Deep Cut-Off Walls constructed under Dams with Trench Cutters

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Abstract

Up to now, the BAUER Trench Cutter Cut-Off Wall (COW) technology has been developed for more than 20 years for use on large dams. The special task of a COW is to mitigate seepage and therefore COW's are utilized either on dam rehabilitation projects or on new dams as well.
Seepage mitigation, for the long-term stability and the safety of dykes and dams, is a major issue to the designers.
Cut-off walls constructed using Trench Cutters nowadays can be installed to depths in excess of 120 m / 400 ft and into bedrock with strengths well above 160 MPa / 23,000 psi. In the near future the job definition by client-side will ask for depths over 200 and 250 m and very hard rock. Modifying Trench Cutters in the way to react on this definition and developing the right construction methods are the main challenges for the future. Above all, the measuring technique must be modified to ensure the quality of the diaphragm wall. Concerning the permeability of the total wall the quality of cold joints is the most important factor, for which cleaning before concreting could be mandatory.
Specific tasks will be discussed through various COW projects recently executed by BAUER Spezialtiefbau GmbH.

Introduction

Among others dams are constructed under the specification that the seepage won't leak through the dam body.

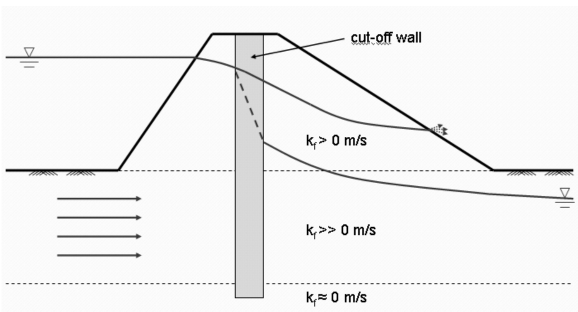

Figure 1: Dam and possible gradient of the seepage

If the seepage leaks for example from the dam abutment or an contact erosion may happen due to the velocity the stability can not be stated anymore and modifications are becoming essential.
If a problem that has an influence on the stability has been identified a suitable proceeding would be the installation of a cut-off wall to restore full bearing capacity. A cut-off wall even upgrades the long term behaviour and so extends the service life of the dam.

The evolution of Trench Cutter

Since BAUER already had carried out projects in the late 70s, within cut-off walls executed by Trench Cutters for the purpose of stabilization and rehabilitation of dams, BAUER consequently selected this technique as a preferable method to ensure complete cut-off walls without fail.
Figure 2 illustrates the very first BAUER Trench Cutter used for the Brombach dam in 1984.

Figure 2: BAUER Trench Cutter, Brombach, Germany 1984

By the evolution during the past 25 years modern trench cutters became high performance status, driven by its beneficial outcome as well as by demand on increasing depths and critical boundary conditions, but also made possible by improved machinery production methods.
In comparison to the technology of the early 80's, in Figure 4 you can see a high-modern BAUER Trench Cutter as it was

used for the project "Hinze Dam" in Australia in 2008.

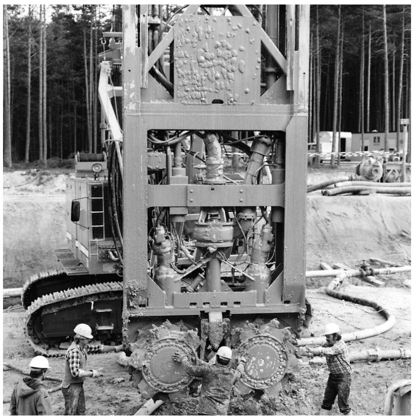

Figure 3: Detail of the trench cutter from 1984, Brombach

Figure 4: Trench Cutter BC50 CBC135, Peribonka 2005

The technical progress of Trench Cutters and especially the technology behind the process you can see, for best, regarding the operator's cabin. In Figure 5 (left) a cabin of 1984 is highlighted, in figure 5 (right) you can see a high-modern operator's cabin as it is used nowadays.

