A NEW METHOD OF QUALITY CONTROL FOR JET GROUTING

ONLINE VIBRATION MONITORING

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SUMMARY

The innovative approach for this new method of quality control is based on vibration monitoring in hardened primary columns. The continuous rotation of the jet grouting rod produces a characteristic profile of vibration which can be measured in single columns and composed structures. Fast Fourier transformations (FFT) of recorded vibration signals allow to interpret the processed acceleration graphs to specify the degree and quality of overlap between primary and secondary columns as well as the diameter of single columns.

A BRIEF OVERVIEW OF JET GROUTING

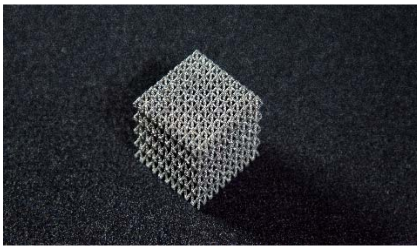
Jet grouting is a geotechnical construction method in which the structure of soil is broken and eroded by a high pressure beam (figure 1).Cement slurry, which is jetted to the full reach of the beam, hardens and creates a column. Several columns may be composed to construction elements such as under-pinning bods or watertight slabs. The capability of the beam can be increased through an additional air nozzle. The high pressure beam may be either cement slurry or water. The jet grouting rod has several channels in which the inner one leads the high pressure fluid (figure 2).
Construction parameters such as pump pressure and volume, pull back time and revolution of the drilling rod are recorded during the process and compared with those of the test columns. The quality control of jet grouting is based on the premise that the geometry and compressive strength of columns in comparable soil layers can be achieved by repeating the construction parameters of the test column. If soil conditions change, however, the effect on the size of the column cannot be detected.

Figure 1: Jet grouting beam

Figure 2: Jet grouting rod

Jet grouting (figure 4) may be compared to a 3D printer as complex structures are comprised of repetitive, additive and identical construction elements (figure 5). The prerequisite is knowledge of location, geometry and properties of the material used.

3 D Printer:	Jet Grouting Process:
exact position of single elements	drilling deviation
exact measurement of single element	diameter of column
properties of material	compressive strength



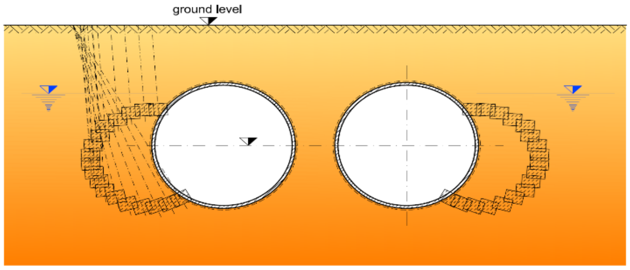
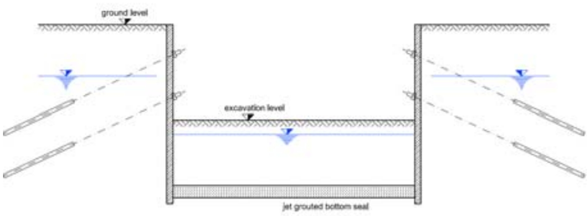


Figure 3: Additive constructed cube (source:www.siemens.com/presse)

Figure 4: Metro station constructed with jet grouted columns

BERLIN IS A FOCUS LOCATION FOR JET GROUTING APPLICATION

The soil in Berlin is relatively consistent and primarily composed of fine sands which reach to a depth of approximately 60 meters. These sands were formed over three ice ages and deposited by glaciers which reached from Scandinavia to the region of Berlin.
Since the ground water level is generally at 3 meters below surface without a natural layer, the construction of a two level underground parking garage requires a special geotechnical approach.
Open draw down of ground water is generally not accepted by civic approval authorities to obtain a building permit as the ground water is protected and extraction volumes are limited.
Compliancy with the regulations for water management is achieved through excavation pits with a horizontal barrier. The lack of natural horizontal barriers in the soil necessitates construction of artificial barriers in the form of deep jet grouted (figure 5), injection or underwater concrete slabs.



