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Construction of a cut-off wall using Mixed-In-Place technology for a flood retention basin in southern Germany

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Abstract. In the area of Feldolling, a village south of Munich, Bavaria, Germany, a flood water retention basin for the river Mangfall is planned and still under construction. In the event of heavy rains or seasonal ice-melting in the Alpes, the flood-prone region can suffer from severe damage to the infrastructure and the residential areas. Those events can therefore even threaten people´s lives. The planned flood retention basin will store more than 6 Mio m³ of water. For the construction of the retention basin, the authorities are building a few dikes of different lengths in addition to a dam to capture the flood water in the retention basin. The inner sealing and the underground cut-off barrier of one of the dikes was constructed using deep soil mixing wall. The implemented deep soil mixing technique is the Mixed-In-Place technology (MIP).
The MIP wall had a width of 550mm and reached a maximum depth of 23 m. The soil conditions were not uniform and varied from gravel and sand to silt and clay. The cut-off wall had to have a strength not exceeding 3 MPa and should be 1.5 MPa on average. To take into account the different soil characteristics and to achieve the required material properties, a lab testing program took place before construction.

Keywords: Flood retention basin, Dike, Levee, Cut-off wall, Deep Soil Mixing, Mixed-In-Place, MIP.

1 Introduction

Flood control measures are important nowadays to limit damage for potential infrastructure and private properties, and in worst case scenarios to save people’s lives. As a result of the climate change, higher discharges can lead to water overflow from rivers. Especially in areas adjacent to snow mountains, snowmelts induced by global warming can also augment that increase of water discharge in rivers. As a consequence, adjacent inhabited areas can suffer severe damages.

The river Mangfall in south Bavaria, Germanyhas a mean discharge of 26.9 m3/s [1]. In the event of 100-year flood, heavy rain and/or snowmelts from the nearby Alps Mountain can raise that figureto 480 m3/s as estimated in [1]. The existing dikes can sustain only the event of a 30-year flood. Such events can put the lives of 40,000 people in danger and cause potential damages of about 1 billion Euros. That makes the flood-prone area of the river Mangfall the riskiest area in Germany.The state of Bavaria put a plan to construct a retention basin of a total capacity of 6.4 million m^{3}in order to avoid such consequences. Location of the retention basin is shown inFig. 1.

In the scope of the works depicted in Fig. 2, Bauer was contracted to install a cut-off wall for the retention dam for the main retention basin as well as other special foundation works like secant pile wall, sheet piles and jet grouting.

Fig. 1: Location of the Detention basin in the vicinity of the Alps Mountain [3]

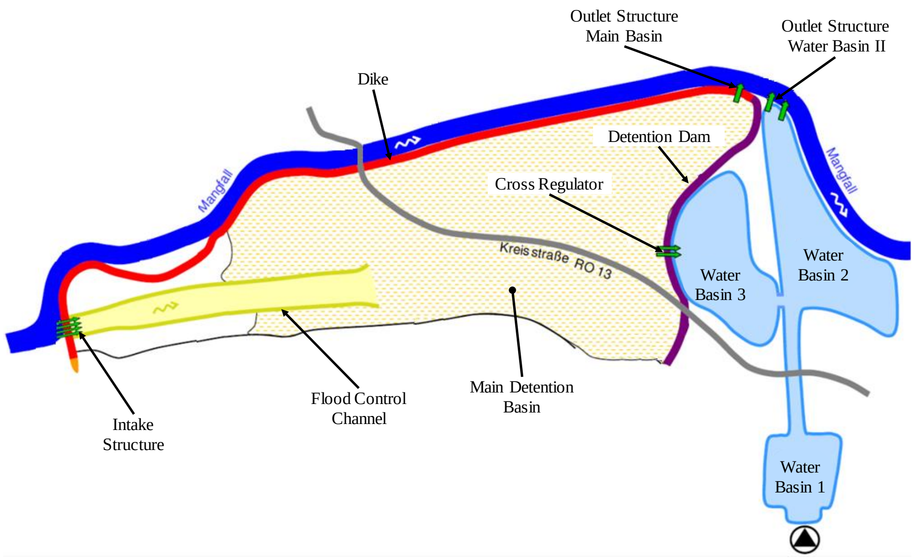

Fig. 2: Scope of works for the detention basin for Mangfall river [23]

