A PERMANENT CONCRETE CUT-OFF WALL FOR THE BAGATELLE DAM, MAURITIUS – CHALLENGES AND LESSONS LEARNED

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ABSTRACT

The Bagatelle Dam will form a reservoir containing 25 million m³ of water. Due to the demanding geology (basalt in different stages of weathering) an underground barrier is required cutting off potential seepages underneath the embankment dam.

In March 2012 construction of the Bagatelle Dam began. After initial grouting of the subsoil forming a permanent barrier, it was discovered that the soil was not conducive to continue construction under optimal conditions. Rehabilitation was required. Experts advising the government on the best option resulted in a redesign of the barrier wall. The installation of a permanent concrete cut-off wall (CCOW) was accordingly designed and awarded.

Figure 1 BAUER Trench-Cutter and Grabs along the CCOW installation

1. THE PROJECT – GENERAL AND HISTORY

The Republic of Mauritius is an island state in the Indian Ocean, some 2,000 kilometres off the southeast coast of Africa. Despite heavy rains, the nation faces problems with fresh water supply on the island, due to the lack of reservoir capacities. Over the past decade climate change and increased demand have led to increasing water-supply problems in Mauritius.

The dam forming a reservoir is intended to meet the water demands of the capital, Port Louis, and the Lower Plaine Wilhems district until 2050. It will also increase the water available for irrigation, as well as meeting the water demands of a number of major new infrastructure initiatives. The construction of the new dam is undertaken by the China International Water and Electricity Corporation (CWE). (Excerpt from The Economist, May 22nd 2012)

In 2012 CWE discovered that the soil was not conducive to continue construction under optimal conditions. An expert has been summoned to Mauritius to advise the government on the best option. It advised the government to build a 'concrete cut-off wall'.

In January 2013, a high-level meeting was held with the consultants in the presence of an independent expert appointed. It was decided by the consultant and expert to stop grouting and create a concrete cut-off wall instead of it. This was submitted to the government to give the green light. (Excerpt from business media, December 02, 2013)

2. THE GEOLOGY

2.1 Regional Geology – General

Mauritius Island has been edified by successive volcanic episodes which started in mid-Miocene, about 10 million years ago.

Two magmatic and structural periods are significant:

- First period: breccias and ancient volcanics
- Second period: intermediate and recent volcanics

Each period comprises successive cycles of volcanic activity (breccia eruptions, lava flows, pyroclastic emissions) followed by cycles of relative quiescence, with erosion accompanied or not by weathering.

Subsequent to the initial explosive episode represented by the breccia, the old lava flows gave rise to the "shield volcanoes". These rocks still form the main relief of the island, principally as narrow ridges. They represent remnants of the ancient collapsed volcanic caldera. *(for more information please refer to the scientific journal Nature Geoscience)*

2.2 Site Geology – Geomorphology

The terrain in the area of the Bagatelle Dam project is generally flat, with very small overall slope towards the coast (west). The Terre Rouge and Cascade Rivers are the main drainages. They form 15 to 20 m deep incisions in residual soils, with steep to very steep slopes. In the vicinity of the dam axis, the Terre Rouge River forms a series of meanders, with local rapids of relatively small vertical drops. Linear sections in the meanders follow a NNE-SSW direction, which is that of one dominant joint family in the project area. The Cascade River forms similar meanders and the linear sections are aligned with those of the Terre Rouge River. Another set of lineaments, WNW-ESE, correspond to the general direction of the drainages in the project area, which is also that of the general topographic slope.

2.3 Site Geology – Lithology and Weathering Sequence

The Basalts in different stages of weathering, forming the foundation of the new dam, are assignable to the Intermediate Series lava. The formation is deeply weathered, the bedrock comprising sequences of basaltic lavas and pyroclastic interlayers. The thickness of individual basalt layers ranges up to about 10 meters.

At the dam the geologists described/divided the basalt in four different units: completely (CW), highly (HW), moderately (MW) and slightly (SW) weathered.

During the tender phase tests were carried out. The testing of the core samples showed the following results:

From the tested rock samples, very high compressive strength with a maximum of 236 MPa and also extremely high destruction energy up to a maximum of 720 kJ/m³ could be derived. The Brazilian tensile strength of the samples is on average 9.7 MPa, the maximum is 12.0 MPa. The Cerchar-Abrasivity-Index is on average 3.7. The average abrasivity of the rock is classified as very high to extremely high in single tests. The examined rock can be classified as very hard, and as very to extremely abrasive. In conclusion, the rock type of basalt can be very heterogeneous. Porous to cavernous and weak parts change with dense and massive rocks of extremely high rock strength.

