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Innovative technologies in the remediation of landscapes left behind by the former lignite mining industry in eastern Germany

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Abstract

Over the last few decades, attractive lake landscapes have been created in Lusatia and Central Germany from old open cast mines of the former lignite mining industry. The main player in this transformation process in eastern Germany is Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft (LMBV).

A large proportion of the open cast mine dumps in LMBV's area of responsibility consist of loose sands that are sensitive to liquefaction. With increasing groundwater rebound after the end of mining, spontaneous liquefaction events were occurring, especially after 2009. It was due to the structural collapse in the water-saturated soil. One of the largest geotechnical events of this kind affected approximately 160 ha of dump area.

At present, approximately 31,500 ha of dump areas are affected by closures or restrictions on use.

The remediation of these areas poses a major challenge due to the risks to people and materials. For this reason, remediation work is currently focusing on securing extensive dump areas against soil liquefaction. This requires geotechnically efficient, economical methods that are geared towards minimising the impact on protected assets.

The technologies presented below involve the optimisation of established remediation technologies such as gentle blasting compaction (GBC). GBC is used to compact the loosely stored dump sands by means of relatively small quantities of charge ignited in boreholes. By using low-weight, all-terrain technology, large dump areas can be efficiently secured. Important data such as the position and depth of the blastholes, charge quantity, time of blasting and vibration velocities are recorded and can be visualised and retrieved. In preparation for a quantitative proof of compaction, freeze samples were taken after dump ground freezing down to great depths. These samples are used to determine the material and relevant parameters for earth stability calculations.

Terrain depressions are low-lying dump areas with groundwater levels close to the surface, and thus an increased risk of soil liquefaction. An alternative to using earthworks techniques for backfilling of terrain depressions is by use of a throwing belt. Therefore tests are currently being carried out to determine optimum operating conditions.

Furthermore, unconventional materials such as perlite were tested for filling terrain depressions. This material has a low weight which minimises stresses in the soil and forms a sufficient load-bearing surface. For this reason, perlite is intended for use as a foundation layer in future conventional backfilling.

Keywords: *lignite mining, groundwater rebound, open cast mines, soil liquefaction, gentle blasting compaction, soil freezing, throwing belt, perlite, filling terrain depressions*

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1 Introduction

The lignite mining regions of Lusatia and Central Germany are characterised by more than 160 years of lignite extraction, which was mainly carried out by open cast mining. With the political change in 1989–90 and the associated economic reorientation in eastern Germany, open cast mines that were no longer profitable were shut down at short notice and had to be remediated. Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft (LMBV) performs this task on behalf of the federal government for the legacies of mining from the period 1949 to 1989 (Sablotny et al. 2024). With increasing groundwater rebound after the end of mining, spontaneous liquefaction events were occurring, especially after 2009. These led to the structural collapse in the water-saturated dump soil. This resulted in large-scale mass movements (so-called flow slides caused by liquefaction) and ground collapses up to 160 ha (Figure 1). At present, around 31,500 ha of dump areas are affected by closures or restrictions on use.

Even before 2009, there were isolated cases of liquefaction events on a small scale. From 2009 onwards, however, liquefaction occurred more frequently and on a larger scale on the inner dumps. In 2024, there were five spontaneous liquefaction events covering areas ranging from 0.2 to 26 hectares.

Figure 1 Soil liquefaction at the Spreetal inner dump on 12 October 2010, with an impacted area of approximately 160 ha (Scholz & Mühlig 2019)

Now that securing the residual open cast mine slopes against flow slides has almost been completed, the current focus of the remediation work is therefore on securing the extensive ‘inner areas’ of the dumps. This requires geotechnically efficient and cost-effective methods that are geared towards minimising the impact on protected property. The technologies presented below involve the optimisation and further development of established technologies such as blasting compaction (BC) as well as new methods that are currently being developed or tested, such as the use of a throwing belt for backfilling deep layers and the installation of perlite for backfilling terrain depressions close to groundwater.

