

Application of a hybrid learning based quality control system for Vibro Ground Improvement

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ABSTRACT: Gaining new insights of Vibro Ground Improvement sites by combining all process data into one big picture was the motivation to start a research project at Keller Grundbau. Together with a team of data science experts of the University of Leoben, Austria, evaluation procedures of the raw data like validation, segmentation and classification were developed to allow for detailed geotechnical investigations. After the successful completion, the development of algorithms to be used for an automated quality assurance system based on the outcomes of the initial research phase was the next step. Finally, the new “Production Process Intelligence” (PPI) application enables project managers to use these algorithms in their daily business. This application uses two parallel methods to check the quality of all executed columns on a Vibro site –Key Performance Indicators (KPI) and machine learning (ML). The results of both methods are overlaid to achieve a high hit rate in detecting potential quality outliers. The paper will pick out specific KPIs, explain their functionality theoretically as well as based on examples from executed sites and compare the results to the traditional, manual quality approval process. The inspection of quality relevant KPIs summarized in a spatial view of the whole project area provides an easy-to-understand view of local coherences and can point out deviations clearly. Furthermore, important details of the production process, e.g. the proper execution of every single compaction step at every Vibro column, can be analyzed automatically. The project manager has reduced effort while the quality of the checks is improved significantly.

KEYWORDS: automated quality assurance, quality control, Vibro Ground Improvement, hybrid learning, machine learning.

1 INTRODUCTION

As Soil Improvement elements are subsurface, element protocols have a high importance in the quality assurance of Vibro Techniques compared to other special foundation methods, because in-situ testing of Soil Improvement is often inadequate or very expensive.

A unique challenge in soil improvement techniques is that the execution process and the properties of the elements are influenced by varying soil conditions. Unfortunately, soil exploration campaigns often lack precision, making it necessary for each installation to yield additional insights into soil layering and mechanical properties.

In 2020 Keller Grundbau started a research project in cooperation with a team of data science experts of the University of Leoben to gain more insights out of the recorded production data sets of Vibro Ground Improvement sites.

On the one hand, algorithms and methods have been found to combine data from all executed columns of a site into one big picture. On the other hand, an automated, gapless quality control of every single column on a very detailed basis has been developed.

2 DEEP VIBRO GROUND IMPROVEMENT MONITORING

The quality approval of Soil Improvement methods like Vibro Techniques is usually done by means of manual interpretation of recorded production data, done by project managers and geotechnical experts. The depth of the elements, the compaction energy, the activation force (pull-down force), the amount of built-in gravel material and the duration of the production are documented in single element protocols for every column.

In case of mid-size to large sites, local coherences of possible quality deviations are lost easily due to the high amount of production data when quality analysis is just available for single elements. Furthermore, the possibility to do detailed quality checks of every single compaction step for

every executed element on a site is very limited in the daily business of a project manager.

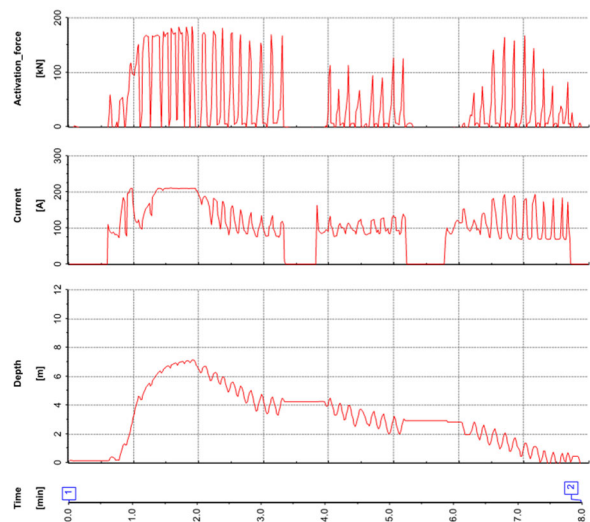


Figure 1. Example of an element protocol of a Vibro-Replacement column

So, there is a need for a different, modern way of quality assurance for the execution of Vibro Techniques.

3 DEVELOPMENT OF AN AUTOMATED QUALITY ASSURANCE APPLICATION

3.1 Findings of the research project

With the goal to improve the quality assurance of Vibro sites, the data specialists of the University of Leoben developed a method to segment and classify the element data sets automatically into sub processes, primarily the penetration and compaction phase of each Vibro stone column as a basis for further analysis.

