Vauk B. B. & Dalchau D. (2024). Jet grouting: Applying lean principles in geotechnical engineering to reduce waste. In D. B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32). (pp. 969–977) doi.org/10.24928/2024/0142

JET GROUTING: APPLYING LEAN PRINCIPLES IN GEOTECHNICAL ENGINEERING TO REDUCE WASTE

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ABSTRACT

Jet grouting is a widely used method for ground improvement and for sealing measures in geotechnical engineering. Due to the nature of the process, the material consumption of water-binder suspension is high. The objective of this research is to enable a more efficient use of resources by evaluating and reducing the waste of the resources used in the jet grouting process, taking lean principles into account.

The objective of this paper is to develop a production flow model for the jet grouting process. This is to enable a continuous improvement of the production processes and a reduction of the associated material consumption through recycling.

A production flow model is proposed to determine the amount of binder suspension required for production as a function of production time. The model presented will be used to control and continuously improve the production process and associated use of resources in future research. This will be done in accordance with the lean principles of customer value, value stream identification, flow, pull and striving for perfection.

KEYWORDS

Lean and Green, Sustainability, Waste, Production Pull

INTRODUCTION

The construction industry is currently facing the challenge of simultaneously achieving greater sustainability and enhancing efficiency. Sustainability and lean construction are increasingly becoming key topics in the german construction industry, with ecological responsibility and efficiency through the optimal use of resources taking centre stage. The objective of sustainability is to achieve long-term ecological, social and economic stability in order to meet the needs of the present without compromising the opportunities of future generations (Schlacke, 2023). This principle is also enshrined in Article 20a of the German Basic Law.

The objective of lean construction is to focus on effectiveness through customer orientation and to continuously improve efficiency by reducing waste. Waste can be classified into construction-specific categories (Koskela et al., 2013), which facilitates its identification. The five key principles of the Womack & Jones (2003) model must be considered in their entirety for the successful implementation of lean construction. Firstly, the principle of value specification defines the value of a service from the customer's perspective, which forms the basis for all subsequent steps. Subsequently, value stream identification leads to the analysis and optimisation of all necessary activities in the value chain. This involves the identification

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and elimination of cost-increasing activities (Muda Typ 2) and the reduction of (un)necessary activities that do not increase value (Muda Typ 1). The objective of the flow principle is to design all activities in a manner that ensures a continuous and uninterrupted process, with the aim of minimising cycle times. The pull principle means that production is controlled by actual demand, which enables agile and demand-oriented value creation. Finally, the principle of striving for perfection promotes a culture of continuous improvement by making incremental changes to get closer to an ideal state.

The jet grouting process is used in geotechnical engineering for the construction of auxiliary structures such as underpinning of buildings, horizontal sealing of excavations and ground improvement. Once the binder suspension mixed with the subsoil has hardened, a structurally stable and sealing earth mortar body is created.

The sequence of production processes in jet grouting can be identified using the value stream analysis method (Rother & Shook, 2003) and described quantitatively using a model to be developed. The erosion process begins after the borehole is drilled with the use of a high-energy hydraulic cutting jet, which consists of a binder suspension (1- and 2-phase system), to erode the existing soil structure and mix it with the binder suspension. The binder suspension, which has been mixed with the eroded soil structure, is returned via the borehole annulus as backflow suspension in accordance with the law of continuity and is then disposed of. In consideration of the lean principles, ideas are presented on how the backflow suspension from the production processes can be reused. In particular, the objective of this work is to contribute to the creation of a foundation for reducing the waste of finite resources through the production flow model presented and to promote the circular economy in geotechnical engineering. This will facilitate the transition towards more sustainable and efficient construction practices.

METHODOLOGY

The methodology describes the systematic methods used in the research to collect, analyse and interpret data. It includes both the theoretical foundation of the selected research approaches and the practical implementation of the study.