2 Gentle blasting compaction

2.1 Basic principles and dimensioning

For several decades, BC has been used in the remediation areas of Lusatia and Central Germany as a tool for securing soil from the risk of liquefaction. The principle of BC, which can only be used in water-saturated horizons, is that the area around the centre of the explosion is subjected to strong dynamic excitation and the grain structure collapses. As a result, liquefaction then occurs in the area around the explosion source. In the course of the subsequent consolidation, the soil settles more densely under the load of the overlying soil. Initially, at the end of the 1980s and in the 1990s, BC was used to create supporting structures – the 'hidden dams'. It was done to secure the slopes of future post-mining lakes. This geotechnical supporting structure required firstly, a high degree of compaction, and secondly, almost homogeneous compaction of the affected slope areas. The stabilisation of the slopes is now largely completed.

LMBV's remediation work is currently focusing on extensive protection of the large inner areas of the dumps from the effects of both spontaneous and initiated soil liquefaction. This requires a geotechnically efficient, economical process that minimises the impact on protected assets. In contrast to BC, designed for the best possible compaction of dump soil, gentle blasting compaction (GBC) (BIUG GmbH & LMBV mbH 2018) is more concerned with the necessary improvement to achieve sufficient safety.

The use of GBC leads to low impact on the large areas to be treated and the neighbouring protected assets.

This required the development of new dimensioning rules for the GBC. In earlier applications of BC, high charge quantities (10 to 40 g/m^3 in relation to compacted soil) were used (Keßler & Förster 1992), which resulted in reliable compaction success. Further investigations into, and experience from, remediation practices have resulted in significantly lower blasting quantities being required to achieve sufficient compaction.

In addition to the total charge quantity, the number and size of the partial charges in the blasthole, the depth of the partial charges and the range of the blasting effect, as well as the type of grid and grid size, are determined when calculating the GBC. These factors are in a complex interdependence with the thickness of the moist overburden above the groundwater level and the thickness of the water-saturated soil layer to be compacted.

Based on many years of experience, LMBV has well-founded recommendations for the dimensioning, monitoring, execution and verification of the GBC.

2.2 Execution of the gentle blasting compaction

GBC includes the work steps of drilling, inserting explosive charges into the boreholes and then detonating them. To treat extensive dump areas using GBC it is necessary to define a regular grid of borehole points. The grid elements adjoin each other without gaps. An equilateral triangular grid is a useful grid shape for the blastholes. The boreholes are usually drilled using dry drilling with a hollow auger. Pipework (PE-HD/PVC-U) is installed in the boreholes, and explosive charges are then placed safely and securely in the borehole through the pipework. The gelatinous explosives are contained in cartridges for installation. The blasts are occasionally realised as individual blasts, but often as blasting groups of three to six blastholes each. Currently three partial loads totalling approximately 5 to 15 kg of explosive per borehole are generally used for the GBC.

Due to the high hazard potential of the liquefaction-sensitive dumps, preparation of the blastholes is the greatest risk for personnel and equipment. For this reason, optimising the technological process of GBC has been an important task in recent years. In field trials, technology based on snow groomers has proven to be ideal for use on loose dumps with a low groundwater level (Figure 2). On the one hand, these converted snow groomers can fulfil the defined geotechnical specifications (maximum mass of 12 t and maximum soil pressure of 10 kN/m^2) and, on the other hand, have the necessary mobility on uneven terrain. The vehicle is equipped with rubber tracks with aluminium webs approximately 1.7 m wide. These tracks enable the load to be applied evenly over a wide area, thus ensuring that the geotechnical specifications are safely met. The undercarriage is also equipped with hydraulic levelling.

This enables an even load distribution of the track contact surface, even on uneven terrain.

In previous applications, the rear-mounted tiller (fitted as standard) on a snow groomer was replaced by a drill carriage with a cable winch.