The original solution for a major part of cut-off wall was a single-phase cut-off wall using grab with a thickness of 80cm, while the remaining part was a deep soil mixing wall with a thickness of 50cm. Bauer proposed to replace the grab single-phase cut-off wall with its Mixed-In-Place technique, MIP. Although the thickness of the proposed MIP wall was smaller than the required thickness of the single-phase wall, Bauer was able to prove that the MIP wall can fulfill the required system permeability or hydraulic permittivity as the single-phase cut-off wall. One more advantage the alternative solution possesses is that soil waste transport would be much less. In contrast to the grab single-phase cut-off wall, where the self-hardened suspension fluid has to fully replace the excavated soil, in deep soil mixing the existing soil is mixed with the introduced cement slurry and form the cut-off wall when hardened. Through the lower consumption of building material alone, the proposed system enabled the public sector client to save costs for the taxpayers in Germany.

Beside fulfilling the geotechnical task of the cut-off wall there is also the sustainable task which has become more into focus due to the mutual efforts of the United Nations with their claimed 17 Sustainability Development Goals or the European Union with their announced Green Deal to make Europe climate neutral until 2050. In this context it should be mentioned, that although geotechnical works will consume energy and materials and therefore account for greenhouse gas emissions, smart design and application of specific technologies can help toreduce the impact of these works and the construction on the environment. Mixed-In-Place as a construction method, has been proven to allow for a significantly smaller equivalent Carbon Footprint, and for an extremely reduced impact to the neighborhood mainly due to less transports with less traffic required, compared to a classical method based on excavation. To provide clients or other stakeholders with reliable numbers to quantify the specific climate impact of a any geotechnical works, available tools are on the market which might contribute to any such sustainability considerations [4**Error! Reference source not found.**]&[5].

2 Deep Soil Mixing

Deep soil mixing describes the process of introducing a binder to the native soils in order to create a homogeneous mixture of soil and typically a cementitious binder, which has better mechanical properties i.e., strength, stiffness, permeability[7].Soil mixing techniques were developed for the first time in the U.S in the 1950's as a piling technique.In the 1970's Soil Mixing Walls (SMW)were developedJapan [4]. Over the years many soil mixing techniques were developed and have been used in different application and under various conditions. The Federal Highway Administration of the US transportation department has classified the different deep mixing methods (DMM) in [7]as shown in Fig. 3.

Deep soil mixing has a wide variety of geotechnical applications. Deep soil mixing has been frequently used for soil improvement for differentpurposes like liquefaction mitigation, improvement of bearing capacity, support of earth embankments, and as foundation elements in some special cases. One more application for deep soil mixing is to construct cut-off walls from the mixed soils, similar to the subject of this paper.Applications also include shoring systems for excavation pits, in case the installed deep soil mixing elements are fitted with structural elements like steel beams of reinforcement cages.