A comprehensive analysis of the process steps was carried out for the development of the production flow model of the jet grouting process. The key process steps were recorded directly on the construction site before and during production using value stream analysis and multi-moment recordings. These process steps were coordinated with the construction and project management teams to ensure precise documentation of the individual processes and their duration. The processing times of the rig were extracted from the machine data, which served as the basis for setting up the process model. Furthermore, the separation technology, consisting of screening systems and hydrocyclones, was carefully dimensioned. The adaptation was based on the expected geological conditions of the case studies, which were derived from the soil reports. The separation performance of the plant was determined in a systematic manner based on the density of the suspension and the remaining sand content of the backflow suspension.

A comprehensive literature review on the subjects of lean construction and jet grouting initially yielded no direct hits under the search terms used. This indicated a need to deepen the research and further elaborate the concepts of lean principles in the field of geotechnical engineering, in particular regarding the jet grouting method.

The investigation of the rheological properties of the suspension and the contents of water, cement and soil in the suspension is based on previous research by the authors. These previous studies form the basis for the current methodological orientation and future research activities based on them, which were also carried out by third parties (Thienert et al., 2017) on the basis of earlier investigations by the authors (Vauk, 2011).

JET GROUTING

SUSTAINABILITY CHALLENGES

Approximately 30 million tonnes of cement are consumed in Germany each year, resulting in an annual CO_2 equivalent of approximately 17 million tonnes (Verein Deutscher Zementwerke e.V., 2022, 2023). In the context of geotechnical engineering, the jet grouting process results in the disposal of approximately 50% of the approximately 220 to 350 thousand tonnes of cement used (Thienert et al., 2017).

"On average, 2,787 MJ of fuel energy and 113.1 kWh of electrical energy were used to produce one tonne of cement in Germany in 2022." (BVSE, 2022) The total energy consumption is thus approximately 887 kWh per tonne (0.2778 kWh/MJ). The operation of a separation plant as used in the case studies requires approximately 33 kWh of energy. This energy is used by two 2.3 kW screening plants and a hydrocyclone with a feed pump, which has an estimated energy consumption of around 25 kW, depending on the pump characteristic curve. The water requirement for the additional cleaning of the separation plant and the energy consumption of the separation process have already been amortised in terms of a positive ecological balance when processing 1 m³ of water-cement suspension (750 l/m³ water; 750 kg cement at w/c=1.0).

The DGNB certificate from Germany (DGNB, n.d.) or comparable certificates such as the LEED certificate from the USA (U.S. Green Building Council, n.d.) adopt a holistic approach to the sustainability of buildings, basing their assessments on defined criteria catalogues and usage profiles (Carneiro et al., 2012). The LC method value stream mapping enables the analysis of production processes from a sustainability perspective, identifying waste in the use of resources (Rosenbaum et al., 2012).

In the production process of the jet grouting method, the water-binder suspension required for the drilling and erosion processes is mixed and stored in the agitator regardless of the actual time-dependent demand (push). It is possible that the maximum processing time of the binder may be exceeded, resulting in the disposal of the fresh suspension unused, particularly in the event of high outside temperatures and production disruptions. If disposal is not carried out after the maximum possible processing time has been exceeded (hydratation), it is no longer possible to achieve the required final material strengths with certainty, which may result in defects (waste).

In the event that a mixed water-binder suspension is utilised during the maximum processing time, the suspension is utilised on a single occasion for the drilling and erosion processes. The water-binder suspension, which has been mixed with the eroded soil structure during the drilling and jet grouting processes, is returned via the borehole annulus as backflow suspension in accordance with the law of continuity (ratio 1:1 of water-binder suspension to backflow suspension). Subsequent to this, the volume of approximately 100% of the introduced suspension is disposed of, containing approximately 50 % of the introduced binder (waste).

USE OF EXCESS BACKFLOW SUSPENSION: FLOW CHART AND PULL CONTROL

Instead of disposal, the excess backflow suspension is to be treated and reused in order to prevent the waste of binder and water.

In instances where the actual demand for water-binder suspension can be determined by a production flow model based on time (depending on the process steps of moving the rig, setting up, drilling and erosion process), it can be mixed on demand (pull). Furthermore, the work content of the workers can be more evenly distributed according to the duration of the individual process steps, thereby increasing labour productivity.