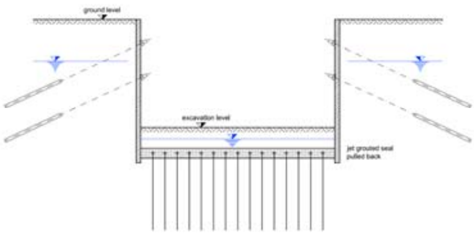


Figure 5: Deep jet grouted slab

Figure 6: Jet grouted slab pulled back by micro piles

The sandy soil, high ground water level and building code regulations present a challenge which can only be technically managed through construction of horizontally sealed excavation pits. Jet grouted slabs, pulled back by micro piles (figure 6), have established themselves as the economically preferred method over injection slabs or underwater concrete slabs.

WHAT METHODS ARE CURRENTLY AVAILABLE TO VERIFY GEOMETRICAL CONFORMITY OF JET GROUTED COLUMNS?

The previous comparison of jet grouting with a 3D printer defined three quality criteria: exact position of each single element, the geometry of each element and the material properties.
Focus in this presentation is on the second of these three criteria, namely geometry of individual construction elements with special attention to the diameter.

An exact location of the jet grouted column may be verified with inclinometer sensors in the drilling equipment that transfer the exact location of each coupling onto the display of the operator. (figure 7)

Figure 7: Plot of drilling rod alignment taken during drilling

The quality of material comprising the column may be established by taking samples in fluid state via pumps in the drilling rod.

What is the current approach used to verify the diameter of jet grouted columns?

- Test columns, which are dug free close to surface

But how are columns, which lie below the ground water level, verified?

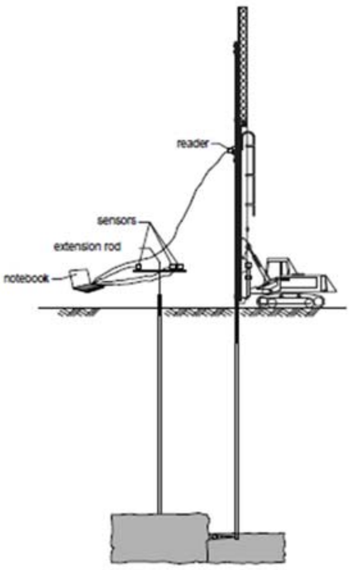
- Test columns, whose diameter is recorded by distance sensors, lowered down into the soft column
- Test columns, whose diameter is measured with a Rover, operating out of the jet grouting rod
- Test columns, whose diameter is measured by contacts points in various distances
- Test columns, whose volume is measured by thermal calculations.

All of the above methods involve measurement of singular test columns which are executed in relevant and representative conditions. These methods assume that the achieved diameter can be repeated by maintaining the same construction parameters such as pressure, rotation, air pressure, etc. However, the soil conditions created by multiple glacial movements and melt are not homogenous. Therefore, the application of parameters from a given test column may not be transferrable, especially in the case of watertight construction.

THE NEW METHOD OF DIAMETER CONTROL BY VIBRATION MONITORING

The measurement is based on energy transfer from the jet grouting beam in the ground. Deformation is the main consequence of the high pressure beam moving through the soil as it is broken and mixed with suspension. A relatively small amount of energy is converted in the form of vibration, which is transmitted as space waves. The speed of the waves is dependent upon the mechanical properties of the soil. Once a column is hardened, it is able to transfer shear forces.

Hit by the powerful jet grouting beam, the column transfers energy along its axis to the top of the column where sensors can read the vibration (figure 8). Measurement of vibration transmitted into the primary column indicates whether the beam of a jet grouted column has encountered a hardened column or soft soil. The amplitude of speed or acceleration represents the key criteria as it differs between a hardened column or soft soil. The acceleration in hardened material, i.e. jet grouted column results in a higher speed and lower reduction in amplitude. Knowing the time during which the grouting beam hits the column allows to calculate the missing link in a trigonometrical calculation (figure 9). Correlated to the rotation speed of the jetting rod provides the angle alpha and thus determines the diameter of the hardened column.



