

EVALUATION OF VIBRATION MEASUREMENT IN JET GROUDED ELEMENTS

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ABSTRACT

Jet grouted seals are an established construction method to build watertight excavation pits in inner city areas. Environmental aspects focus to prevent ground water draw down outside of the construction site by implementing bottom seals for excavation pits. This article introduces a new type of quality monitoring by which the vibrations in the primary columns are read while jetting the secondary columns. The present state of the art focusses on the recording of the execution parameters as applied for the test columns. The new concept refers to recorded signals from installed sensors to evaluate the contact between the primary and secondary columns. Field tests have been carried out in Berlin to explore the influence of the type of construction joints, the relevant distance of sensors to the jetting location and the curing time of the hardened columns. The results allow to develop acceptance criteria for a proper connection of new to old columns.

Keywords: jet grouting, watertight excavation pits, structure borne noise, primary columns, secondary columns

APPLICATION OF JET GROUING

The support of existing buildings in the vicinity of deep excavation pits in inner city areas demonstrates the versatile application of jet grouting. When applying jet grouting, a high-pressure jet beam with cement slurry or water erodes the adjacent ground and forms a column. This allows to construct a wide range of underground elements, such as:

- Underpinning structures
- Improvement of existing foundation
- Gap closure for sealing purpose
- Bottom seals for excavation pits.

The jet grouting technique has undergone systematic improvements in recent years. A key technique is the implementation of inclinometers inside the drilling rod that allows to read the deviation of the drilling rod while drilling and the recording of structure borne noise in hardened columns triggered by the energy impact of the high-pressure beam.

THEORETICAL BACKGROUND TO THE GEOMETRIC DETERMINATION OF JET GROUDED TEST COLUMNS

The jet grouting process is always associated with energy input into the subsoil. The jet beam cuts through the existing soil and swirls it with the water-cement slurry introduced. If the high-pressure beam meets already hardened jet grouted columns, a force impulse is introduced into the column. Within the column, the induced structure-borne sound essentially propagates in the form of compression waves with a high propagation speed. This physical effect is used to determine the moments at which the jet hits and leaves the column using suitable sensors.

By measuring the structure-borne noise in the hardened column, it is therefore possible to clearly distinguish when the jet beam passes through the surrounding subsoil or hits a jet grouted column. As long as the jet beam cuts through the ground, the resulting ground vibrations are characterized by the fact that the high-frequency components of the signals in particular are strongly attenuated and the amplitudes decrease very quickly. When the jet beam hits the hardened jet grouted column, the structure-borne sound waves propagate in the column in a broadband manner, i.e. in a wide frequency band, due to the higher strength of the column material compared to the ground.

This difference in terms of structure-borne sound propagation in cured jet grouted columns and in the ground is used to detect the overlap of the jet beam with the cured column. The diameter of the cured columns is calculated based on the measured contact time of the jet beam with the cured column and concluded distance of the jet grouting rod to the center of the cured column.

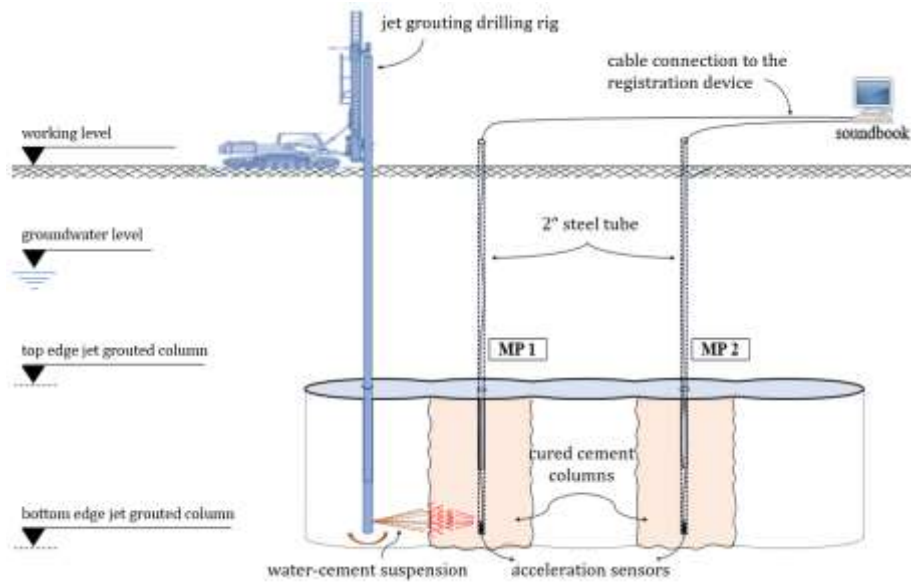


Fig.1: Test arrangement for the test column measurement

DATA ACQUISITION AND EVALUATION

The structure-borne sound in the cured column is recorded using an acceleration sensor. This is placed in the center of the column. To register the relevant frequency components of the signal, the analog signal is digitally sampled at a high sampling rate.