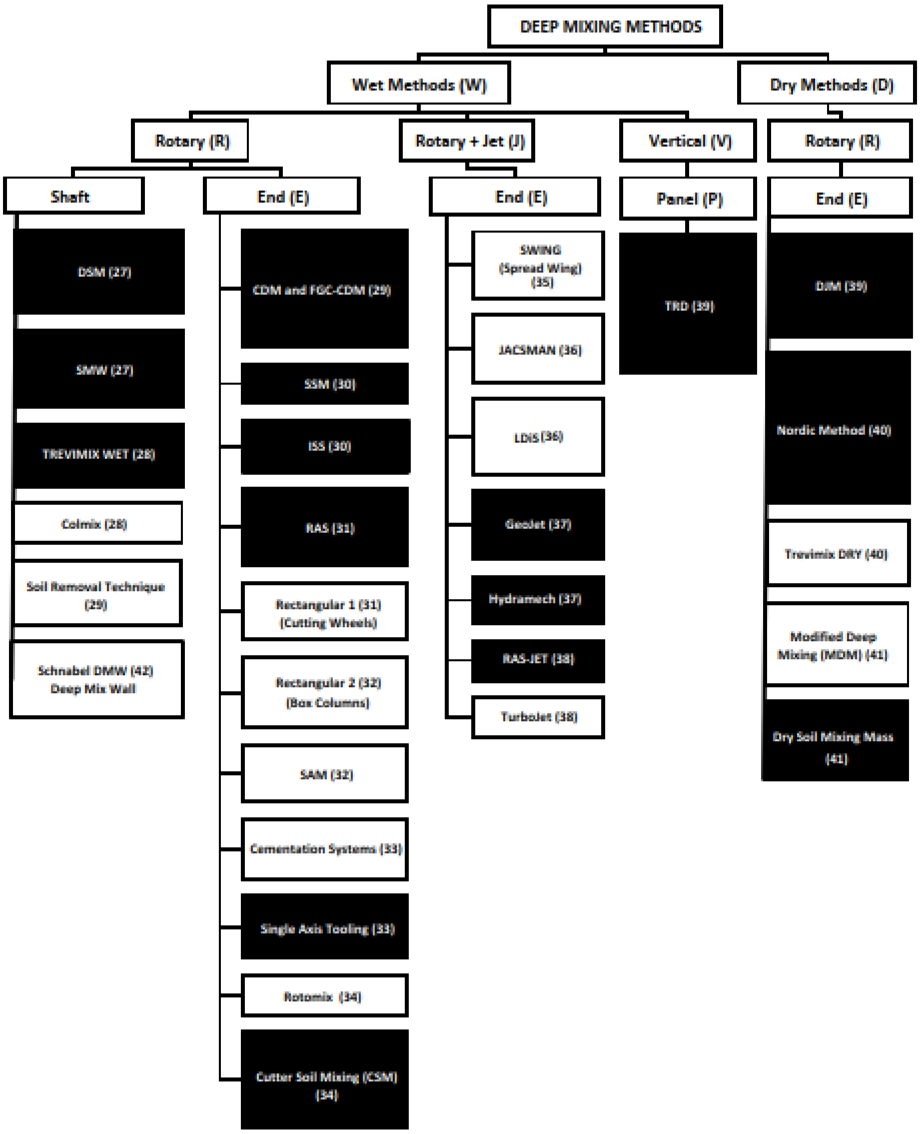

Fig. 3: Classification of Deep Mixing Methods as per FHWA [7]

In general, deep soil mixing techniques demonstrate few advantages in comparison to traditional special foundation techniques. Some of those advantages arehaving better production rates and hence being a more economical alternative, producing minimal installation impacts of noise& vibrations, causing minimum soil disturbance for neighbouring buildings, applicability in almost all obstacle-free soil types, and being environmentally friendly because of less produced spoils[8].

On the other hand, deep soil mixing suffers from some drawbacks like its limited depth of treatment, although the reachabledepth significantly differs from one method to another. It also cannot deal in the same effective way with very dense or very stiff soilsas well as soil layers with boulders.Unlike engineered construction materials like concrete and steel, the characteristics of the produced elements cannot be predicted even for one method at a time. They are rather dependent on the soil conditions at each project.

2.1 Mixed-In-Place (MIP)

In 1987, Bauer developed the Mixed-In-Place Technique, also known as MIP, and applied it in Nuremberg for an excavation support system for the first time. Bauer further developed the technique to what we know today, the triple auger MIP since the early 1990’s. Fig. 4 presents a modern rig equipped for MIP as well as a schematic site setup. MIP was successfully applied in different applications and on 3 continents.Applications ranged fromlandmark projects to small projects. Due to its distinguished mixing quality, MIP were applied in all possible applicationsfor deep soil mixing i.e., cut-off wall, retaining walls for excavation pits, foundation elements, soil mass improvement for liquefaction mitigation, and for increasing bearing capacity of an earth embankment.