Figure 1 shows the flow diagram of the suspension in the production process and the separation plant to be proposed. The requisite binder suspension, comprising water and cement, is combined in the mixer and previously stored in the agitator for delivery to the drilling rig. The drilling rig is supplied with the binder suspension via the high-pressure pump, and after the drilling and erosion process, it is pumped into disposal troughs or earth basins as backflow suspension via the return pump (1). After solidification, the backflow suspension is previously disposed of.

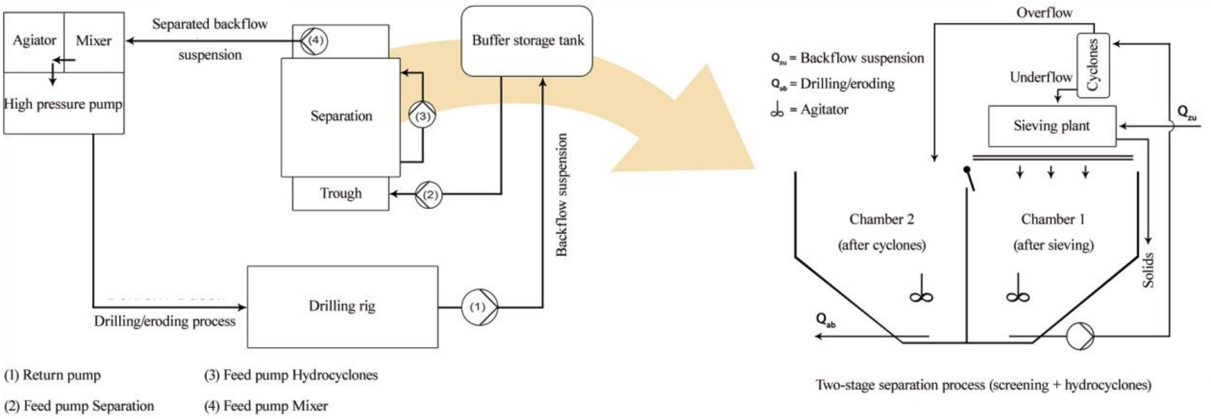

Figure 1: Flow diagram of the suspension and separation plant (Vauk, 2011)

The treatment of backflow suspension by separation is proposed. The use of a separation plant (two-stage separation consisting of screening and hydrocyclones) allows the backflow suspension to be treated for reuse. (Vauk, 2011) The separated backflow suspension is pumped to the mixing plant via the feed pump of the mixing plant (4), treated by the addition of binder and fed back into the production process.

In order to determine the time-dependent quantity of binder suspension required for the drilling and erosion process in accordance with demand, a production flow model is proposed. This model enables the time-dependent demand for binder suspension to be determined in advance, and the flow diagram to be designed in accordance with the lean principle of pull. The binder suspension required for the production process is drawn into production by the drilling rig from the high-pressure pump (pull). The separation plant is responsible for preparing the requisite quantity of binder suspension for production, with no excess. This is done according to demand. The proposed production flow model based on the pull principle ensures that the required quantity of binder suspension is known at all times. This allows the separation plant to be continuously improved in terms of its capacity (flow rate) and required separation performance (separation cut, screen area, mesh size of the screens, number of hydrocyclones, pressure of feed pump for hydrocyclones, etc.). This, in turn, enables the binder suspension to be recovered more economically.

In order to optimise the utilisation of the cement contained in the separated backflow suspension and thus reduce the need to add fresh cement, it is necessary to empirically test the effects of this reduction on the compressive strength of the elements produced from the suspension in the sense of a suitability test. In the authors' opinion, the addition of fresh cement should be gradually reduced, for example to 90 %, 80 % or 70 %. It is recommended that this test be conducted prior to any reduction in the addition of cement to the separated backflow suspension. Furthermore, it is essential to ensure that the cement already present in the suspension is processed before solidification commences.