Figure 2 shows a typical acceleration-time curve during a jetting process. The diagram illustrates the rise and fall of the signal and thus the beginning and end of each contact of the jet beam with the column to be measured. In this application example, the signal is repeated approx. every 9 s and has a duration of approx. 2 s. Between the signals attributable to the contact of the jet beam with the cured column, structure-borne sound signals with lower amplitudes are recorded. This reduced vibration excitation is due to the smaller stabilizing nozzle located opposite the main nozzle.

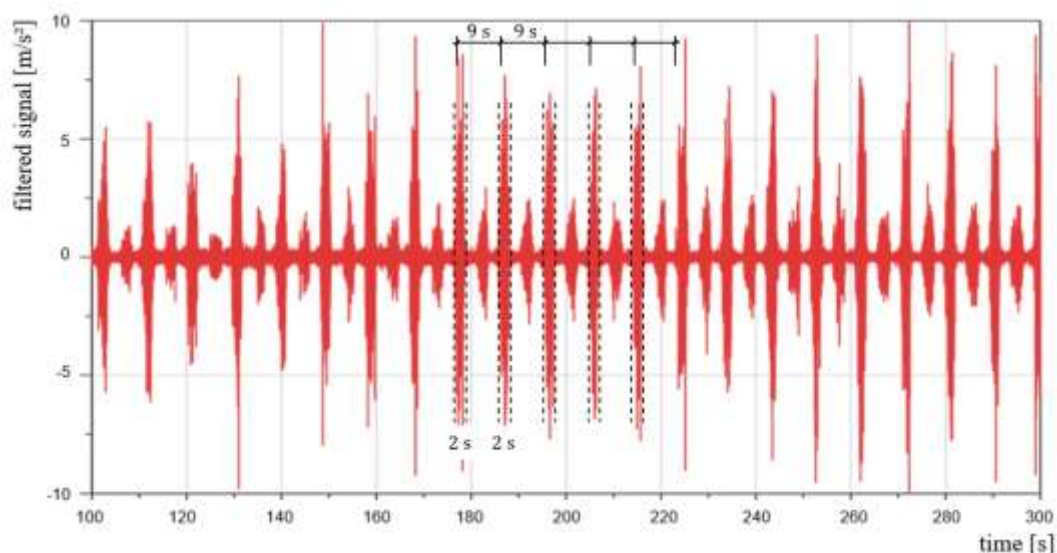


Fig.2.: Time curve of the vibration acceleration in a hardened column

A spectrogram (Fig. 3) can be used to illustrate the time-varying frequency content of the recorded vibration signal. The structure-borne sound components with the highest energy (yellowish) occur during the contact of the jet beam with the column and are generally in a frequency range between 1 kHz and approx. 6 kHz.