Furthermore, a working platform was mounted on the left-hand side of the drill carriage (in the direction of travel). When working together with the drilling vehicle it is advantageous to use a service vehicle that is also based on a snow groomer, ideally of the same type. This allows synergy effects to be achieved for repairs and maintenance, for example. Instead of a carriage, the service vehicle has one or more magazines for the drill rods, which are lowered hydraulically onto the ground surface.

Figure 2 Use of light, mobile drilling technology for the Seese-Ost inner dump (LMBV mbH & BIUG GmbH 2022)

Due to these characteristics, this light, mobile drilling technology can be used much more flexibly, efficiently and, above all, safely than conventional self-propelled drilling rigs, especially on unsecured dumps. The latter can only be used to a limited extent here due to the significantly higher ground pressure and less freedom of movement. Furthermore, the new mobile drilling equipment achieves significantly higher speeds than self-propelled drilling rigs. This advantage is significant when the equipment must be moved between distant drilling starting points or an emergency escape run is necessary.

Execution of the GBC is continuously recorded using data technology. The contractor enters the data into an online memory, in accordance with specified forms (Figure 3). These are transferred to LMBV’s GBC database. Important data, such as the position and depth of the blastholes, charge quantity and time of blasting, can be used for documentation and monitoring of the GBC via LMBV’s TEKTOview visualisation software tool.

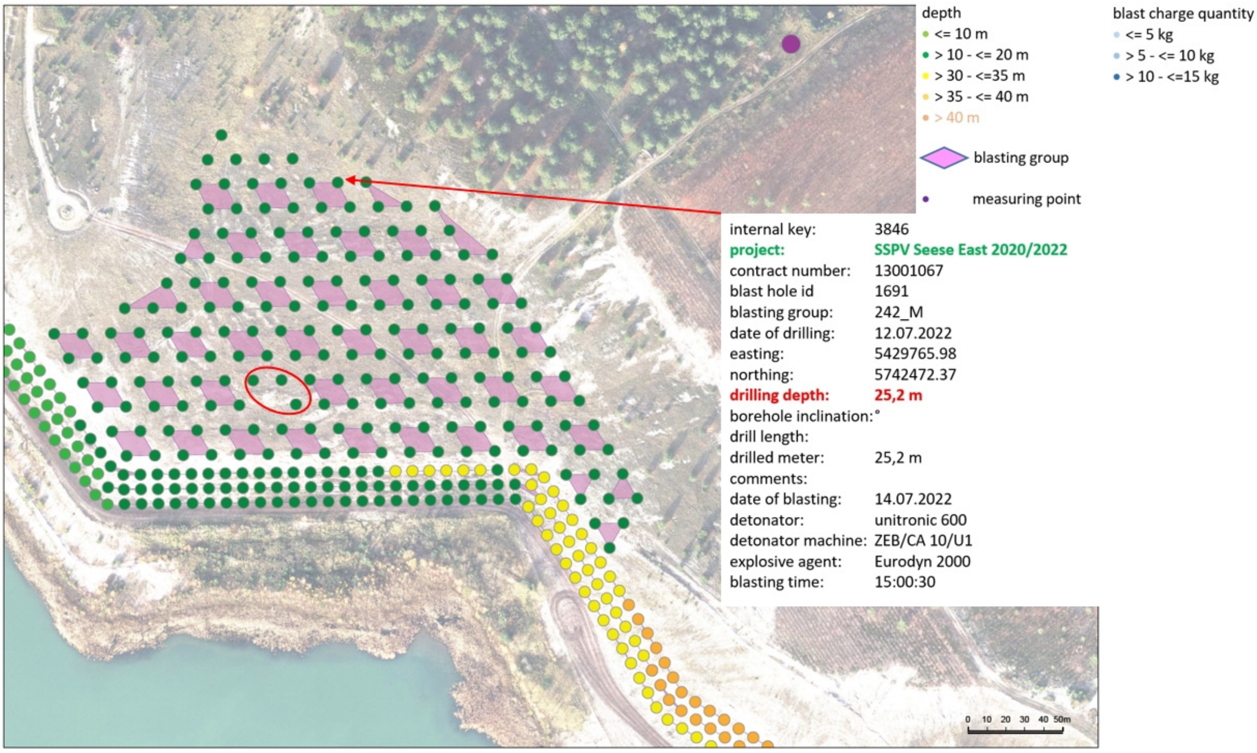

Figure 3 Data processing of the gentle blasting compaction (LMBV TEKTOview 2022)