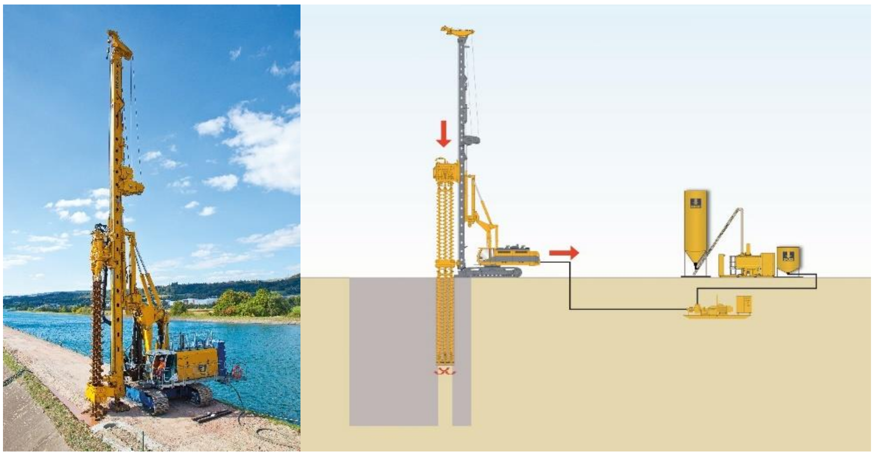

Fig. 4: Modern Rig during installation of a MIP cut-off wall (left), and a typical site setup for MIP works (right)

Currently, MIP walls have nominal thicknesses of 400mm or 550mmwith depths to nearly 24 m. Adjacent MIP panels form together continuous walls. The panels are constructed using Bauer's patented double pilgrim sequence. Similar to the standard pilgrim sequence for diaphragm walls, primary panels are installed first, before closing the gaps between them with the secondary panels. Additional panels are then installed in the overlap areas between primary and secondary panels, ensuring that each location within the wall is mixed twice. The triple augers string penetrates the soil while introducing a cementitious slurry till it reach the end depth. Afterwards, the triple augers switch their sense of rotation to start the homogenization process. Additionally, during the upstroke, the triple augers string is moved down and upwards to enhance the homogenization effect.

Through its unique and patented triple auger mixing tool as well as the double pilgrim sequence, MIP canhomogenize the cement mixed soil not only locallyat each level, but also along the whole panel length. This way it ensures the same mixing quality along the whole panel.In the same way, it can dilute the negative effect of an intermediate unfavourablesoil layer along the whole length, which eliminates the presence of weak spots in the same panel.

3 Geotechnical Works

The scope of works in Feldolling – besides the execution of cut-off walls for the sealing of the dam - also included the construction of some buildings that are necessary to operate the retention basin during a flood. Therefore, a bored pile wall (1700m², D=880mm), several sheet-pile walls (3300m²; depth down to 14m)and jet-grouting (1000m³) are executed.

For the sealing of the existing soils under the future dam the client planned a grab cut-off wall, D=800 mm, up to ~ 20m deep. The sealing of the dam itself was planned as soil-mixing wall (e.g., MIP cut-offwall).

3.1 Soil conditions

Before the call for tenders, extensive soil exploration works have been carried out over the full length of the foreseen dam. In figure 5 a part of the underground soil conditions is shown. It depicts the various soil layers within the cut-off-wall with gravel, sand silt and clay.

According to the soil report [9], ancient glaciers in that area formed a basin with tertiary subsoils. On top of the tertiary subsoil, glacier movements brought boulders, gravel and sand. Lakes appeared after the melting of the glaciers and fine-grained soils were washed in and deposited on the ground. Due to heavy movements, growing and reducing size and location of the glacier snout, layers were formed asshown in Fig. 5 as an example.Those varying soil layers wastaken into account when planning the execution of cut-off-walls.