During the penetration phase, the vibrator displaces in-situ soil while the vibratory motion is generated by an eccentric weight driven by an electric motor, with the power of the vibrator being monitored in real-time. The vertical penetration is influenced by the pull-down force, also called activation force, which, along with vibratory power, dictates the penetration rate related to the ground's stiffness. These parameters are recorded continuously, along with temperature readings to ensure that the vibrator does not exceed specified operational limits. The penetration continues until a defined operational depth is reached, typically within a bearable soil layer. Abort criteria, based on vibration power and activation force, are also in place to ensure that the required soil bearing level is achieved.

Once the final penetration depth is attained with the vibrator, the compaction phase begins. The vibrator is pulled upwards and the void underneath is filled with gravel. Then the vibrator is re-penetrated into the filling material to compact the loose gravel into a dense state and displaces compacted gravel material horizontally into the in-situ soil, initiating a vertical reciprocating motion to build up the stone column in single compaction steps. Each compaction step adds gravel to the hole and compacts it to the desired stiffness, which is monitored through vibrator power and pull-down force. The local soil's density and load-bearing capacity result in varying column diameters over the depth. The reciprocation process continues with pauses for gravel filling until the column is completed. Monitoring the whole compaction phase also enables the calculation of the built-in volume of gravel.

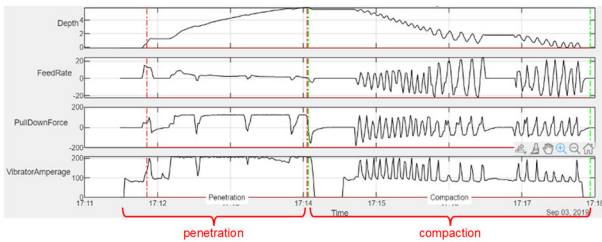


Figure 2. automatic separation of penetration and compaction phase in the execution of a Vibro stone column

Two different approaches of quality approval have been developed within the research project to analyze the element data sets independently from each other:

- **Key Performance Indicators (KPI):**
Several KPIs have been developed taking into consideration the advice and feedback from Vibro experts to analyze the penetration and compaction phase of the column production automated.
- **Machine learning (ML):**
Utilizing autoencoders an unsupervised machine learning approach was introduced to identify unusual patterns in the data sets that differ from typical operational behaviour.

In the final step, the results of both quality analysis methods are combined to a hybrid learning analysis.

Finding anomalies in the data sets and therefore possible quality outliers is the main target of this automated quality assurance. Overlaying the results of both analysis methods in the hybrid learning approach enhances the system redundancy and reduces the likelihood of missing anomalies.

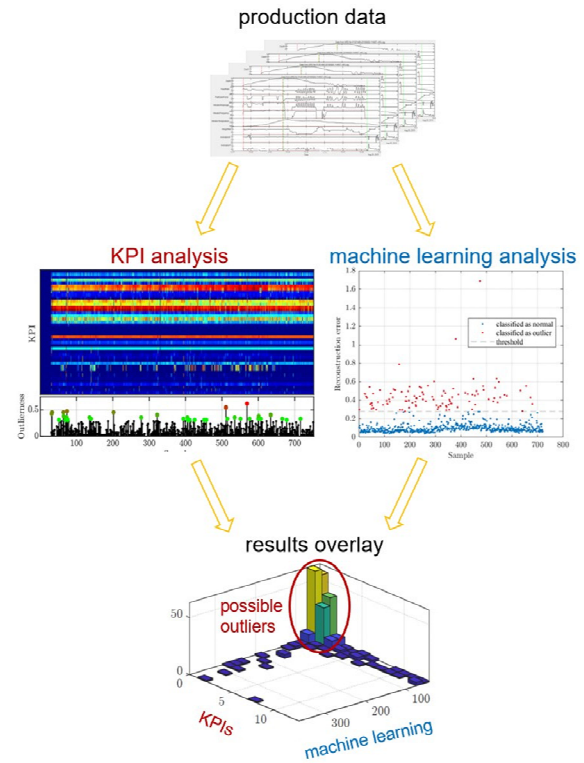


Figure 3. Principle of the hybrid learning analysis

3.2 Implementation of the insights into a quality analysis application

To introduce the findings of the research project into the daily site management, an easy-to-use application was developed, which presents a spacial view of all executed columns of a site to the project management. Possible elements of low execution quality are highlighted in order to be manually checked by an expert. Based on the results of the quality evaluation, the expert needs to decide whether mitigation measures are required to compensate the low quality or not.

The application assists by bookmarking the potentially low-quality area at the element protocol that led to the interpretation of being a quality outlier. Elements with a positive quality interpretation do not need to be checked manually by a project manager anymore.