PRODUCTION FLOW MODELLING FOR PULL CONTROL

In order to reuse the backflow suspension in the erosion process, it is necessary to determine the binder content that remains in the separated backflow suspension. In order to ensure that the static compressive strength of the jet grout body produced meets the required specifications, the missing binder content, which results from the water-binder value (target value) minus the remaining binder content, should be added.

Verification of the binder content after separation is not possible using electrometric, thermal and kaliometric methods (Vauk, 2011). As the solids properties change over time depending on the eroded subsoil (homogeneous areas), the time-dependent formation of the backflow suspension is to be described by the following production flow model.

The time required for the erosion process of a jet grouting element is dependent on the erosion performance of the subsoil in homogeneous areas:

$$t_j = \left(\frac{E}{\pi \cdot \left(\frac{d^2}{4} \right)} \right)^{-1}$$

with

t_j	Erosion time per metre [min/m]
E	Erosion rate (depending on the subsoil) [m³/min]
π	Constant
d	Diameter of the jet grouting element [m]

The suspension volume required for the erosion process for each homogeneous area is obtained from the erosion time t_j and the distance to be eroded l_j at a constant binder suspension flow rate of $Q_{j,min}$ per minute:

$$Q_j = Q_{j,\min} \times t_j \times l_j$$

with

Q_j	Suspension volume per homogeneous area (erosion process) [m³]
$Q_{j,min}$	Suspension volume per minute (erosion process) [m³/min]
t_j	Erosion time per metre [min/m]
l_j	Erosion distance per homogeneous area [m]

The suspension volume required for the drilling process for each homogeneous area is calculated from the drilling time t_d and the drilling distance l_d at a constant binder suspension flow rate of $Q_{d,min}$ per minute:

$$Q_d = Q_{d,\min} \times t_d \times l_d$$

with

Q_d	Suspension volume per homogeneous area (Drilling process) [m³]
$Q_{d,min}$	Suspension volume per minute (Drilling process) [m³/min]
t_d	Drilling time per metre [min/m]
l_d	Drilling distance per homogeneous area [m]

Depending on the geotechnical terrain model, a binder suspension requirement Q_E per jet grouting element results for n homogeneous areas:

$$Q_E = \sum_{i=1}^{n} \left(Q_{d,i} + Q_{j,i}\right)$$

with

Q_E	Binder suspension requirement per jet grouting element [m³]
$Q_{d,i}$	Binder suspension requirement (drilling process) [m³]
$Q_{j,i}$	Binder suspension requirement (erosion process) [m³]
n	Number of homogeneous areas [-]

The production time t_E, in which the binder suspension Q_E is required, is calculated from the drilling time $t_{d,i}$ and the erosion time $t_{j,i}$ for n homogeneous areas:

$$t_E = \sum_{i=1}^{n} \left(t_{d,i} + t_{j,i}\right)$$

with

t_E	Processing time (drilling process and erosion process) [min]
$t_{d,i}$	Drilling time [min]
$t_{j,i}$	Erosion time [min]
n	Number of homogeneous areas [-]

Taking into account the set-up time (moving and setting up the rig), the binder suspension requirement Q_E over time is calculated using the cycle time t_c per jet grouting element:

$$t_c = t_R + t_E$$

with

t_c	Cycle time (set-up time, processing time) [min]
t_R	Set-up time (moving and setting up the rig) [min]
t_E	Processing time (drilling process and erosion process) [min]

This results in the requisite binder suspension volume Q_E over the cycle time t_c, which is also produced as backflow suspension due to the volume balance (binder suspension to backflow suspension ratio of 1:1). The dilution of the backflow suspension (rinsing water) results in a dilution factor of 1.30 for cohesive homogeneous areas and 1.15 for rolling homogeneous areas. This indicates that 15 to 30% more backflow suspension is produced than the fresh suspension used (Vauk, 2011).

The time-dependent calculable binder suspension requirement Q_E over the cycle time t_c and the resulting backflow suspension quantity allows for the determination of the time-variable solids content of the suspension from the individual homogeneous areas with greater precision. The separation plant is to be dimensioned on the basis of the proposed production flow model, with regard to the required capacity according to the pull principle, and the achievable separation performance is to be continuously improved.