3.2 Technical aspects of grab cut-off-wall and MIP-cut-offwall

A specious advantage of the grabsingle-phase cut-off-wall is that it relies on full excavation of a trench and replacing the soil by a ready-mixed self-hardening slurry which in its relevant properties can previously be tested and adjusted so that it meets the requirements of the project specifications. The fact that –unavoidably– remaining soil and sedimentation of solids within the slurry might alter the characteristics over depth is practically accepted and actual characteristics are being checked within the well-established QA/AC system. As for Mixed-In-Place technology, the slurry represents only a smaller fraction of the actual cut-off-wall material, and the natural soil is the other fraction.The soil-slurry mixture needs to be suitability tested before execution and later quality tested during the execution of the works.

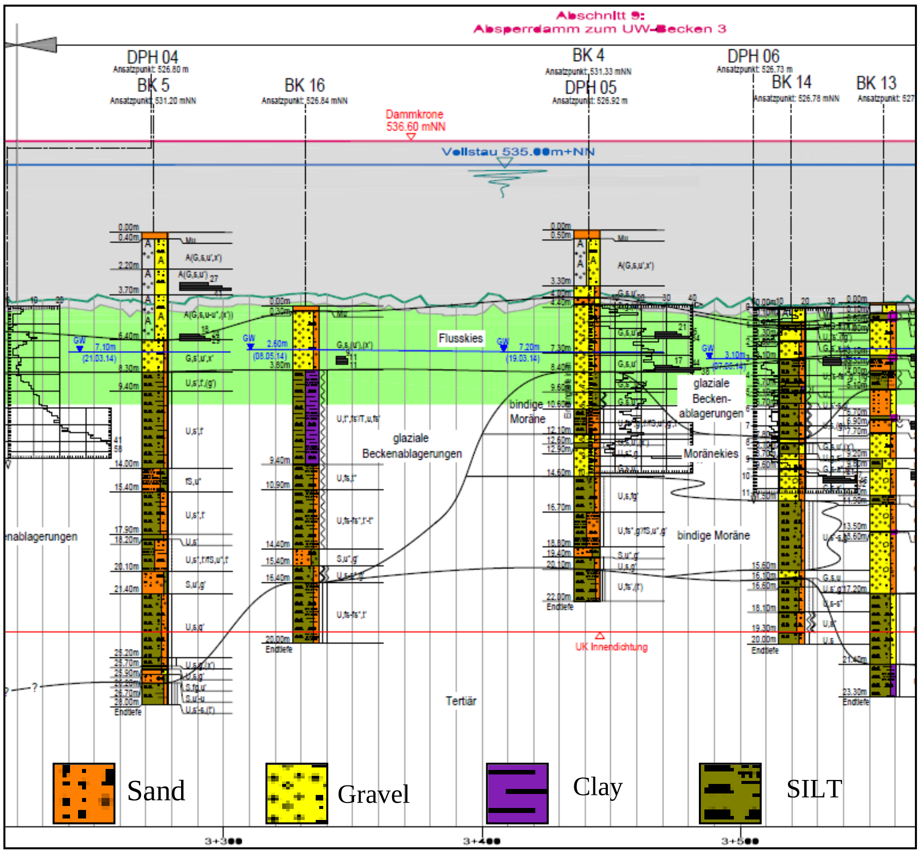

Fig. 5: Typicalgeotechnical cross section (in German, legend in English) [9]

Also, a grabcut-offwallslurry needs to overcome challengesliketrench stability, where it shall support layers consisting only of gravel without sand or fine-grained soils, as it has to completely replace the excavated soils with the self-hardening slurry. On the other hand, this risk is minimized with cement soil mixed wall, as it just added the cement slurry to existing soils, without replacing it.Similarly, the associated efforts to dispose the excavated soils can be completely minimized.

Based on the soil explorations as well as the previous experienceof executed MIP-walls the soil was assessed as suitable for the MIP,afteradditional soil explorations andquality assurancetests were carried out. The replacement of the grab cut-off wall by the MIP-wall required a close coordination with the designengineers of the client. A technical statement was written to prove that the MIP fulfils the exact requirements of the contract. Chapter 4describes that matter more intensively.Nevertheless, about 6300m² partiallyreinforced grabcut-off wall wasconstructed because of depths of up to 40m as one section, which could not be reached by MIP (max. 24m of depth).

