.

Figure 1 Jet beam

Figure 2 Underpinning existing foundation

The main difference to injection technique is the quality of the cement slurry that does not penetrete the voids in the ground but rather erodes the ground and fractures the soil.
Jet grouting is used for underpinning existing buildings (see figure 2) , closing and sealing gaps at the joints of diaphragm walls or as bottom seals for excavation pits The adavantage of jet grouting with a multi-channel drilling rod (see figure 3) is that the drilling unit can be placed in locations with constrained space and produce an impressive construction element.

In Berlin, Germany , the ground conditions with loose sand, high ground water table and a missing natural sealing layer request artifical bottom seals to deep excavation pits since the environmental laws to not permit a ground water draw down outside the excavation pit during construction.
Therefore, the bottom seal construction (Figure 4) using jet grouting technique is widely established and has developped as the standard construction element.

Figure 3 Multi-channel drilling rod

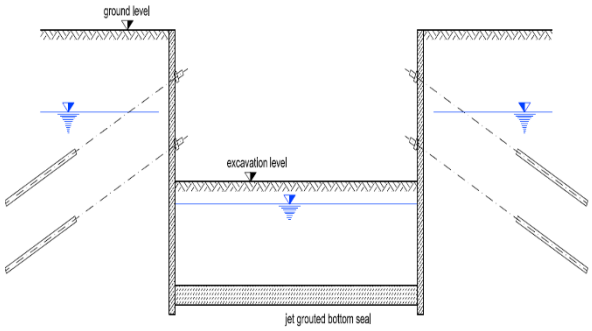


Figure 4 Bottom sealed excavation pit

2. Present quality control for jet grouting

Soil investigations reports, that describe the ground conditions and the ground water situation, together with the geotechnical properties of the relevant soil layers, are extremely important for the application of jet grouting.
Since the geotechnical properties of the soil vary with the depth, it is recommended to place trial columns for jet grouting in the designed depth to confirm the expected diameter of the columns prior to the contruction phase. Once these columns have been constructed, the diameter and the compressive strength of these trial columns serve as the reference for the entire construction phase and the base for the spacing of the columns in case of watertight bottom seals.

The geometrical control of trial columns is difficult if these columns can not be excavated. If the trial columns are below ground water level, methods like pentetration cones or thermal measurement are applied to conclude on the geometrical properties.
Other procedures like the “inverted umbrella method“ or the „Rover method“ touch the inner surface of the eroded column from the center of the column while the slurry is still soft.

All of these methods have a significant disadvantage since they provide a singular result only which is taken at the location of the trial columns. Further repetitions of the diameter measurements during the construction process are not standard procedure since they are very time and space consuming to repeat these confirmation tests. The trial column method therefore goes along with the recording of execution parameters like recording the drilling depth, rotation speed, slurry pressue and volume and withdrawls speed.

Both components, trial columns and recording of the production parameters, provide the basis for the quality control of jet grouting works. This has been adapted from the injection technique where a similar concept is used, but both techniques in terms of their mode of operation are not compareable at all.
What happens if soil conditions change between the investigation points and are unknown to the planner and the contractor?

In case of watertight bottom seals, the result of the construction work can easily be verified by thermal measurements during a test water draw down in the construction pit. If this situation arises, a conflict commonly arises between the client and the contractor regarding the responsibility for the additional costs to repair the „default bottom seal“.

This situation may be avoided if the following method of vibration monitoring is implemented in the production process.

Figure 5 Drilling rod with built-in rover

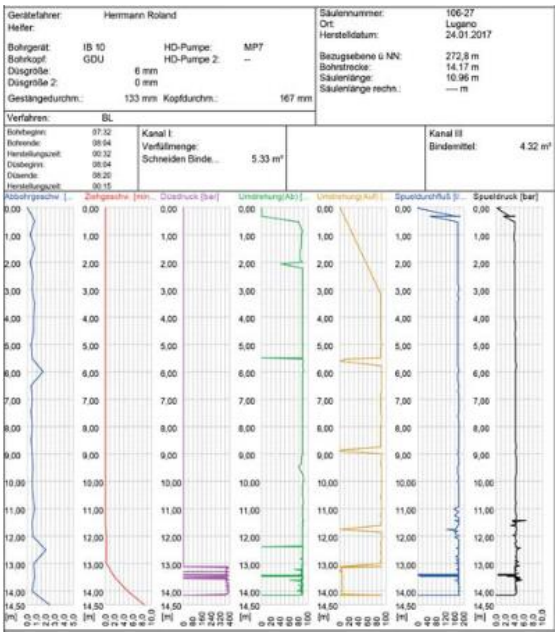


Figure 6 Recording of execution parameters (source: internet presentation Fa. Bauer)