3. SPECIFICATIONS – MAIN FINDINGS OF THE STUDIES PHASE

The main findings and assessment of the geological & geotechnical conditions are summarized below (Excerpts from Specification):

- The contact between the overburden and the bedrock lies at depth ranging between approximately 10 and 20 metres.
- Basalt boulders with very strong, sound core are found generally within the upper 3 to 4 metres. Generally, completely or highly weathered matrix fully envelopes the individual boulders.
- The contrast soil/bedrock leads at their thin transition zone to significant changes especially in geomechanical and permeability conditions.
- Drilling confirmed that the bedrock includes interlayers of residual soil or scoriaceous, weak basalt. Geophysical logging showed that difficult drilling core recovery of weak layers underestimates the in situ condition.
- The results of in situ permeability tests in soils, including CW and HW rock, showed high dispersion. In addition the variation with depth is irregular and shows that the overall permeability is at least one order of magnitude higher in the uppermost soil layer – see table below.

Table 1 The mean permeability values for two depth intervals

Depth interval	All depths	Depth 0 to 5 m	Depth 5 to 10
Mean permeability (m/s)	5.19E-06	7.91E-06	7.79E-07

Another high permeability interval was identified between about 12 and 17 m depth.

Figure 2 Core boxes showing weathered basalt with some cobbles (left) and fresh competent basalt (right)

4. THE INITIAL DESIGN OF THE BARRIER WALL FOR THE PROJECT AND EXPERIENCE WITH THE INSTALLATION OF THE GROUT CURTAIN

The aim was achieving a watertight grout curtain in the foundation of the dam.

The permeability of the upper residual soil was not constant, caused by the variable degree of weathering of the rock into soil with variable soil grading and pore volume leading to relative high permeability with no systematic distribution within the residual soil. Different rock layers with different stages of weathering increased additionally the complexity of grouting results.

The Engineer considered for the sealing of the dam foundation a core trench and some grouting of moderately weathered rock. The core trench was partly used checking the results of the grouting. The grouting appeared to be not successful with the different heterogenic soil-rock layers.

The following observations regarding the success of grouting were described:

- Increased grout take was recorded in some of the quinternary holes indicating that even with quaternary holes no satisfactory grouting of the dam foundation could be achieved.
- Permeability testing had been performed in the grout curtain. The comparison of permeability of not grouted foundation with the permeability in grouted foundation indicated clearly, that with grouting in the soil and to some extent also in bedrock no improvement in the water tightness of the dam foundation could be achieved.
- Further, it was observed by a careful inspection of the cores of bore holes that no continuous grout curtain could be achieved.

The results of the testing and inspections led to the re-design of the barrier wall in the foundation of the dam.

5. REDESIGN TO A CONCRETE CUT-OFF WALL

Following the expert assessments to abandon grouting, a plastic concrete cut-off wall as a permanent durable barrier was planned and designed.