Coherences in case of a local concentration of possible quality outliers are easily established by means of the spacial views. Using this quality assurance application, the effort for project managers is reduced significantly as well as the quality of their checks.

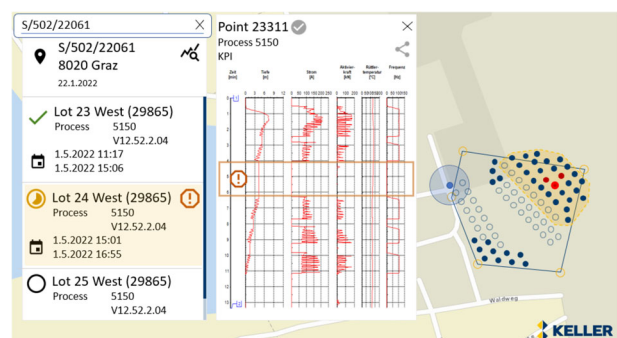


Figure 4. Screenshot of quality analysis application for project managers in the development phase



Figure 5. Screenshot of quality analysis application for project managers in the development phase

4 QUALITY ASSURANCE EXAMPLES

In the following sections, some selected examples of the developed KPIs are discussed to show their role in the overall quality assurance application.

4.1 Compaction Step Quality KPI

Analyzing every single compaction step of every executed column is such a high effort that it is not possible to be done by a project manager in addition to all other daily tasks, especially for big sites with a lot of production data. The detailed analysis, done by the new application, enables a significant increase of the quality assurance level.

This KPI checks if the production parameters at every compaction step comply with pre-defined values:

- Pull/Push-ratio:
For every compaction step the Vibrating tool is withdrawn a certain distance to ensure that the built-in aggregate can fall into the remaining void. Then the Vibrating tool is pushed down again to compact and displace the built-in material into the surrounding soil, creating a sufficient column diameter, interlocking the surrounding soil and the column material. To remain within a certain pull-/push-ratio is an indicator for a constant column diameter for the whole column length as well as for a sufficient compaction level for every compaction step.
- Compaction energy (Vibrator Amperage) and Activation Force (Pull-down Force):
To displace the in-situ soil and to build in aggregates is often indicated by a significant increase of the energy consumption of the Vibrating tool as well as the pull-down force.

In case the pre-defined, associated limits for the pull/push-ratio, the compaction energy and the pull-down force are not reached at every compaction step, the column will be marked as a possible quality outlier and highlighted in the spacial view for further checks by the Project Manager.

Whereas a single low-quality compaction step during the production of a whole column is usually not a sign of a quality issue, a series of such compaction steps could make it necessary to mitigate the possibly low quality e.g. by executing an additional element close by.

Standard values for the limits of the production parameters pull/push-ratio, compaction energy and pull-down force are pre-defined in the application, but as they can differ from project to project, these values also can be adapted by the project manager prior to the analysis.

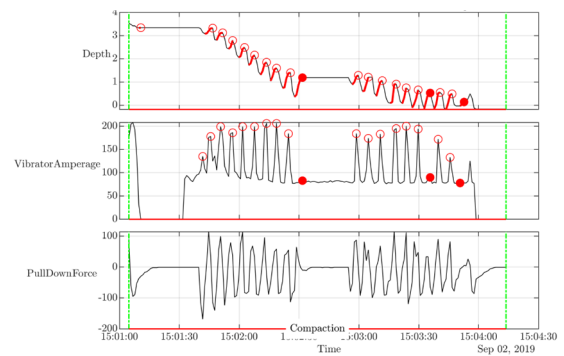


Figure 6. Example of a “Compaction Step Quality” KPI analysis showing three locations of possibly low quality.

4.2 Column Diameter KPI

To check the diameter of a Vibro stone column, the amount of built-in aggregates of a single filling process is distributed over the compaction length between the one and the next filling. Assuming that every gravel fill has approximately the same amount of material, the column length between two fillings correlate to the diameter of the executed column .

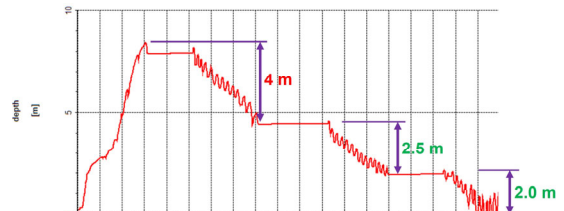


Figure 7. Time vs. Depth diagram of a “Length per gravel fill” KPI analysis for a stone column diameter analysis

Figure 7 shows an element protocol with different lengths between filling processes, leading to the conclusion that the column diameter over length differs from the average column diameter, whereas it is smaller in the lower and larger in the higher part of the column.