4 Quality

In principle, all civilworks carried out for the construction of the flood retention basin weresubject tocertain pre-specified and demanded quality controls. Especially for the deep soil mixing technique, it had to be proved that the MIP was suitable for the existing soil conditions not only based onprevious experience but also on the basis of laboratory testing.

4.1 Quality assurance

Firstly, the client and his Engineerhad to be approvethat MIP is technically equivalent to the grab cut-off wall. For that, Bauer technical department provided a technical-note, inwhich they compared the MIPcharacteristics to the project specificationsthat are fulfilled by a grab cut-offwall. In the following the most important requirements of the project specificationsare listed:

- Nominal thickness 80cm
- Depth: 5-30m; embedmentinsealing soil layer
- Overlapping of panels at the top: 25 cm
- Minimum wall width: 50cm (30m depth)
- Verticality: Proof by inclinometer measuring
- Compressive strength: $1 \leq f_{m,k} \leq$ 3 MPaafter 28days
- Permeability: k_f< 10E-8 m/s
- Temperature: > 5°C

In the technical noteit was demonstrated, that the MIP-cut-off wall can fulfil all requirements. The nominal wall thickness of the MIPwasone of the most important quality issues, as itwas only 55cm instead of the required 80 cm. However, the function of the cut-off wall depends on the impermeability of the cut-off system and not only on the nominal thickness.Therefore, sure had to be made that the MIP-wall can delivera system-permeability as required in the specifications. Tests in the laboratory were carried out and the required system-permeability was demonstrated. The tests weredone using soil samples collected during an additional testing campaign.The campaignhadtwo objectives: First, to make sure that the MIP-wallcan embed into the sealing soil layer. Secondly, to obtainadequate soil samples for the laboratory tests.

Stiffness of the MIP material. The laboratory tests had to be done carefully, because it was necessary to estimate the influence of the different amounts of cohesive and non-cohesive soils. Producing the MIP in areas with mainly gravel and sand will lead to higher wall strengths. But as the list above shows, strengths over 3 MPawere not allowed, as too big compressive strengths are correlated tohigher stiffnesses. When the future dam is constructed, settlements and deformation of the damwill occur during the first flooding of the retention basin.Therefore,the stiffness of the cut-off wall must be limited to accommodate such deformation without developing anycracks. On the other side, the minimum required compressive strengths of 0.5MPa has to be attained to avoid any erosion of the MIP-wall during floods.The obtained original soil was mixed with different mix recipes to ensure that in all cases, with the existing soil stratification and particle size distribution, the boundaries of the compressive strength can be maintained.

Depth of the MIP-wall. The requirement to drill down to depths of 30m turned out to benot necessary demonstrated by the additional soil exploration campaign. A maximum depth of 22.5m was sufficient for the cut-off, which was possible for the MIP equipment to reach. As described in2.1, using MIPcontinuous walls can installed. The minimum wall width was definedas 40cm,otherwisethere could thesystem permeability will not be given. The wall width at the top of each MIP-panel is still 55cm, but because of drilling deviations the overlapping at the bottom of the MIP-panels can be smaller. Therefore, inclinometerswere installed in 2 of 3 augers to measure the verticality of each panel, which isdepicted on the screen of the rig operator in real time. That enables the operator to react to bigger drilling deviationsbecause of unexpected obstacles in the underground. Hence, the rig operator can easily installanother panel in the area with bigger deviations, while the slurry is sill fresh and maintain the minimum thickness of the MIP wall at the bottom. The combination of using inclinometer to measure the verticality and GPS to get the exact location of each panel at the top makes it possible to depict the as-built for the MIP wall in CAD software and thus prove that the wall has no severe deviations and installed as per the project specifications.