Figure 5: Trench Cutter operator's cabin, 1984 (left) and a operator's cabin in 2008 (right)

The Trench Cutter Technology

The trench cutter (Figure 6) is an excavating machine that operates on the principles of reverse circulation. It is made up of a heavy steel frame (1) with two gear boxes (2) at the bottom of the frame. Cutting wheel drums fitted with a series of teeth are fixed to the gearboxes; they rotate in opposite directions, break up the soil and mix it with the bentonite suspension (3).

As the cutter penetrates, soil, rock and bentonite are conveyed towards the openings of the suction box (4), from where they are pumped by a centrifugal pump (5) through the slurry pipe incorporated in the cutter’s frame, via the mast head into the slurry conveying system to the de-sanding plant. There solid soil and rock particles are separated from liquid bentonite which is pumped back into the trench or for storage and later reuse.

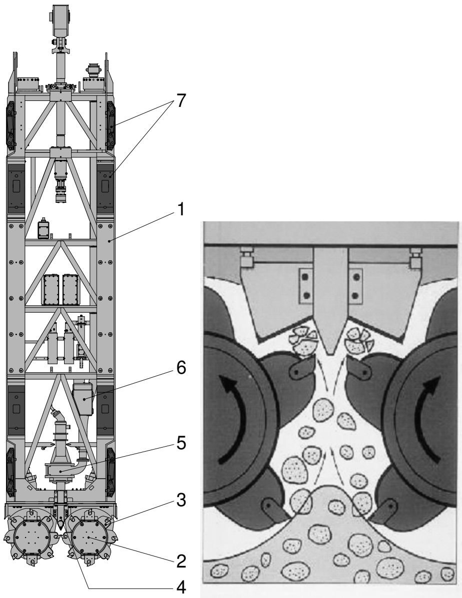

Figure 6: Trench Cutter principle sketch

The torque output of the cutter wheels in combination with the weight of the cutter is sufficient to cut into any type of soil, to crush cobbles, small boulders or weak rock and to over-cut concrete of adjacent panels as well.

Figure 7: Standard Cutting wheels for low strength rock (left) Round shaft chisel cutting wheels for high strength rock; patented BAUER tip-aside teeth (right)

The verticality of the trench cutter and thus the trench alignment are measured on two axes by means of two independent inclinometers (6). Data provided by the inclinometers is processed by a computer on-board the base carrier and displayed on-line. Adjustment of verticality in the two directions is carried out by a system of steering plates (7). Throughout the excavation process the rig's operator is prompted by the machine's software that calculates its status and indicates the most appropriate action take. All information can be downloaded on a "Panel Report" that can be printed after completion of each panel and used for Quality assurance and quality management (QA/QM) purposes.
After the excavation, of which the procedure is essentially independent, the actual purpose of the wall defines the next production steps. For use as retaining wall there has to be installed reinforcement according to its structural design.
Whereas the installation of stop ends in which usually a rubber water-stop is inserted is advisable for diaphragm walls at relatively limited depths, cut-off walls are constructed by over-cutting, accepting so-called cold joints. Referring to the more often extraordinary depths of COW's, anyway, installation of stop ends and its later demount are quasi impossible.

Execution of Cut-Off Walls

One of the most challenging COW projects up to then until few years ago had been carried out at the Dhauliganga power plant, located in the Indian Himalaya in the border triangle between India, Nepal and China.
The dam was built as a 56 m high concrete-faced rock fill dam with a crown length of 270 m. The cut-off wall is located at the upstream toe of the dam and was constructed in the cut-off wall technique. The COW with a total area of 8000 m² and with a thickness of 1 m reaches a maximum depth of 70 m.
The dam axis is located at a V-type valley with steep side slopes. The bedrock is formed of biotite and augen gneiss with bands of mica schist. The main characteristics however are the presence of boulders at any depth with a size from 20 cm to meters throughout the whole valley section.
The selection of appropriate equipment was dictated by three key requirements:

- Wall depth 70 m (with a required contact width of 750 mm between primary and secondary panels).
- presence of boulders in an unknown quantity and at unknown depth
- 0.5 m of socketing of the wall into bedrock (at any inclination of the slopes)