2.3 Measurement and test program

A comprehensive measurement and testing program must be implemented to monitor the professional execution of the GBC and to verify its success.

This includes measurement according to position and height, pore water pressure measurements (recording of pore water overpressures), water level measurements, video recordings, vibration measurements and seismic measurements (immersion wave tomography and surface wave seismics), pressure soundings, radiometric combination pressure soundings and, if necessary, liner drillings or freeze drillings (Figure 4).

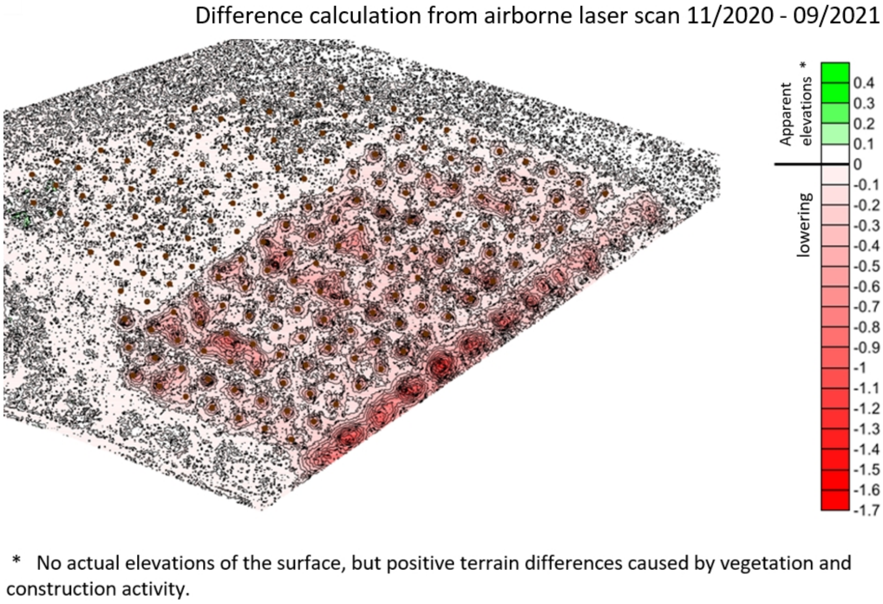

Figure 4 Difference image from airborne laser scans before and after the gentle blasting compaction, with colour-coding of the subsidence amounts in metres (LMBV mbH & BIUG GmbH 2014)

2.4 Proof of the compaction success

The primary objective of LMBV's work is to establish public and geotechnical safety and thus terminate supervision of the mining authority for the respective areas. For the inner dump areas in need of remediation it is essential to prove sufficient bulk density resulting from the stabilisation. Additionally, it must be proven that the risk of liquefaction of the existing water-saturated dump sands is eliminated.

The qualitative verification of compaction is carried out with the aid of soundings (pressure, dynamic and radiometric combination pressure). Comparison of pre- and post-probing is used to confirm the increase in bulk density resulting from the remediation.

Additional information is obtained by recording ground subsidence using mine surveying measurements. Furthermore, the GBC-induced excess pore water pressures in uncompacted and compacted areas are compared. The use of submersible wave tomography and surface wave seismics supplements the knowledge of the compacted soil. All these factors serve to verify the success of the remediation.