3. New quality control for jet grouting by vibration monitoring

This entirely new concept is based on the material behaviour of the cement slurry and the established construction sequence when building composed jet grouted structures. They provide the input parameters for this new approch in combination with mechanical improvements in the drilling technique combined with state of the art data collection and interpretation as applied for vibration recording of mechanical structures. Essential is the superposition of 4 factors

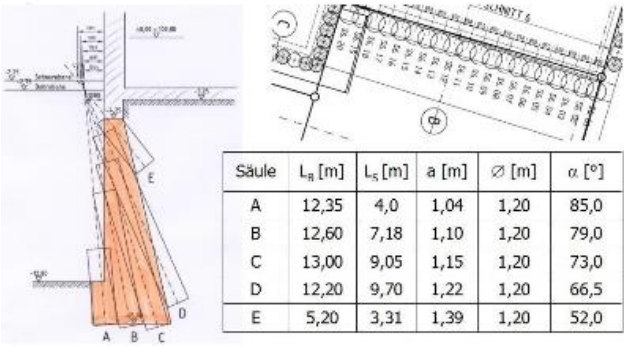
1) Construction sequence
2) Alignment control of the drilling rod
3) Vibration monitoring
4) Data processing

These 4 components, integrated in the construction process, represent a new quality control for jet grouting. It differs from the estabished quality standard since it is designed specifically for jet grouting only and it detects irregular ground conditions.

3.1 Construction sequence

Composed jet grouted structures can be built in two different ways, either as „wet in wet“ or as „primary and secondary“ columns. This is an essentiall difference in the following considerations.

The advantage of „wet in wet“ appears if construction joints are intentionally dissolved and the homogenity of the composed structural element is of high priority. This is the case for under pinning structures where the panels in line with the drilling directions are structurally combined and therefore built in one unit.



Säule	L_R [m]	L_S [m]	a [m]	∅ [m]	α [°]
A	12,35	4,0	1,04	1,20	85,0
B	12,60	7,18	1,10	1,20	79,0
C	13,00	9,05	1,15	1,20	73,0
D	12,20	9,70	1,22	1,20	66,5
E	5,20	3,31	1,39	1,20	52,0

Figure 7 „Primary and secondary“ construction Figure 8 „Wet in wet“ construction
(source:internet presentation Fa. Implenia)

Applying the „primary and secondary“construction method supports the clear structural composition of two units, i.e. primary and secondary rows, put together along defined construction lines.
However, this composition of definded elements provides an additional advantage which is essential for the quality control of jet grouting.
The primary columns are already hardened and have a defined geometrical dimension . This allows to address the row of primary columns as a structural beam, able to carry structure borne noise inside a defined geometry.Once the high pressure beam hits the primary row of columns which is part of the overall construction process, the vibration induced might allow to draw further conclusions about the shape of the surface and the quality of the interlock between the primary and secondary columns.

It is essential for composed jet grouted structures to set up the construction sequence in a way that the vibration induced by the production of the secondary columns is carried in the hardened primary columns as structure borne noise. This allows to measure in process and interpret the vibration signals carried in the primary columns.

3.2.Alignment control of the drilling rod

It is imperative in jet grouting of composed elements to know the exact location of the drilling rod in relation to the other columns.So far, two systems are available for the contruction process. The location control of the drilling rod after reaching the final depth by inserting inclinometer sensors or reading the results of anbuilt-in inclinometer after retracting the rods by means of induction perpendicular to the drilling axis. New, however , is the reading of the inclination of the drilling rod by implemented sensors in every drilling rod section.
Compareable to a chain inclinometer assembly, the two directional inclination readings can be transferred along the drilling axis via couplings that are able to transfer electrical information of measured inclinations.
Magnetic points at every rod provide a reference system, regardless how the rods are screwed together. This combination of upgraded drilling rod in combination with the magnetic point allow to determine any misalignement of the drilling rod while drilling.

This detailed information about the location of the drilling rod in relation to the primary columns is essential for the interpretation of the vibration monitored in the primary columns.