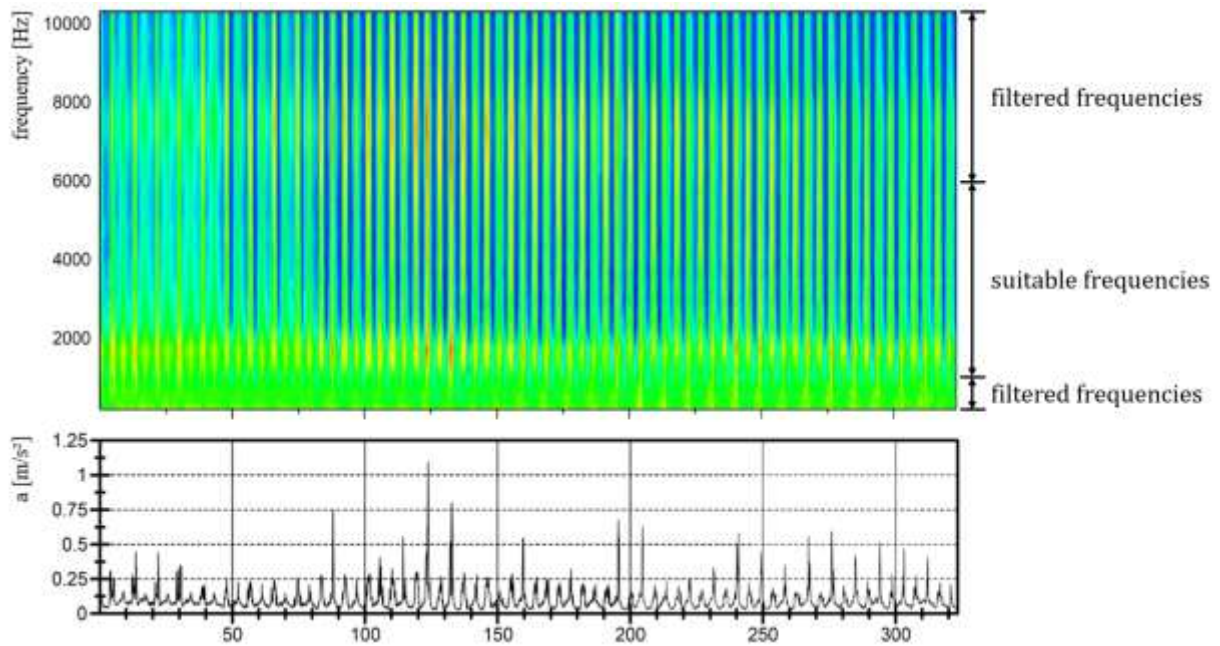


Fig.3: Spectrogram visualizing the time related frequency content of the acceleration signal

Further processing of the acceleration time signal is conducted using

- a) suitable bandpass filter in the range of the relevant frequency content (e.g. 1 kHz to 6 kHz);
- b) the calculation of moving effective values (RMS values: Root Mean Square) with a suitable time window length (equation 1)

$$a_{RMS} = \sqrt{\frac{1}{\tau} \int_{t_1}^{t_2} a^2(t)} \quad \text{with } t_2 - t_1 = \tau \text{ (e.g. } \tau = 0.1 \text{ s)} \quad (1)$$

- c) reduction of the RMS- measurement data through classification.

The exact parameters for the limits of the bandpass filter and the sliding time window of the RMS value formation may differ slightly depending on the project or the given boundary conditions. The advantage of using the described bandpass filter is that only the signals that are attributable to the jetting process are included in the further evaluation. Rather low-frequency vibration excitations resulting from general construction site operation - including the motor and drilling operation of the drill itself - are thus filtered out of the relevant signal. The RMS-value formation enables the temporal representation of the energy of the structure-borne sound signal and generally leads to an increase in the significance of the recorded events.

The result are effective values as shown in Figure 4, from which the contact times can be read.

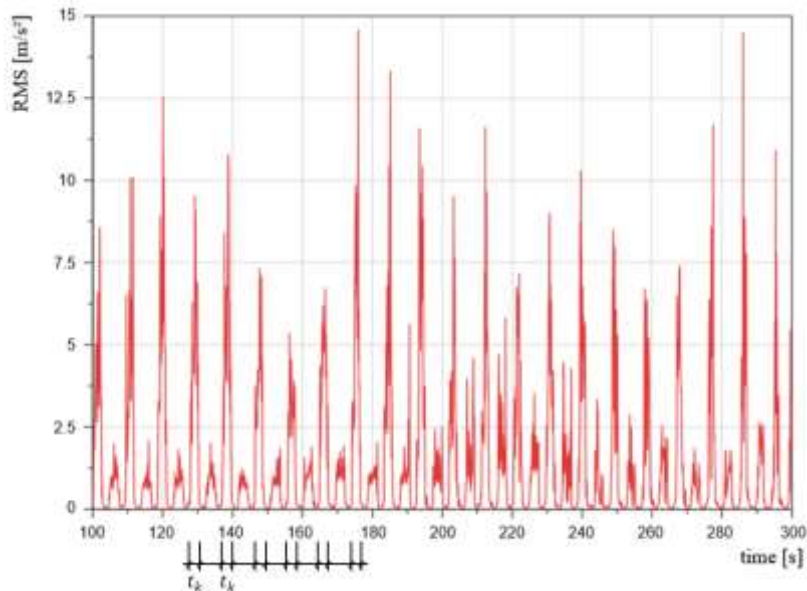


Fig.4: Example of the RMS-values of the filtered signal (1 kHz)

By determining the contact time t_k per rotation, the column diameter can be calculated considering the distance between the drilling rod and the center of the cured column. The basis for calculating the diameter is the application of Thales' theorem (Fig.5). This states that in a circle whose diameter represents the distance between the center of the test column and the agitating jet beam, all angles are perpendicular to the circumference of the circle. The angle between a diameter and any secant of the semicircle is therefore always 90° .