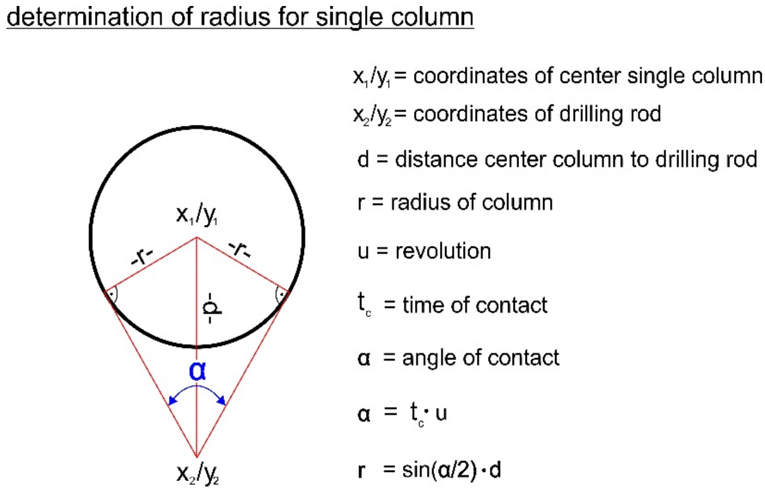


Figure 8: Set up for measurement **Figure 9: Trigonometrical relations**

FULL SCALE SITE TESTS IN BERLIN TO CONFIRM THE PRINCIPLES OF VIBRATION MONITORING

In August 2016 field test were carried out to compare calculated diameters with actual diameters of excavated columns (figure 10). A center column, already hardened, was hit by a jet grouted beam from the left and from the right inside an excavation pit. The distance of the columns to each other was known. A steel pipe with integrated vibration sensor was integrated into the center column. While jetting the adjacent columns against the center columns, the vibration induced in the center column was recorded.

Since the adjacent columns were constructed using a cement power beam, the middle column was covered on both sides with jet grouted bodies. The red spray paint makes it easier to see the difference between each column

Figure 10: excavated test columns

Figure 11: excavated primary column

After the adjacent columns were removed (figure 11), the geometry of the primary column was ready for onsite measurement. The comparison between the calculated radius using trigonometrical equations and the measured radius on site showed a very high degree of conformity

DATA COLLECTION OF VIBRATION

The acceleration sensor registered signals using the piezo electronic principle and was able to measure frequencies of at least 10 kHz. The recording was done at very high sampling frequency of over 20 kHz to capture information from the entire frequency range. Time signals were recorded. The high rate of data sampling produced a very large data size, which had been 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 12) shows the typical high frequency sampling of signals (left) as measured on the hardened primary column during jet grouting on a comparable project.

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.