Permeability of the MIP material. The permeability to be reached has to behalf of the originally required specification for the grab single-phase cut-off wall, as the cut-off wall thickness was reduced to 40cm (instead of the originally specified 80cm). Thus, the system permeability was assured. That was proven through laboratory tests prior toconstruction. As the MIP execution works took place in the spring and summer of 2021, the required temperature of> 5°C was always achieved.

Additional QA measures. Additional risk mitigation measures werealso prescribed in the technical noteof the MIP in order to have agreed solutions for any foreseen problems that might occur. To avoid any misinterpretation of some single compressive strengths results (being too big or too low), it was mandatory to collect more samples than needed of the same area. It was also possible with the help of the narrow soil exploration raster to optimizethe mix recipe of the slurry for the different soil profiles, even for predominant cohesive and non-cohesive soil profiles.

Before the commencement of the MIP a detailed QA-plan was crafted according to the technical note, project specifications and in agreement with the client’s Engineer. The QA-plan described the scope of all quality control worksrequired to ensure that the constructed MIP wall is fulfilling the project requirements. It included which kind of tests, the required frequency, where and how to conduct the tests as well as the acceptable limits.

4.2 Quality control

During the works ofthe MIP-wall all quality tests and checks were carried out according to the QA-plan. This section presents some of the carried-out quality control tests.

Machine protocols. First, in order to monitor the amount grout slurry mixed with the soil, machine protocols were generated for each MIP-panel, which recorded the grout volume injected into the soil vs. the depth, as shown in Fig. 6.

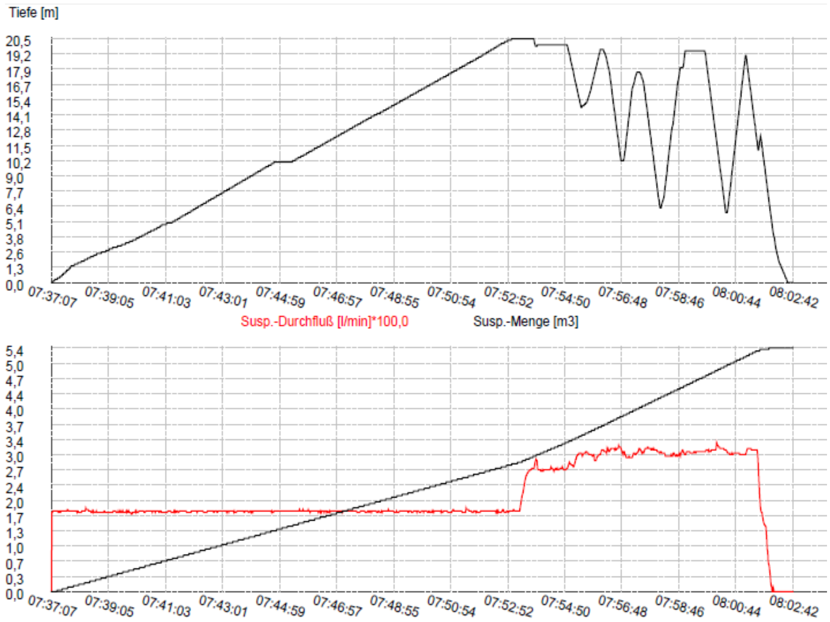

Fig. 6:Machine protocol of a MIP-panel (depth & flow rate over time)

That makes sure and comprehensible that the rightamount of cement has been mixed with the soil, which ensures that required stiffness of the MIP can be achieved. The production documentation also includes information about the name of the panel, date, depth, operator’s name, and time consumed for that panel.