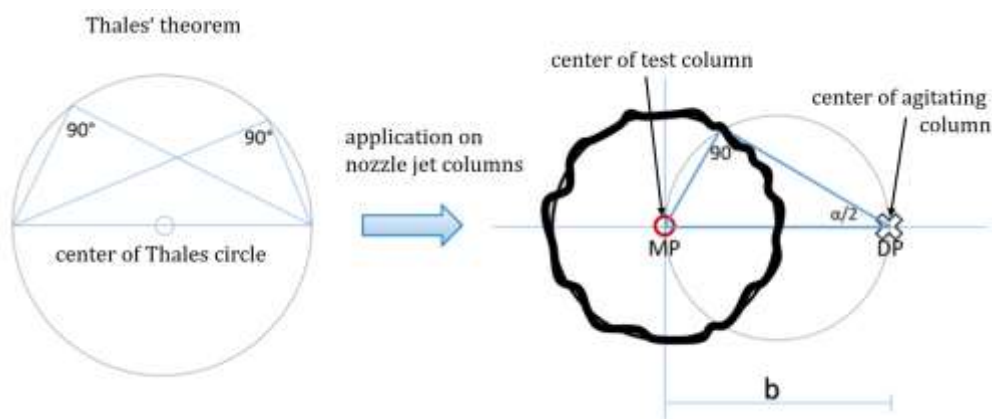


Fig.5: Sketch for calculating the diameter of a cured column

By measuring the contact time of the jet beam with the cured column, the angle at which the right-angled triangle is to be formed in the Thales-circle is determined. The radius of the cured column can be derived from this using simple trigonometric relationships. This conclusion assumes that distance b does not exceed a specified value, as outlined in equation 3.

$$b < \frac{D}{\sqrt{2}} \quad D = \text{diameter of the excitation column or cured column} \quad (3.)$$

If the distance b is greater, the radius of the hardened column can be determined assuming that both columns have the same diameter (Fig. 6).

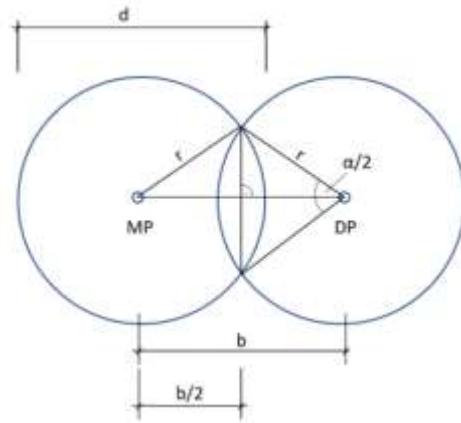


Fig.6: Sketch for calculating the diameter of a cured column with larger distance b

The radius r can then be solved using the trigonometric relationship (see equation 4):

$$\cos(\alpha/2) = \left(\frac{b/2}{r}\right) \tag{4.}$$

Convert equation 4 to the radius r:

$$r = \frac{b/2}{\cos(\alpha/2)} \tag{5.}$$

The diameter d is then obtained by doubling the radius r (see equation 6):

$$d = \frac{b/2}{\cos(\alpha/2)} \times 2 = \frac{b}{\cos(\alpha/2)} \tag{6.}$$

Each contact of the jet beam with the cured column allows conclusions to be drawn about the geometry of the test column. By pulling up the nozzle jet rods when jetting the sample column, contact times are created with each revolution, which can be evaluated. As a result, the test column is made up of discrete disks with corresponding diameters. This results in the 360°-profile of the test column when executed from both sides, as shown in Figure 7.