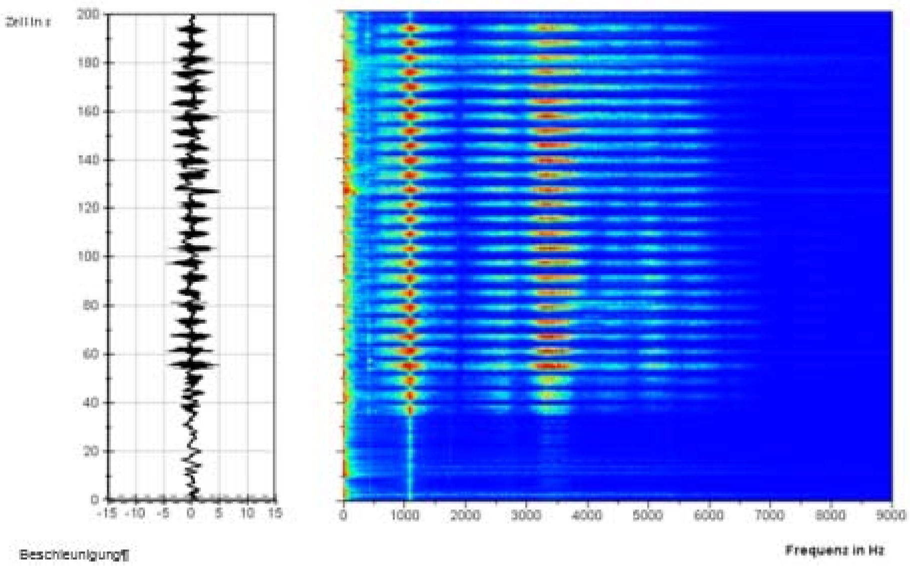


Figure 12 Time and spectrogram of acceleration during jet grouting against the primary column

The periodic repetitions (horizontal lines) in the spectrogram show a clear difference between the vibration into the primary column and the soil. It also shows frequency ranging at 1 kHz and between 2.3 kHz and 6 kHz while the beam had contact with the primary column. Signals up to approximately 1 kHz are also superimposed by other causal factors at the construction site such as the drilling equipment itself.

DATA PROCESSING

The example shown is based on frequency contents in the range of 2 kHz and 6 kHz. The whole signal is passed through a band pass filter (Butterworth 6. degree with Hanning-window).

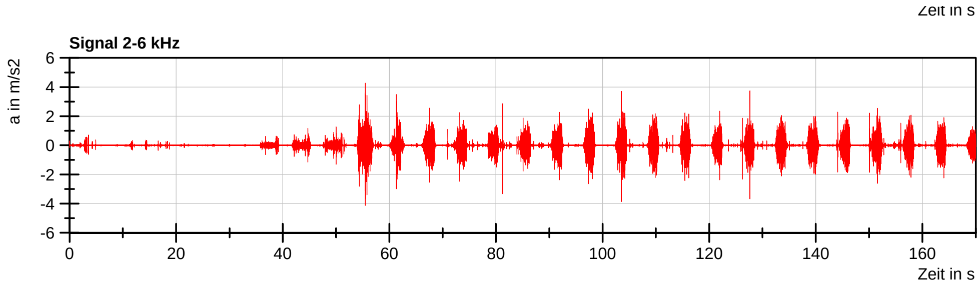


Figure 13: Filtered signals by Bandpass (2-6 kHz)

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

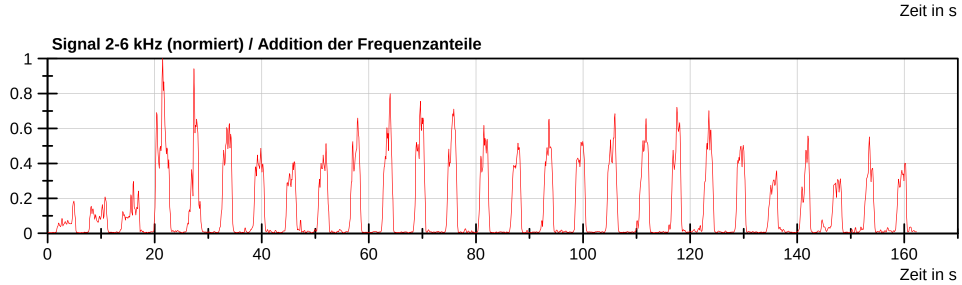


Figure 14: Retransformed data

INTERPRETATION OF RECORDED ACCELERATION ROUTINES

Based on the field tests to following conclusions can be drawn:

1) There is a significant difference between the jet grouting beam hitting a column or the soil
2) The vibrations induced by the high power beam are transferred along the axis of the hardened jet grouted columns and are recordable
3) The distance of the peaks confirm the rotation speed of the jet grouting rod
4) The contact time of the high power beam on the jet grouted column is readable under the acceleration peaks
5) The contact angle to calculate the radius of the jet grouted columns is very reliable
6) The value of the acceleration peaks varies according to the highly turbulent situation during jetting