Figure 9 Interface at the flushing head

Figure 10 magnetic point for reference purpose

3.3 Vibration monitoring

If a jet grouting beam penetrates soil alone, its vibrational energy dissipates over a relatively short distance as the individual sand grains absorb and dampen the energy transmission.
Alternatively, if the beam encounters a row of hardened primary columns, the high frequencies induced will travel over a relavtively longer distance. A jet grouting beam which encounters a hardened row of columns will not result in deformation, rather a large portion of its energy will be transferred as structure borne noise. Under this premise, a vibration sensor drilled into the hardened primary columns can deliver acceleration profiles which allow to determine if the high power beam reached to the hardened primary row or not.
The recording of the vibration signals takes place in the primary columns. Since the row of columns is comparable to a structural beam, the sensors do not have to be placed in each column but can be positioned at a defined distance to the area where the jet hits the primary beam. The sensors are piezo-elements that are positioned in small diameter observation tubes, positioned in the primary beam.

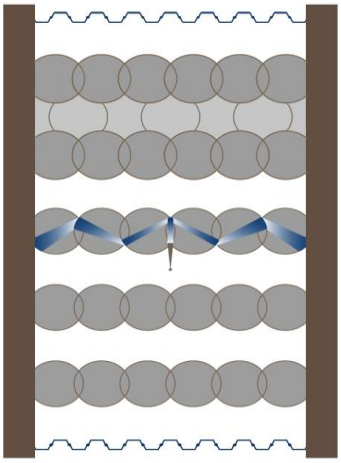


Figure 11 Vibration transfer

Figure 12: Data logger on the acceleration cone

A distance between 10 to 15 meters from the jetting location to the reading location is sufficient for the operational monitoring. The piezo elements are connected to data loggers that are positioned on top of the tubes and designed to record the readings for a full production period. The data logger or acceleration cones have their own energy supply and are independant.

3.4. Data processing

The vibration sensor registers signals using the piezo electronic principle and is able to measure frequencies of at least 10 kHz.
The recording is performed at very high sampling frequency of over 20 kHz to capture information from the entire frequency range. Time signals are recorded during the site recording. The high rate of data sampling, however, produces a very large data volume which has to be processed and reduced for further application.

Knowledge of the signal characteristics is extremely important to reduce the data volume without losing critical information. The following graphic (figure 13) shows the typical high frequency sampling of signals (left) as measured on the hardened primary column during jet grouting.

The spectrogram is shown on the right. Time intervals of T = 0.2 s are basis for a Fast Fourier Transformation (FFT) to show 256 spectra in relation to the time progress.

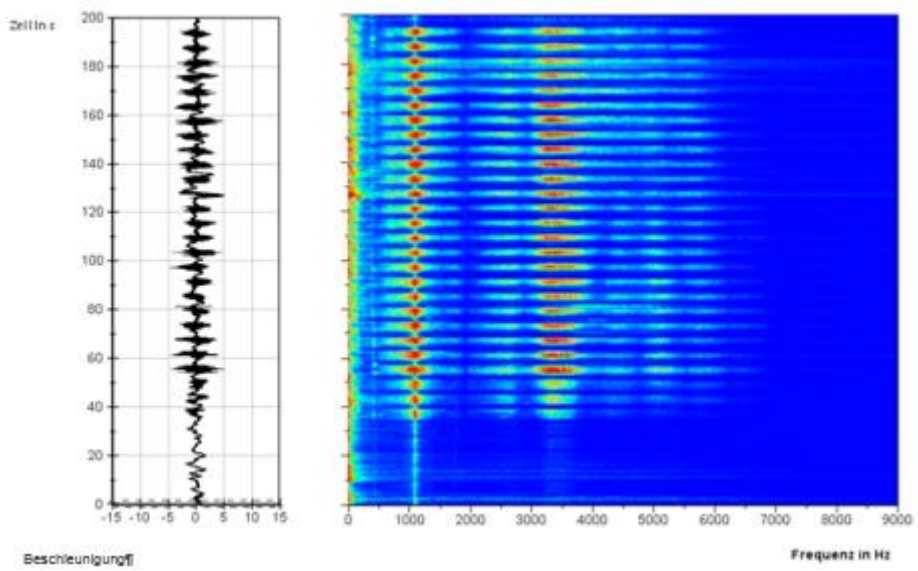


Figure 13 Time versus acceleration and time versus frequencies during jet grouting against a primary column

The periodic repetitions (horizontal lines in figure 13) in the spectrogram show a clear difference between the vibration induced in the primary column and the soil. It also shows frequency ranging at 1 kHz and between 2.3 kHz and 6 kHz while the high power jet beam has contact with the primary column. Those signals that range up to approximately 1 kHz are also superimposed by other causal factors at the construction site such as the drilling equipment. Since these frequencies are influenced by site activities, they are omitted in the further process. The following graph displays frequency contents in the range of 2 kHz and 6 kHz after passing through a band pass filter (Butterworth 6. degree with Haenning-window).