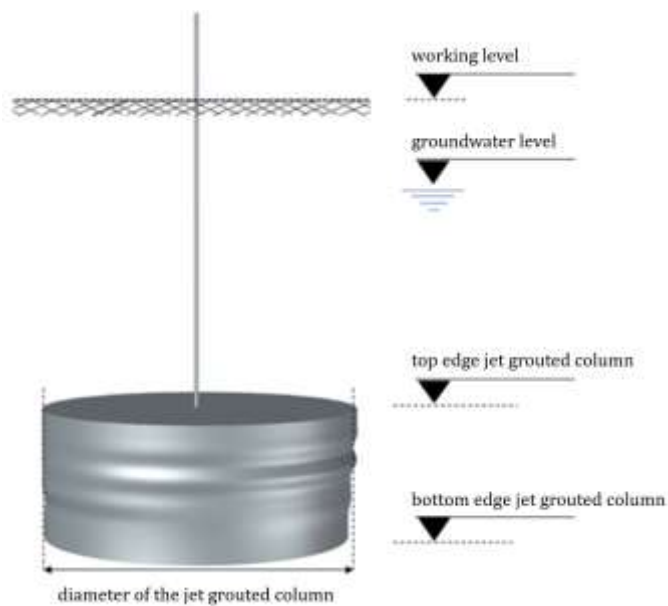


Fig.7: Geometry of the evaluated test column.

QUALITY MONITORING IN COMPOSED JET GROUTED STRUCTURES

The structure-borne sound input of a high-pressure jet can also be detected in composed jet grouted structures and evaluated regarding quality assurance. The prerequisite for this is the positioning of structure-borne sound sensors in the primary rows produced. As a rule, jet grouted columns are produced in primary and secondary rows. The production sequence is shown in Figure 12 in green and blue.

The primary rows are cured when the secondary columns are produced. This production sequence makes it possible to monitor the execution of the secondary rows, using the structure borne noise in the cured primary columns. to evaluate them according to defined quality criteria.

The decisive factor for the quality of a watertight seal is the actual connection of the secondary columns to the hardened primary columns. The construction plan, which includes the drilling points of all columns, is usually designed so that the center of the secondary columns is opposite the overlap of the primary rows. The contact of the secondary column with the primary column that occurs at this position during jetting generates a characteristic measurement signal on the sensor of the primary column that is repeated during the production of each secondary column.

FOUR CHARACTERISTICS OF A CONTACT SIGNAL

Following the conclusions of Eberhardt, S.A. (2024), four basic characteristics of a contact signal can be distinguished, which are generated when the secondary columns get in contact with the primary columns:

1. The **standard case** captures both already cured primary columns and reaches the critical point of the gusset as planned with the nozzle jet. This can be seen in the effective value signal of the acceleration (RMS = Root Mean Square) (Fig. 8).

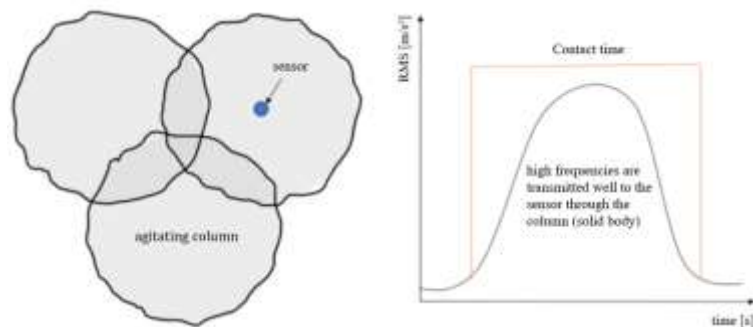


Fig. 8: Expected contact

2. In contrast to the normal case, there is the so-called **gusset defect** (Fig. 9). In this case, the geometrically most distant point (gusset) was not completely eroded. In the recorded signal, it is characterized by a clear amplitude reduction in the RMS-values of the acceleration.

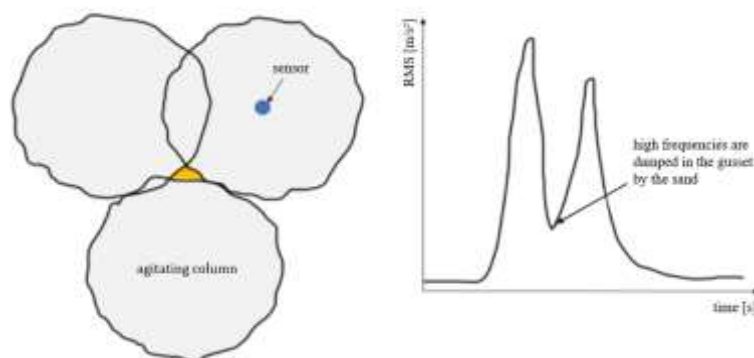


Fig. 9: Gusset error

- 3 If, on the other hand, only one of the two opposing pillars is projected in the case of a **one-sided contact**, this is represented by a one-sided shift in the RMS-acceleration curve (Fig. 10).