VIBRATION MONITORING ON COMPOSED STRUCTURAL ELEMENTS

Watertight jet grouted construction slabs are usually constructed of primary columns “wet in wet” (figure 16). This means that the columns are constructed sequentially without waiting for the previous column to harden.
Secondary columns are jet grouted against the primary columns after they have hardened. Jetting energy is transferred in the drilling depth against a linear row of columns (figure 15).
This constructing sequence of primary and secondary rows of jet grouted columns allows to apply vibration monitoring to check on the overlap.
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 affect.

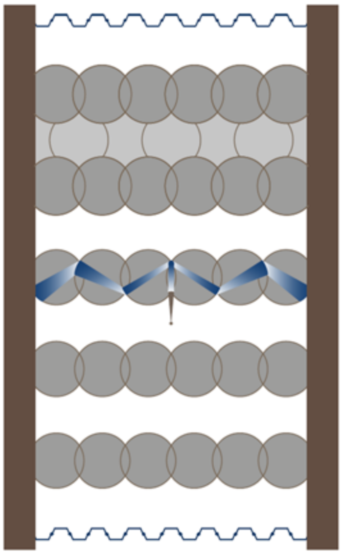


Figure 15: Vibration transfer

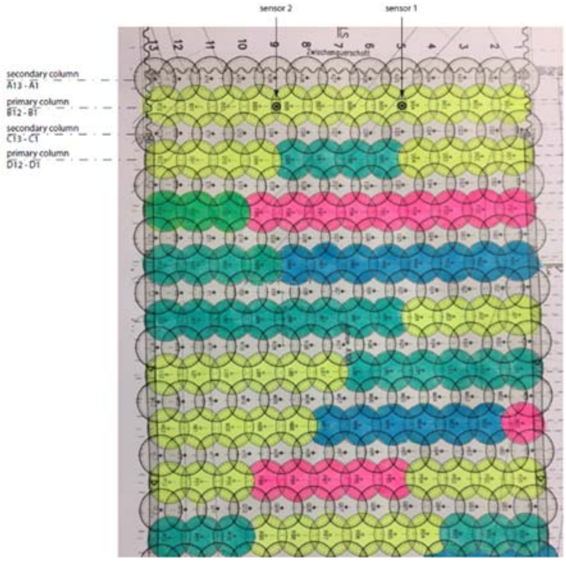


Figure 16: construction drawing

Alternatively, if the beam encounters an element of hardened primary columns, its high frequency vibration penetrates the element over a relatively longer distance. A jet grouting beam which encounters a hardened column will not result in deformation, rather a large portion of its energy will be transferred as a vibration impulse into the primary column (figure 15). The vibration will be transmitted within a row of column as structure borne noise.

Under this premise, a vibration monitor 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. This "impact cone" (figure 19), designed with integrated energy source and data logger, can be set to record defined frequencies, in this case high frequency which is typical for transfer along a hardened primary row of columns.
These ideas carry the results gained on the vibration monitoring of single columns and were suitable to be tested on a construction site in the heart of Berlin.

SECTION 16. OF THE A 100 IN BERLIN, THE FUTURE CITY HIGHWAY BETWEEN NEU-KÖLLN AND TREPTOW

The traffic infrastructure in Berlin is designed with an inner city and outer highway ring. The inner city highway ring could not be completed during the division of Berlin between 1961 and 1989. Construction of Section 16 finally commenced in May 2013 following long, political discussions. A piece of highway with 3 lanes in each direction over 3.2 km should join the Intersection Neu-Kölln with the exit at Treptower Park. Construction is planned from 2013 through 2022 with a budget of 473 million Euro. The project is divided into 7 lots. The investor is Bundesrepublik Deutschland. Contractor for lot 5 is company Porr with its partner for geotechnical works Stump.
The routing of the highway was planned into a 7 meter deep excavation pit, horizontally sealed, to comply with noise and air pollution standards. In addition, noise barriers with a height of up to 6 meters will be added.
All of the requirements together culminated in design of horizontal slab for lots 1 to 4 with underwater concrete and lots 5 and 6 with jet grouting method.
Jet grouting was applied to seal an area of approximately 12.000 m² in Lot 5 and approximately 2.500 m² in Lot 6, partially pulled back by micro piles.