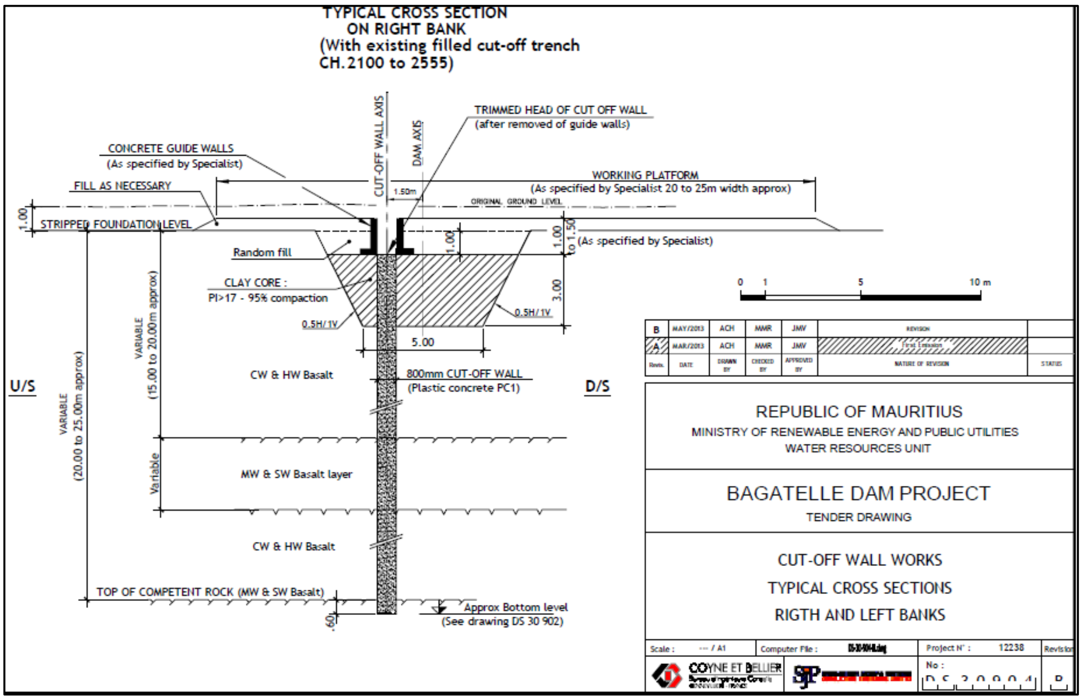

Figure 3 Tender drawing showing working platform, guide wall and cut-off wall (black)

According to the preliminary design the main characteristics of the cut-off wall were as follows:

- Total length 2.4 km
- Maximum depth 30-35 m
- Total area 57,000 m²
- Nominal thickness 800 mm

The two-phase COW has the specific design as follows (Excerpt of Specification):

- On the left bank:
  - the COW will be founded in the first meter of the first competent rock layer concreting with plastic concrete class PC1 (see technical specifications)
- On the right bank:
  - COW founded down to the competent rock approx. 3 to 5 m below the river Cascade riverbed, through alternating CW to SW basalt layers
  - concreting with plastic concrete class PC1 (see technical specifications)
- On the central part:

- dam foundation level reached the first competent rock layer, covered by dental concrete, and even locally several meters of mass concrete o concreting with plastic concrete class PC2 for upper part of the COW
- concreting with plastic concrete class PC1 for lower part of the COW

6. THE CONCRETE SPECIFICATION

The Contractor had to design, and recommend for the approval by the Engineer, appropriate concrete mixes for the cut-off wall, meeting the requirements listed in Table 2:

Table 2 Requirements of hardened PC1 and PC2 concrete as per Specification

Class of Concrete	#1	#2 (for central part only)
Permeability	< 1x10-8 m/s after 28 days	< 1x10-8 m/s after 28 days
Compressive strength (28 days)	Between 1 MPa and 1.5 MPa	up to 10 MPa
Deformation modulus	100 to 150 MPa	1 to 5 GPa

In addition, the minimum allowable strain at failure measured by triaxial tests during mix design tests had to be between 2% and 3%, for concrete #1.

The Contractor had to conduct trial mixes and perform relevant tests to demonstrate the suitability of the mix design.

7. THE CONCRETE MIX DESIGNS

To limit the number of suitability trials on site two preliminary mix designs had been established and validated by laboratory trials, in advance. However, it was always considered, in order to simplify the later procedures at the batching plant on site, to limit the mix design variations between concretes #1 and #2 to a minimum, i.e. on proportions of available constituents only. To control the different mechanical properties, the most effective parameter was seen in the water/cement ratio. The following mix designs were finally approved to meeting the specified requirements:

Table 3 Concrete Mix Designs for PC1 and PC2

Class of Concrete	#1	#2 (for central part only)
Sand 0/5	1032 kg/m³	1025 kg/m³
Gravel 6/10	442 kg/m³	482 kg/m³
Cement (CEM III/B 32,5 N):	80 kg/m³	240 kg/m³
Sodium Bentonite	45 kg/m³	38 kg/m³
Water	395 kg/m³	332 kg/m³
Water/Cement - Ratio	4,93	1,38
Slump	240 mm	240 mm