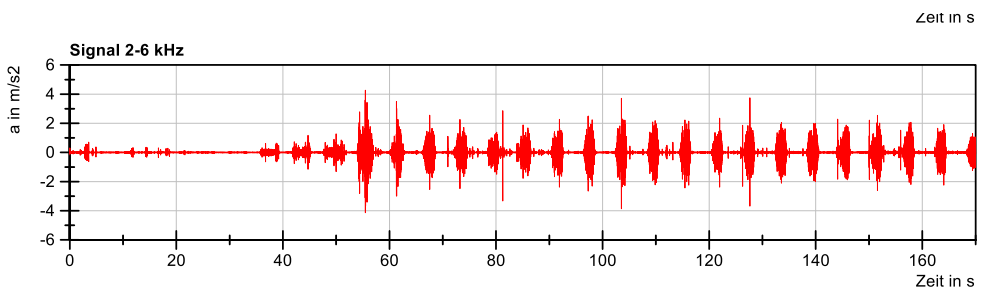


Figure 14:Processed signals by bandpass filter (2-6 kHz)

The advantage of using the addition of spectral elements (FFT of T = 0,2s) lies in a significant reduction of data volume, maintaining the key information in the graphs.(see figuer 14)

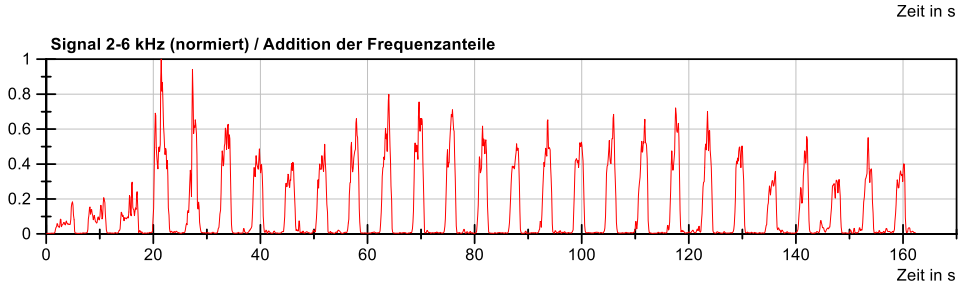


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Figure 15:Reduced data by addition of spectral elements

These processed data reveal the referenced acceleration graphs (see figure 15) induced in the primary columns during production of a secondary column, conveying only those frequencies which were initiated by the high power beam.

4. Test application of vibration monitoring on site

Bottom seal construction in jet grouting technique has established itself in Berlin, Germany as the standard construction element for excavation pits because the environmental laws do not permit a ground water draw down outside the excavation pit. Typical ground conditions for Berlin show high groundwater table and loose, fine sand. The vibration monitoring was tested under these conditions on an infrastructure project in Berlin.

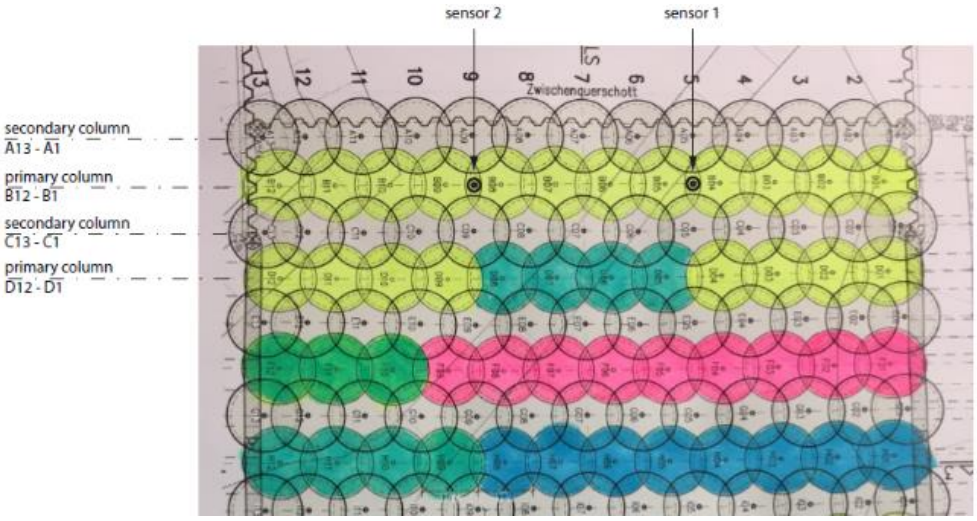

Figure16:Location of sensors and test columns

Two standpipes werer drilled with an internal diameter of 1 inch and accommodated the piezo - sensors 1 and 2. They were positioned in the primary row (B-B) at a distance of 12 meters (see figure 16). The recording took place while jetting all columns in the secondary row (A - A) and (C-C).