Figure 17: Highway BAB 100 - 7 construction lots

Tests were made during the summer of 2017 in areas of Lot 5 to verify the integrity and overlap of jet grouted columns (figure 18)

SET UP OF TEST ARRANGMENTS ON THE CONSTRUCTION SITE

The overall concept for the test was set up to read the acceleration graphs in the row of primary columns using standpipes with integrated sensors. The row of primary columns was about 32 meters long with two monitoring locations. The recorders were installed approximately at the points of division into thirds in the row of primary columns axis. The diameter of the test column was 3,40 m. The secondary row A had 12 columns, the primary row B had 12 columns and the secondary row C had 13 columns.

Figure 18: Overall layout of the construction site **Figure 19: Data logger**

The vibration sensors are constructed to fit into the standpipes. Once the monitoring stage is accomplished, these sensors are easy to retrieve and may be used again. They are not lost.

Figure 20 displays the processed acceleration graphs which were recorded while jetting column C 4. The time is recorded on the horizontal axis. The vertical axis shows the adjusted acceleration. The distance of the peaks reflects the rotation speed of the rod. The intensity of the signal distinguishes between the big and small nozzle.

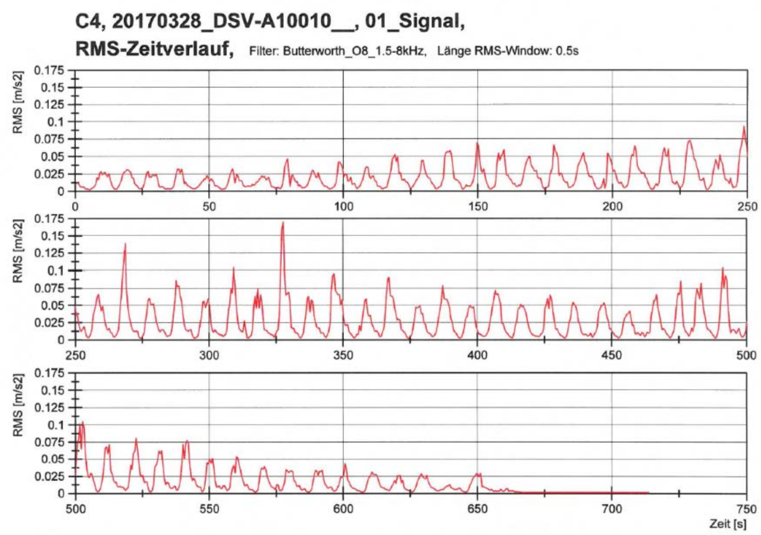


Figure 20: Vibration signals during the construction of secondary columns C 4

INTERPRETATION OF PROCESSED DATA

Hitting a single column shows a single peak in a symmetrical graph. However, hitting a sequence of columns, this geometry is reflected in a "double peak" as can be seen on the Figure 21 and 22. The double column shows the addition of two single column profiles which are essentially merged into one interlocking body