Properties of fresh slurry. In addition to the machine protocols,the slurry was tested before it is mixed into the ground. Under normal conditions the mixing plant works with calibrated scales that mix predefined amounts of cement, bentonite and water together. Several slurry tests wereexecuted each day. The test results must be within the predefined range, that was set in advance by the technical department and agreed with the client’s Engineer. The following tests were executed and documented:

- Density (test with suspension scales)
- Temperature
- pH-value
- Marsh-time
- Sedimentation behavior

The above-mentioned tests madesure that the slurry was mixed correctly and corresponded closely to the one used in the suitability test done prior to the execution time. Controlling the density showed that the correct amounts of cement, bentonite and water were mixed together. The mixing temperature was alsocontrolled and had not to exceed 35°C or fall below 5°C as it can hinder the hardening process. The pH-value is a typical QC test for self-hardening slurries and adopted for MIP, mainly to allow for another test to verify a consistency in mixing the cement-bentonite slurry, and significant changes would cause raising a red flag to double-check the mix proportions at the batching plant. The marsh-time test measuredthe viscosity of the slurry to ensurethat the workingcharacteristics (pumping ability and stability in different soils) of the slurry wasensured. The sedimentation behaviortests are also carried out to further ensure the stability of the slurry as well in the slurry vessels as in the panel.

Properties of hardened cement soil mix. The third part of the quality control checks included the compressive strength and permeability tests, which were executed in the predefined frequency in the QA-plan. The testing timeswere7 and 28 days after collecting the samples (both from fresh slurry and from different depths of the mixed panel). Tests after 7 days gave an early indication whether the development of compressive strength wasadequateand facilitatedquick measures, in casethe strength development wasnot promising like by installing additional panels around the executed panels with insufficientstrength development. The 28days tests showed compressive strengths withinthe predefined and originally specified range(1-3 MPa), as shown in

Fig. **7**.

Proben-Nr.	Baust.-Nr.	Prüfdatum	Höhe mm	Durchmesser mm	Gewicht kg	F_m kN	Alter [d]	Rohdichte kg/m³	f_{mi} N/mm²
38723	27	04.05.2021	96,0	99,0	1,445	13,92	28	1955	1,81

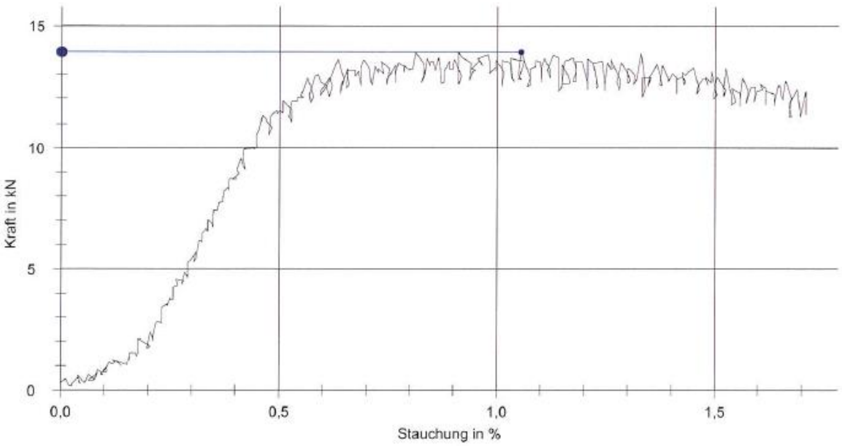

Fig. 7: Extract from lab results report showing the compressive strength of MIP sample

5 Conclusion

Cut-off walls are an integral part of dams, dikes, and leveeswhere they act as a water sealing barrier. Traditional techniques to install cut-off walls like diaphragm walls (grab or cutter) can be successfully replaced by soil mixing techniques. MIP technique is one of these soil mixing techniques, which can produce cement soil mixed walls, that can fulfill equivalent requirements for cut-off wall using the traditional techniques. This paper presents a project where Bauer Spezialtiefbau GmbH installed a MIP wall as cut-off wall in the scope of the construction of the flood retention basin in Feldolling, Bavaria, Germany. Despite the non-uniform soil conditions, which is a major component of the end product, along the cut-off wall axis, the MIP technique could deliver a homogeneous wall. That could be achieved by the implementation of a sound QA-plan, based on Bauer's experience from previous projects.

Soil mixing walls are a more cost-effective option as they use the existing soil as aggregates. As substantial amounts of construction material are saved in this way, they are also considered to be more sustainable.Also, as less construction material is used, less site transports are required, which again contributes inreduction of the cost and the carbon footprint of the project.

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