LEAN AND GREEN: ENVIRONMENTAL AND ECONOMIC BENEFITS

Taking In consideration of the principles of flow and pull as outlined in the LC methodology, the throughput time for the production of a jet grouting body comprising n jet grouting elements and the associated distribution of material consumption over the throughput time can be determined on the basis of the proposed production flow model. The throughput time is calculated as follows, taking into account the cycle time per jet grouting element:

$$TPT = \sum_{i=1}^{n} t_{c,i}$$

with

TPT	Throughput time for the production of the jet grouting body [min]
$t_{c,i}$	Cycle time per jet grouting element [min]
n	Number of jet grouting elements per jet grouting body [-]

The value stream analysis will facilitate a further reduction in throughput time by means of an analysis and optimisation of the processing and cycle times in accordance with the flow principle.

The implementation of the production flow model in the machine control of the jet grouting plant (drilling unit, high-pressure pump and peripherals) will also result in a continuous improvement of the production process in terms of labour productivity through automation. While manual operation of the mixing plant and the high-pressure pump currently utilises personnel capacity, the binder suspension required for production is to be automatically determined, mixed and drawn into the drilling and erosion process by the drilling rig according to the pull principle.

The solids properties of the backflow suspension should be able to be determined more precisely on the basis of the production flow model and the separation technology should be adjusted to this more efficiently. This would enhance the efficiency of the separation process, thereby increasing the recovery rate of the backflow suspension.

The required construction time should be estimated during construction based on the production flow model and the actual set-up times from the available machine data. Continuous construction time forecasting during construction would enable transport to be planned with greater precision in advance and transport costs to be reduced in a multi-project approach by sequentially linking construction sites.

The reduction of material stocks is to be achieved through the implementation of material requirement forecasts and needs-based material orders. In addition to the potential economic benefits, there is considerable ecological potential through the reduction of binder consumption as a result of a higher recovery rate of the binder suspension used and a resulting significant reduction in the amount of waste produced.

In light of the ecological objectives resulting from the ESG criteria (Environmental, Social, and Governance) and the obligation for companies to report on sustainability in accordance with the CSRD (Corporate Sustainability Reporting Directive) in the European Union, the necessity for improvement in production from a sustainability perspective is becoming increasingly important, regardless of economic interests (European Union, 2022).

CASE STUDIES: REPROCESSING OF EXCESS BACKFLOW SUSPENSION

The separation technology has already been successfully implemented on two construction sites in Germany (Figure 2). By separating the backflow suspension, the solids content could be largely separated from the water content of the backflow suspension and returned to the production process.

Figure 2: Schematic representation of the separation plant for processing the backflow suspension (Keller, n.d.a, n.d.b)

The savings at a construction site in Heidelberg, Germany, amount to 30% of the otherwise incurred disposal volume of the backflow suspension (Keller, n.d. a). The backflow suspension that was not disposed of could be reused for necessary drilling processes after separation.

The savings at a construction site in Dortmund, Germany, amount to 10% of the otherwise incurred disposal volume of the backflow suspension and 35% of the binder used. This is because the suspension at this construction site could also be partially processed for the erosion process (Keller, n.d. b).

CONCLUSIONS

The proposed production flow model enables the precise determination of the required amount of binder suspension and its time-dependent control in accordance with the lean principles of flow and pull. The parameterisation of the separation technology, adapted to the geological and process engineering conditions in accordance with the production flow model, can facilitate efficient reprocessing, taking into account relevant homogeneous areas. Potential secondary effects include increased labour productivity and reduced transport costs, as production times become more predictable and sites can be effectively sequenced.

The precise determination of the binder content in the separated return suspension represents a challenge that requires further research. The precise determination of the binder content is crucial for the further development of the sustainability and efficiency of the process, as it enables a more precise remixing of the required amount of binder.

Another field of research is the development of an advanced machine control system. A control system based on the pull principle has the potential to enhance labour productivity through automation and to improve the recovery rate of the backflow suspension by enabling the separation of the backflow suspension as required.

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