Quantitative verification of the elimination of the risk of soil liquification in the dump by means of geostatic proofs requires representative parameters that characterise the compacted dump sands as precisely as possible. These parameters can be determined using soil physical laboratory tests on practically undisturbed soil samples. However, the measurable increase in density resulting from GBC is relatively low and therefore the extraction of practically undisturbed samples from below the groundwater level with typical liner drillings is problematic. An alternative is ground freezing down to greater depths with subsequent sampling from frozen core drillings (Figure 5).

(a) (b)

Figure 5 (a) Seese-East freeze plant (2023); (b) Freeze drill core from a depth of 27–28 m (Reinhardt et al. 2024)

This very complex special technology for ground freezing was carried out on LMBV on the Seese-East (2023) and Seese-West (2024) inner dumps, which were stabilised using GBC. Nitrogen icing was used in Seese-East, and the currently more economical brine icing in Seese-West. The continuous extraction of frozen drill cores to a maximum depth of 37 m provided samples of good quality that are well suited for analysing shear strength in the static triaxial device (Reinhardt et al. 2024).

Furthermore, the usual soil mechanics tests are carried out to determine characteristic values describing the material (density, Proctor density, void ratio, grain distribution, loss on ignition, texture coefficient, rounding coefficient). When carrying out triaxial tests (Figure 6), the in situ condition of the sample should be maintained until the start of the shear phase, i.e. a negative influence on the sample quality during preparation, mounting, thawing and consolidation must be avoided. The consolidation stresses correspond to the stresses in the sampling depths. The appropriate degree of water-saturation corresponds to the in situ conditions. The test is performed as a CAU-pS test (anisotropy consolidated, undrained passive compression).

Figure 6 Triaxial system (GMB GmbH 2025)

The strength parameters obtained from the triaxial tests can be used to establish area-related correlations with the exploratory results and the parameters of the mine surveying, geophysical and hydraulic measurements.

The evaluation of the triaxial tests has not yet been fully completed. However, the test results to date show that the samples from the GBC horizon of the Seese-Ost inner dump have sufficient undrained residual strength. This confirms the improvement effect of the GBC. Proof of the success of the remediation can be provided. The extraction of undisturbed freeze samples for the subsequent performance of triaxial tests is used in cases where conventional methods such as liner drilling have not yielded accurate results due to poor sample quality or where it is not possible to utilise existing correlation relationships due to high variance.

3 Throwing belt

Areas of terrain depressions with high groundwater level and liquefaction-sensitive subsoil are particularly at risk. Therefore it is necessary to backfill these terrain depressions for preparation of further remediation measures.

The volume to be backfilled can be up to 300,000 m^3. Until now, backfilling of terrain depressions with high groundwater levels has been carried out using mobile earthworks technology or telescopic conveyor belts. An alternative technology for raising the terrain is the use of a throwing belt (Figure 7).

(a) (b)

Figure 7 (a) Throwing belt principle (GMB GmbH & LMBV mbH 2025); (b) Throwing belt in test operation (GMB GmbH & LMBV mbH 2025)

Soil is thrown onto the area to be backfilled by a short, high-speed conveyor belt. The soil is continuously fed to the centrifugal belt via a hopper trough located above and a rotary valve located between the trough and the conveyor belt. The rotary valve guides the material falling from above towards the conveyor belt and accelerates it in the direction of the discharge.

The aim of the test in 2020 was to determine the technological parameters of the process for different soil fractions, to explore the possible applications and limits of the technology, and to find comparisons with other technologies. The throwing distance was defined as a key criterion for the use of the technology in remediation mining. The main factors influencing throwing distance were the grain fraction and wind conditions. An increased water content of the materials had only a minor effect on the throwing distance. The required minimum throwing distance of 30 m was achieved after appropriate technical adjustments. The mass flow rate fluctuated between an average of approximately 30 m^3/h and a maximum of 60 m^3/h. The proportion of fine grain (silt and clay) had a significant influence on the mass flow rate. The test proved that the technology for throwing defined moist soil (fine sand to fine gravel, fine grain content up to 6%) is suitable for the backfilling of terrain depressions with a low groundwater level. However, material with a high proportion of fine grain proved to be poorly suited or even unsuitable. This material often led to clogging of the hopper trough. Parallel to the technical suitability tests, extensive monitoring was carried out with measurements for settlement, pore water pressure and groundwater level, vibration, dust and noise, along with the monitoring of geotechnical parameters (grain distribution, water content, density) before and after implementation of the measure.