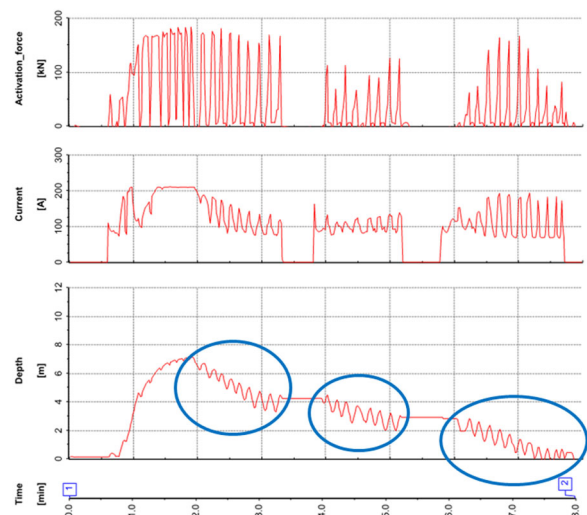


Figure 8. Time vs. Depth diagram of a KPI analysis “Compaction steps per gravel fill” for a stone column diameter evaluation

If a constant column diameter needs to be produced at a project, the stiffness of the different in-situ soil layers influences the amount of compaction steps needed to build in the required aggregates for achieving the given column diameter. So, the number of compaction steps within one gravel filling distance gives a hint on the soil density/stiffness. In Figure 8 less

compaction steps were needed in the lowest column meters than in the ones close to the surface. So, the soil in the last layer is likely to have a lower stiffness than above.

4.3 Competent Layer KPI

When penetrating a Vibrating tool into a competent layer, either the penetration speed will reduce while the pull-down force and compaction energy are still high, or the pull-down force and compaction energy will increase, caused by the higher resistance due to the competent layer. This behavior is used by the quality assurance application to evaluate the quality of the embedment of a column into a competent layer.

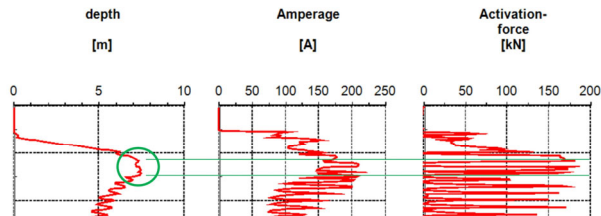


Figure 9. Example of a “competent Layer” KPI analysis of an executed stone column

Except for floating foundations where the design does not require any embedment, the detection of and penetration into a competent layer is checked automatically for every element. If the criterions are not met, the related elements will be presented to the project manager for further manual interpretation.

4.4 Idle Time as a cause of overheating

In addition to quality related parameters, the application does also evaluate parameters that describe influences on the shift performance.

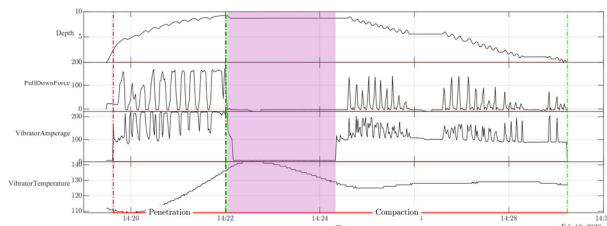


Figure 10. Example of a “overheating idle time” KPI analysis of an executed stone column

A KPI to examine production time lost due to shutdowns as a cause of overheated Vibrators, is an indicator for hard soils or hard intermediate soil layers in the working areas. In case outliers of this KPI occur often, this may lead to the decision to pre-drill the columns before executing the vibro technique.

5 SUMMARY

The current, pure manual process for quality assurance is slow, time consuming and thus not suitable for modern vibro execution with high shift performances. Therefore, a new approach based on state-of-the-art data analysis and visualization implemented into a web-based application became necessary.

The hybrid learning architecture of the new application combines the advantages of KPI-based evaluations and machine learning algorithms to improve anomaly detection for Vibro Ground Improvement processes. The implementation of the new application in daily business led to several advantages. The quality assurance has reached a higher level, because the checks are not limited any longer to randomly selected elements, but all columns are checked with high diligence. Elements with possibly low quality are highlighted by the

application and manually analyzed by an expert. Consequently, the overall safety of vibro products has increased although the effort for the project manager was reduced.

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