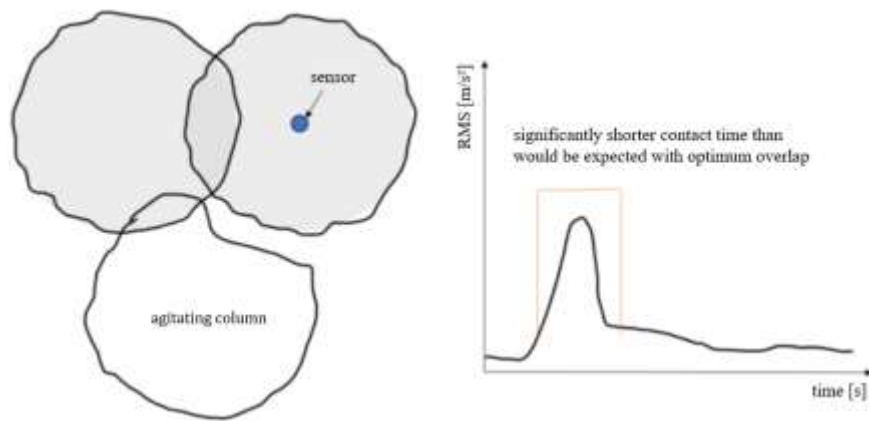


Fig. 10: One-sided contact

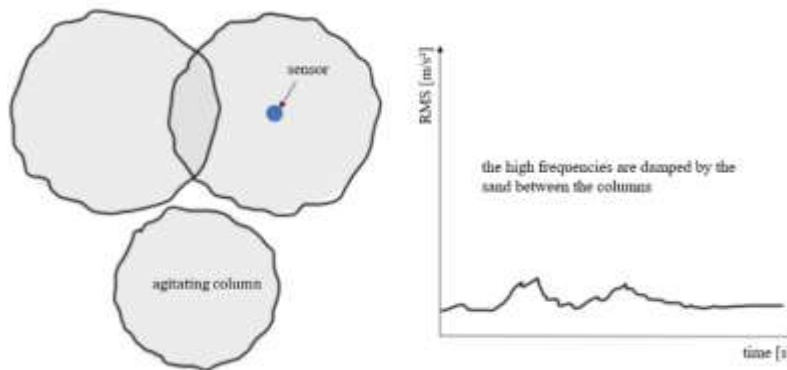


Fig. 11: No overlap

4. If there is **no direct contact** between the nozzle jet and the cured primary rows, the high frequency components of the structure-borne sound signal are strongly attenuated and only transmitted to the primary column to a small extent. The amplitudes of the RMS-values are correspondingly small

These basic signal characteristics represent reference profiles that enable monitoring the connection of the secondary columns to the primary columns during installation.

Recording and evaluating the vibration signals according to these patterns introduces a new form of verification of contact-compliance. The basic test results suggest that the sensors can be positioned up to approximately 7.50 m from the nozzle source and still record sufficiently high-quality structure-borne sound signals in the primary column. It is therefore not necessary to install sound sensors in each primary column for the continuous detection measurements.

These acceptance criteria allow to implement sensors in primary columns in a regular pattern and enable a continuous quality check of the contact of primary and secondary columns. Upgrading every 6th primary column with a sensor in a row provides adequate quality assurance. The sensors are either installed in steel tubes or lost, in case of execution without steel tubes. Reference is the transmission of structure borne noise over 7,50 m from the location of jetting to the location of the sensor.