The columns had a design diameter of 3,40 meters at 16 meters depth. The cement slurry was jetted at 400 bar and supported by compressed air. The reading for column C 4 was chosen to represent the results obtained for 12 columns in row A and 13 columns in row C. The signals were processed as explained in chapter 3, using the Fast Fourier Transformation (FFT), Butterworth filter and the addition of spectral elements.

The horizontal axis records the time in seconds, the vertical axis shows the acceleration values , adjusted in RMS (m/s²).

The graph in Figure 17 shows the production process of column C4, over the period fo 650 seconds. The primary column was hit 65 times by a jetting beam.Jetting only is recorded, not the drilling stretch.

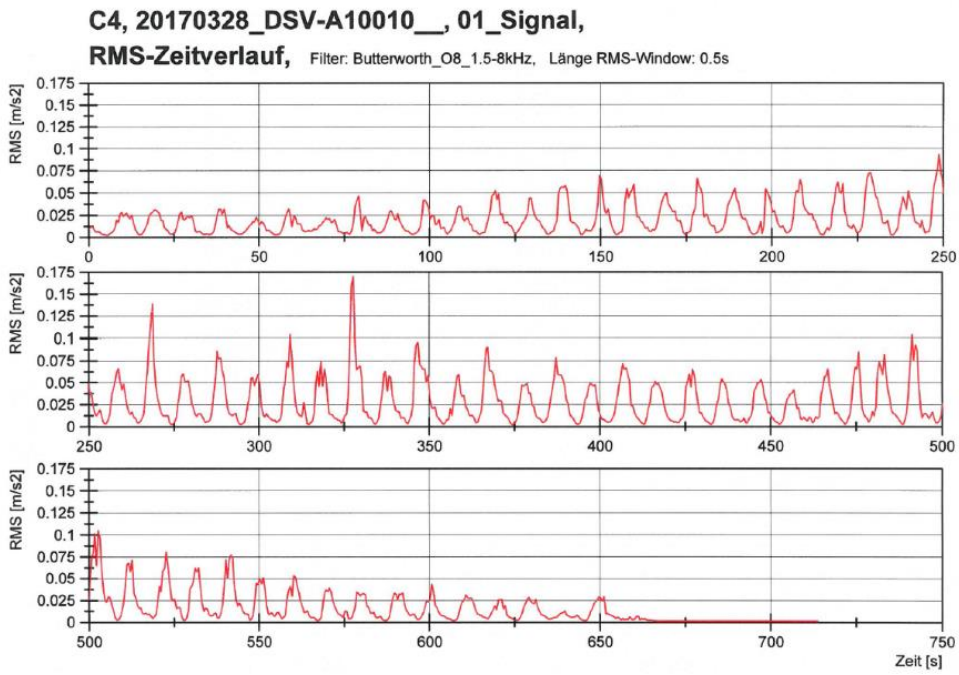

Figure 17: Production process of column C4

5. Concluding assessment of data for column C 4

1. Considering a column length of 100 cm, the jetting rod was withdrawn at a speed of about 7 min/ m.
2. The time related distance of the peaks shows double of the rotation speed, since the jetting monitor was fitted with two opposite sitting nozzles of different diameter. (7 mm and 4 mm)
3. Between execution time 300 sec and 400 sec , the impact profiles alternate reflecting two different energy inputs from two different nozzles.
4. Within the first 100 seconds, the energy impact into the primary columns is cushioned probably due to the eroded soil not jet blown out.
5. Some peaks show a „M - profile“ top which is likely to indicate the orthogonal hit on the left bend, the intercut of two columns and teh right bend.
6. Detailed research shows that the higher peak in the „M - profile“ is closer to the location of the sensor.
7. The width of the impact signal represents the contact period of the jetting beam on the primary column. Contact period and rotation speed allow to conclude on the contact angle of the jetting beam on the primary column.
8. In combination with the exact location of both, primary and secondary columns, it is possible to conclude on the radius of the primary column by using the theorem of Thales.

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