8. EXPERIENCES WITH TWO DIFFERENT TYPES OF CONCRETE IN A PANEL

According to the project specifications two different concrete types had to be installed, in the cut-off wall in the central part. The necessity of a rather structural concrete type #2 (refer to Table 2) was obviously derived from a finite element design study; due to particular consideration of expanding deformations of the heterogeneous rock formation. It might be worth to note that only after the commencement of the actual construction works it was explained that also the strength of the structural concrete #2 was considered relevant. Main Equipment used on the Project

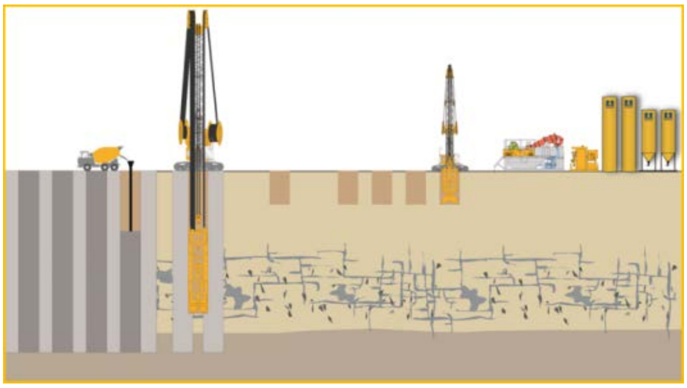

Figure 4 Principle – Installation of a double-phase concrete cut-off wall

Table 4 Excavation equipment used for different weathering conditions

BAUER assessment regarding “weathering grade vs excavation technique/tool”		
In situ clay to completely weathered basalt	CW	Grab
Completely weathered	CW	Grab
Highly weathered	HW	Grab / Cutter
Moderately weathered	MW	Cutter
Slightly weathered	SW	Cutter

Main equipment for excavation:

- 1x MC 128 – HDS 100 – BC40, excavating predominantly MW, SW and fresh basalt as well as larger boulders including overcut ensuring the wall continuity.
- 1x MC 96 – HDS 100 – BC40, excavating predominantly MW, SW and fresh basalt.
- 1x MC 96 – HTS 58-48 – BC40, excavating predominantly MW, SW and fresh basalt.
- 1x MC64 – Hydraulic Grab, excavating predominantly CW and HW basalt.

9. EXECUTION OF THE DIAPHRAGM WALL

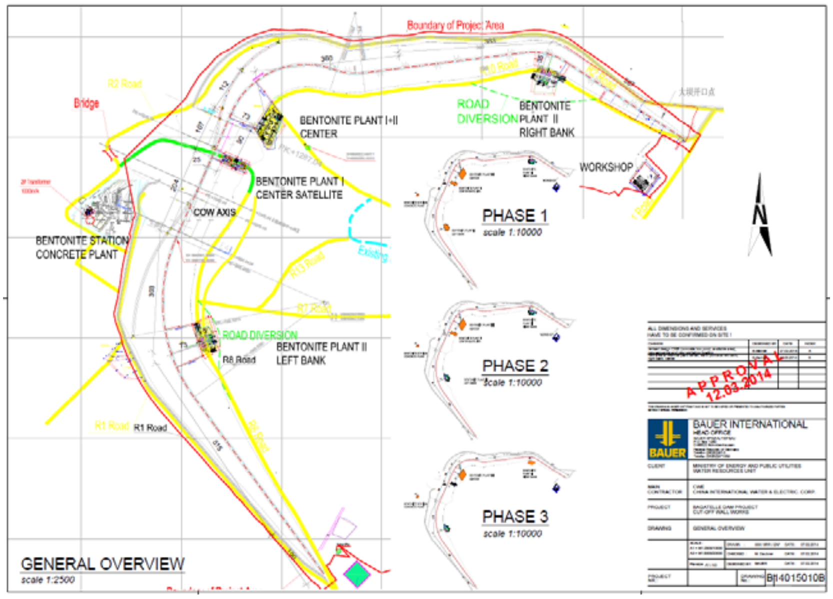

Figure 5 General Overview of the Dam Layout with Left Bank, Central Part and Right Bank

9.1 Excerpt of Technical Specifications of Cut-Off Wall Works

The construction of the two-phase cut-off wall shall comprise as main components the following:

- The guide walls and the platform including ramp connections should be designed and specified by the Sub-Contractor to suit the technical requirements for his equipment. The working platform will comprise both excavation in a trench and fill to suit the requirement in terms of maximum inclination.