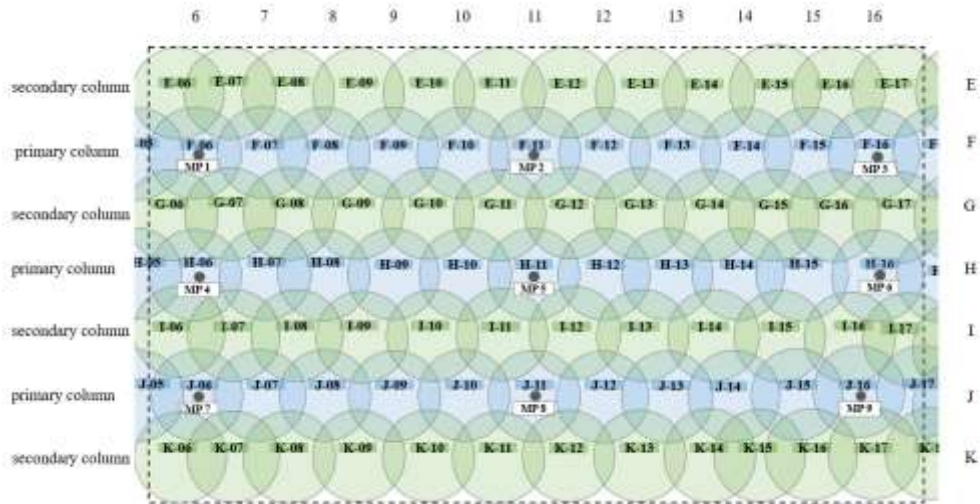


Fig. 12: Systematic location of acceleration sensors in a bottom seal

The influence of the type of construction joint in the grouting sequence was investigated in more detail by Kant, E. (2023) and found to be negligible. The curing of the primary columns within the regular execution times does not play a significant role for the distance grid of the measuring sensors. The diagram in Fig. 13 contains the processing of signals derived from a power density spectrum and shows that meaningful evaluations can still be made even at 7.50 m between the sensor and the nozzle rod.

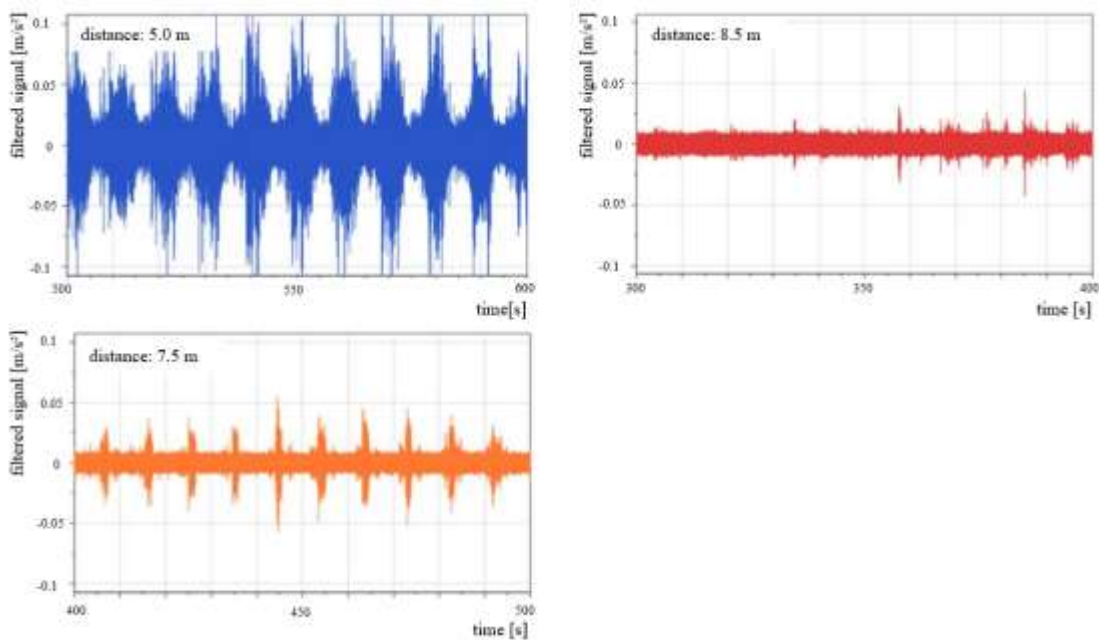


Fig. 13: Distance related signal strength of structure borne noise in primary columns

DETECTION OF UNERODED AREAS

Uneroded areas due to unknown subsoil obstacles contribute a significant project risk. Obstacles in the path of the high-pressure jet block the cutting effect behind it and create interference zones that are larger than the actual obstacle. Such obstacles can be old wells that are not recorded in the as-built documentation, lost exploratory/drilling rods or randomly found boulders. (see Fig. 14).