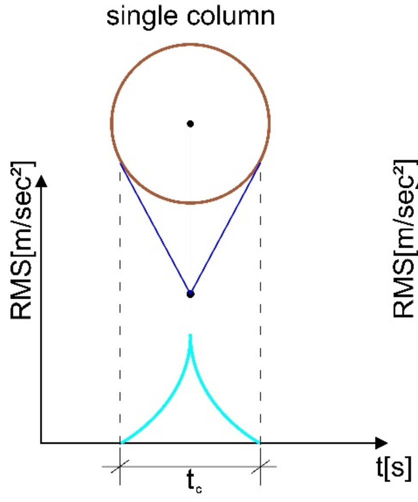


Figure 21: profile single column

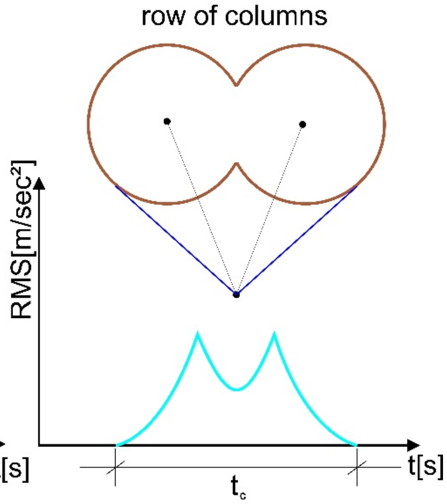


Figure 22: profile row of columns

Four basic profiles were extracted from the recorded acceleration values to determine the correlation criteria.

1. <u>Column without contact</u>

No significant vibration is measured if the jetting radius is not achieved to reach the primary column. The energy released does not reach to the column as it is absorbed in the soil.

2. Column without contact in the gap

If the jet grouting beam makes contact with a primary column, but the radius is not sufficient to erode soil in the gaps between the primary columns, then the soil remaining in those gaps will dampen the energy. In this case an energy drop is visible in the middle of the contact zone.

3. Regular column

The signal increases to a top value and decreases to the symmetric axis, confirming the basic profile of figure 22.

4. Oversized secondary column

If the secondary column has an unplanned wide diameter, then the beam has to cover a longer distance and exhibits longer contact time at unchanged rate of rotation.

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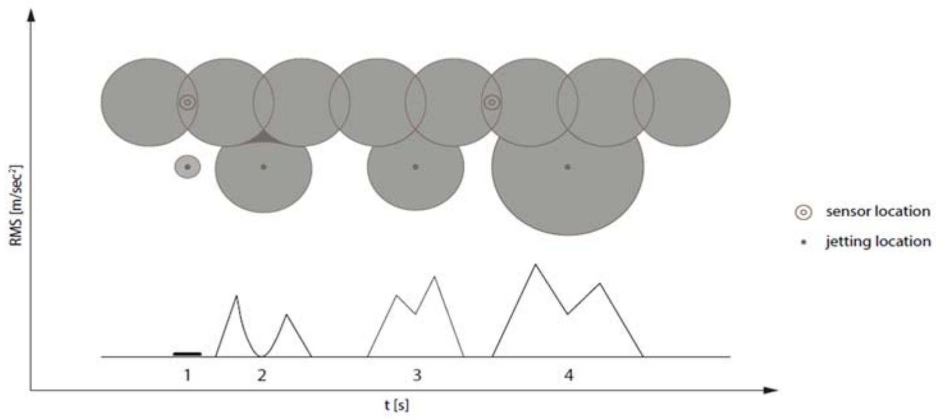

Figure 21: Graphs of possible signals

CONCLUSIONS DRAWN FROM THE TESTS ON SITE

Vibration monitoring on jet grouted columns opens a new type of quality supervision and supports the composition of new structural elements.

1) The actual diameter reached is focus of vibration monitoring for jet grouting rather than the compliance of execution parameters with test columns, as applied in the present state of the art. Thus the potential risk of unexpected ground condition is significantly reduced
2) Vibration monitoring on single columns allows diameter determination at any depth below ground level, without having to dig them free.
3) Vibration monitoring and sophisticated data processing provides an assessment of the interlock on composed jet grouted elements.
4) Vibration monitoring does not interfere with the production process on jet grouting.
5) Data loggers at every 5th column in the primary rows allows to cover the interlock of 100 % between primary and secondary columns.
6) Supporting structural elements for metro stations or emergency tunnels expands the future application range of jet grouting, if supervised by vibration monitoring.

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REFERENCES

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