9.2 Slurry

The standard requirements for the bentonite suspension of the slurry were:

- Density 11 kN/m3
- pH-value 9.5 to 12
- Marsh apparent viscosity 45 s on an average
- Sand content < 2%.

10. CHALLENGES AND LESSONS LEARNED DURING EXECUTION

10.1 Working platforms resisting heavy rainfall

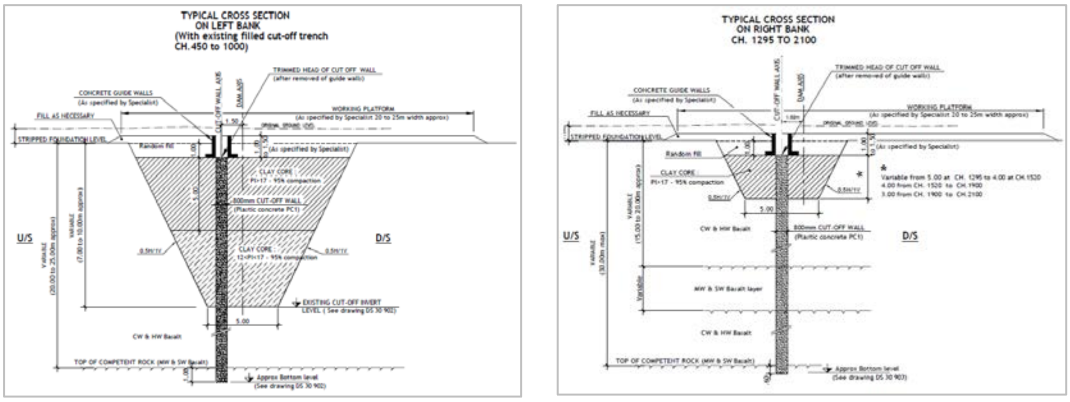

Figure 6 Working platforms as per specification

To install the concrete cut-off wall as a seepage barrier successfully, heavy equipment was to be placed along the axis of the barrier wall. The top soil (natural ground), in situ clay to completely weathered basalt, had to be protected in areas at foundation level and a proper working platform for the heavy equipment was to be installed withstanding even heavy precipitation.

Such an ‘All Season working platform’ was designed enabling unhindered working throughout the project.

Regular maintenance and permanent drainage during heavy rainfall was essential. Proper discharge of storm water was arranged protecting the nearby rivers.

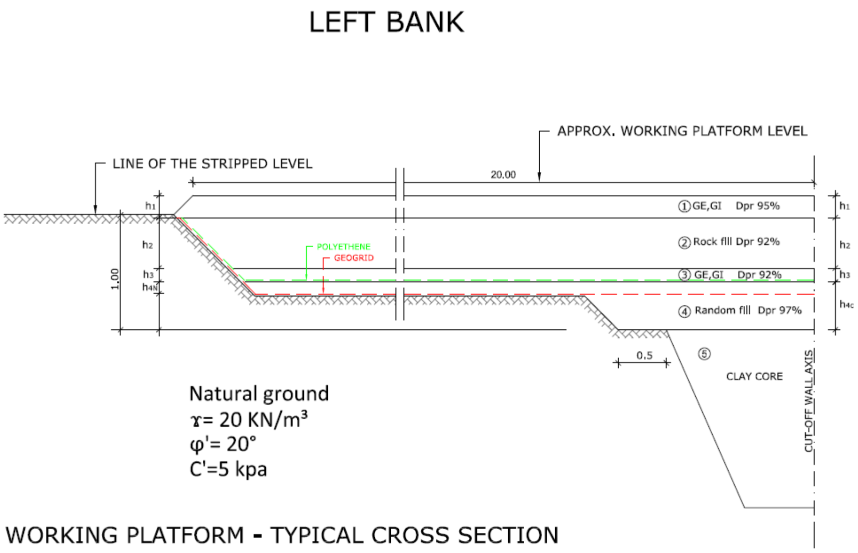

Figure 7 Detailed design of working platform by BAUER

10.2 Cutting through rock

The basalt, in the central part at foundation surface, was extremely heterogeneous. Weathering grades and strength of basalt varied significantly. Therefore it was difficult to predict on the basis of a limited number of samples and limited number of testing on such samples. The compression strength with a maximum of 236 MPa measured at samples in combination with very high destruction effort (measured in kJ/m³) required to break the rock was to be cut for the excavation of the trenches.