After evaluating the 2020 test the technology was optimised in terms of design and process engineering, which will be examined in a final practical test in 2026. The plan here is to also discharge material with a higher proportion of fine grain to make use of unclassified dump soil for economic reasons. Technical additions such as the use of a bar sizer and an additional conveyor belt are also planned. Bar sizers have proven their worth in conveyor technology for separating difficult-to-screen and highly inhomogeneous material flows. The bar sizer designed is a reliable solution for coarse separations in the selected range of ≥ 30 mm for long-term trouble-free operation without energy costs and with low maintenance requirements. This is designed to withstand both roots and larger stones to prevent jamming/damage to the rotary valve and the centrifugal conveyor. A conveyor belt transports the screened material from the bar sizer to the centrifugal conveyor.

4 Perlite

In the Spreetal redevelopment area, securing the edge trench of the dump poses a particular geotechnical challenge. The groundwater level is close to the surface, meaning that backfilling using conventional earthworks techniques is no longer possible. The subsoil consists of loosely bedded sandy dump soil, which is categorised as highly susceptible to liquefaction. Therefore geotechnical events (flow slides caused by liquefaction and ground collapses) cannot be ruled out during backfilling of the terrain depression with conventional remediation technologies. As a result, critical infrastructure could be damaged.

The use of light-weight perlite is therefore planned for remediation of the underground section. Perlite is a volcanic rock that is formed by the decomposition of obsidian. The low mass of perlite minimises stresses in the soil and forms, in connection with a geogrid, a sufficient load-bearing surface. For this reason, perlite is intended for use as a foundation layer in future conventional backfilling .

In a pilot project at the Spreetal inner dump site, the perlite material was tested with regards to various characteristic values and boundary conditions:

- the conveying and installation method (pneumatics, dust formation)
- in situ properties with regards to bulk behaviour and walkability
- surface stabilisation with geogrids to create trafficability and overfilling of the perlite by means of earthworks

- evaluation of behaviour in and with water (buoyancy safety)
- the settlement behaviour after covering with soil.

Various installation methods were tested, with the vehicles, silos and pneumatic system being placed at a safe location around 70 m from the application site (Figure 8).

The material was applied by hand or by suspending the pipe outlet piece from a mini excavator. The occasional extreme dust formation was minimised by injecting water at the pipe outlet end. The freshly poured, uncompacted material proved to be walkable but had limited trafficability (with deep ruts). By applying a geogrid to the perlite surface, good trafficability was achieved.

Measurement after perlite application showed that the majority of settlement had occurred immediately after the soil cover had been applied. Based on the measurements, settlement predictions were calculated for various perlite thicknesses and soil covers. With a perlite thickness of 2 m and a soil cover of 6 m, settlements of approximately 0.6 m can therefore be expected (Soltau et al. 2025).

(a) (b)

Figure 8 (a) Placement of perlite in the test field; (b) Covering of the perlite area with soil material (Soltau et al. 2025)

The use of perlite as the basis for a subsequent soil cover has proven to be practicable. However, due to the high costs involved, the use of this technology to secure dump areas that are close to groundwater and sensitive to liquefaction will remain limited to individual special cases.

5 Conclusion

As the agency responsible for mining rehabilitation in eastern Germany, Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft develops new and optimises existing technologies for the effective, safe and durable re-utilisation of areas affected by mining. A particular challenge is securing large dump areas against both spontaneous and initiated liquefaction of the dump material. The technologies presented here represent an innovative approach to improving and optimising remediation work.

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