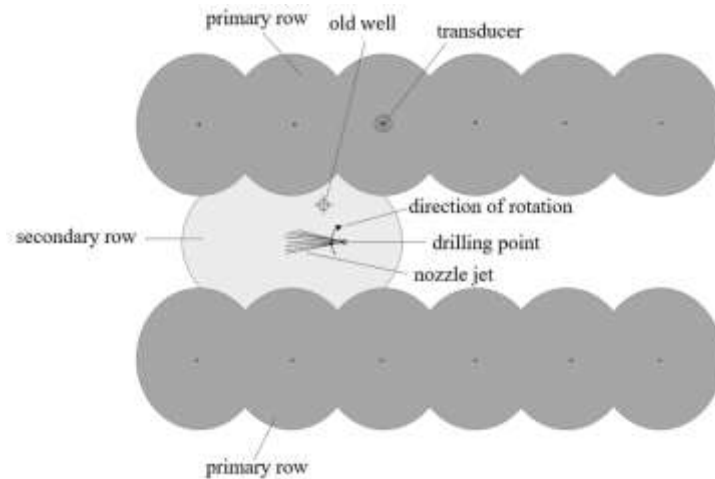


Fig. 14: Site plan of jet grouted bottom seal with uneroded areas caused by an old well

The risk of uneroded areas can be significantly reduced by measuring structure-borne noise in cured primary columns during execution. The structure-borne sound measurement can indicate possible obstructions if the high-pressure beam does not generate the expected signals. Regular disturbances in the signal transmission manifest themselves with every revolution and at all depths. Obviously, the nozzle jet is impaired by an obstacle, which likely leads to uneroded areas. (Fig. 15). If such anomalies are detected during construction, additional columns reduce risk with little effort.

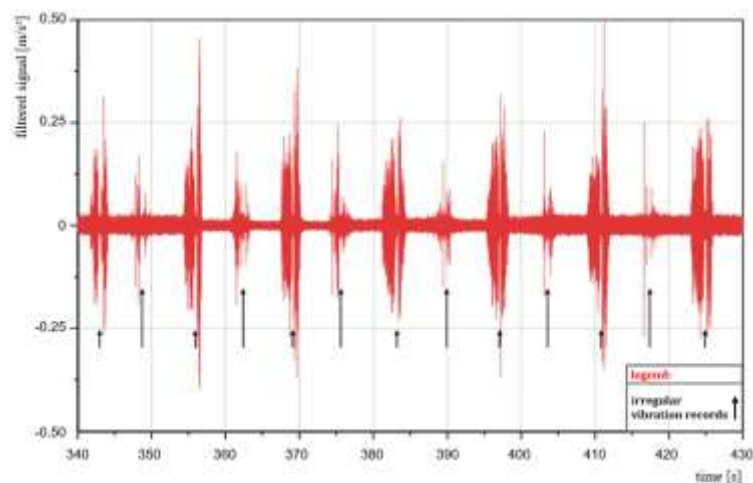


Fig. 15: Signal recordings triggered by uneroded obstacles

SUMMARY

According to the current state of the art, the jetting parameters are verified on test columns and repeated for each column thereafter. This is done under the assumption that the encountered soil conditions are comparable to the ground conditions at the test columns. Jetting against hardened columns with built-in vibration sensors allows to confirm the geometry of the transition between old and new columns by reading the signals of the vibration sensors. This is an immediate control of the jetting parameters.

This technical innovation, adopted for the construction of bottom seals with primary and secondary rows, supports the quality assurance during construction based on contact criteria recorded by vibration sensors. The evaluation of recorded signals allows to monitor the integrity of composed jet grouting structures during construction. In case of unexpected signals, corrective measures like additional columns can be constructed in short-term, while all the equipment is still on site.

CONCLUSIONS

The technical success of bottom seals in combination with the watertight retaining walls is usually checked by a test lowering phase inside the trough in which the ground water is lowered prior to the excavation works. Temperature measurements of the groundwater trapped in the bottom sealed excavation pit are carried out during this test phase to identify temperature changes during the lowering of the groundwater in the trough. As a possible result, conclusions about leaks can be drawn in the excavation pit walls or the jet grouted bottom, namely where cold water from outside flows into the warm water in the trough.

In preparation for this test phase, additional tubes are usually drilled in a standard grid and equipped with temperature sensors. This time-consuming localization of possible leakages could be replaced by the structure-borne sound measurements in primary columns described above. The contact between the individual jet columns can already be tested during construction. The implementation of additional tubes and their upgrading with temperature sensors is cost-intensive and requires additional construction time, which can be significantly reduced with structure-borne noise measurements during construction.

Another aspect of more efficiency in the construction process could be the improvement of the transmission width of the structure borne vibration as it is limited. So far, a distance of 7,50 m between stimulator and receiver has been evidenced by site tests. More site tests are recommended to increase this distance by additional elements like selected cement components or steel fibers mixed into the cement slurry.

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