In addition intermingled layers of completely weathered basalt, clayish type of soil, caused additional challenges running the risk to completely block the cutting surface of the cutter wheels.

The circumstances particular in the central part of the dam led to a net performance below 50% of the working time. Cleaning wheels, changing teethes and relocating equipment were the most significant other activities. Due to actual progress for installation of the cut-off wall and milestones to be reached, at peak times three cutters and two grab units worked 24 hours and 7 days a week.

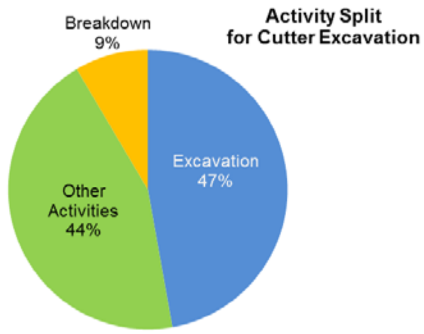

Figure 8 Main activities during cutter excavation

With good performance of the experienced staff and equipment with low downtime also working 24/7, the concrete cut-off wall through rock was installed in time.

10.3 Cut-off wall installation at different elevations assuring a continuous wall

At the Central Part the working platform elevation was at EL 360 m whereas the platform at the adjacent Left Bank was at approx. EL 372 m and at the Right Bank at approx. EL 375 m.

After initial installation of the cut-off wall in the Central Part, working platforms and ramps had been installed to overcome the elevation change to the Banks in certain steps. A particular platform design to assure safe working on backfilled parts was required.

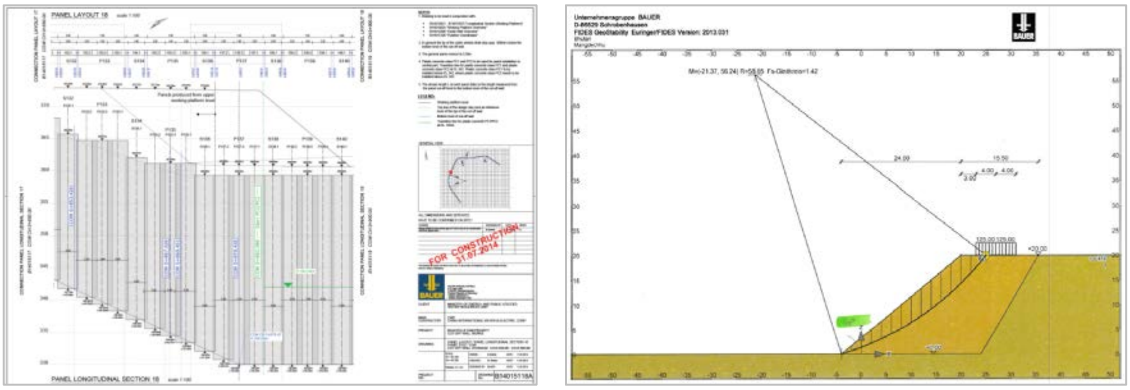

Figure 9 Top of COW (cut-off level) and stability design for elevation changes Central Part to Banks

Figure 10 Changes in elevation Central Part to Left and Right Banks

10.4 Hardened concrete testing and quality control

To proof and ensure the required hardened concrete properties a site laboratory was equipped with 6 water permeability testing cells and one triaxial cell for confined compression strength (CCS) and deformation modulus testing.

As different testing conditions such as various confining pressure, back pressure, saturation time or deformation speed and the different methods of CCS testing (consolidated, unconsolidated, drained or undrained) showed significant influence on the confined compressive strength and deformation modulus results, it was obligatory to clarify the exact testing procedure for the particular specified and required concrete properties.

11. CONCLUSIONS

Installation of a concrete cut-off wall for a positive, clearly defined seepage barrier in challenging ground conditions experience is essential. Mobilization, setting up on site, testing materials and method was the basis for the successful installation of the specified barrier wall.

12. ACKNOWLEDGMENTS

Proper planning was essential to keep safe working conditions, protection of the precious environment and good performance to finish this challenging project with timely critical parts successfully in time.

We would like to thank client's representatives and client's engineers for their courageous decision changing a grout curtain barrier into a concrete cut-off wall for the defined safety of the future dam. With a main contractor providing services and a committed team this completion in time was possible.

13. REFERENCES

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