A combination of the reverse circulation cutter technique with standard hydraulic grabs and heavy chisels was selected.
The COW operations started mid January 2002, following a two month mobilization period, and the last panel was finished mid March 2003 – 2 months ahead of schedule.
The key equipment had been the BAUER trench cutter BC40, equipped with specially designed rock cutting wheels (Figure 7).
The main advantages of the cutter BC40 on this particular project were, besides the capacity to excavate a trench of 70 m depth, the forming of rock socket into bedrock, the breaking of large boulders and, last but not least, the possibility of forming joints between primary and secondary panels simply by over-cutting the primaries.
With respect to various experiences like that from the Himalayas and due to the progressive developing of trench cutter technology by our sister company BAUER Maschinen GmbH there had to come another, even more challenging COW project which actually was the hydroelectric project Peribonka in Canada executed by BAUER Spezialtiefbau GmbH in 2005 [1].
The key part of the whole project was the construction of a cut-off wall underneath the future main dam to a maximum depth of 116 m with a thickness of up to 1.5 m. Therefore, up to now, the biggest BAUER cutter was constructed being able to work down to 135 m below ground, equipped with the most powerful drive gears "BC50". Figure 4 may give the impressive dimensions of that BAUER cutter BC50 CBC135.
However, prior to constructing this cut-off wall, the alluvia in the glacial gully were to be pre-grouted to mitigate the high permeability and not to allow an uncertain stability during the wall excavation, due to possible large losses of bentonite slurry into the ground.
Furthermore the pre-grouting campaign targeted to cement the boulders which could be in the vicinity of the wall, thus preventing that such boulders or pieces of boulders fall into the trench during excavation [2].
The most recent COW project was the Hinze Dam Stage 3 project at the Gold Coast, Australia -again carried out with a BAUER trench cutter BC40, and among various other plants.
At the Hinze Dam a cut-off wall was built to allow an upgrade of the existing dam, to double its storage capacity. Due to the presence of networks of rock joints at the natural sub-base of the dam, higher water storage could result in unacceptable levels of water pressure at the dam foundation, and thus would endanger the dam stability.
A plastic cut-off wall was designed as a remedial measure.
The wall was to be excavated with a cutter, and keyed into the problematic rock horizons.
Among other challenges, panels as deep as 55m had to be cut through very hard and abrasive rock. Therefore, different types of cutter teeth, made of various grades of special steel were tested to minimize wear and tear as well as optimize performance data.

Specific tasks

Cutting in extreme rock conditions
Embedding the COW in bedrock is one of the most important tasks to ensure a complete wall with an overall minimum

permeability considered in the design of COW's. Furthermore, even in jointy rock, it is inevitable to cut through very hard and sometimes also extremely abrasive rock, e.g. at Hinze Dam project.

The bedrock of Peribonka into which the cut-off wall had to be socket into consists of granite proposed with unconfined compressive strength in a range of 120 MPa to more than 200 MPa.

The previous design intended a cut-off wall with remaining windows which should have been sealed by local pressure grouting afterwards. The special proposal by BAUER included a full embedment of cut-off wall even in the very steep rock and through rock overhangs. As this proposal was put in action, BAUER had to carry out very deep excavations down to 116 m below working platform. But extraordinary depth wasn't being the only one challenge.

Because of those very steep and concurrently hard rock flanks there was required a special procedure to enable the full embedment (socketing) into bed rock. In particular, in some areas the rock flanks were vertical. The solution was to work towards the steep flanks while the lower part of the counteracting panels was produced of structural concrete, as shown in figure 8.

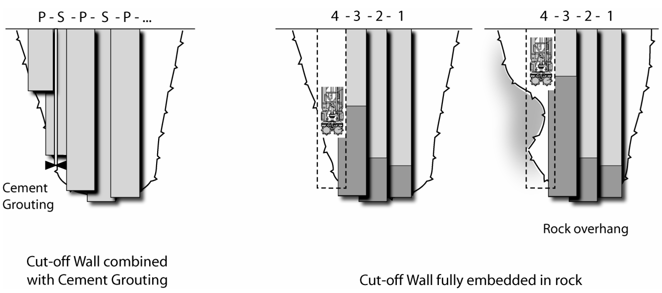

Figure 8: Previous design of cut-off wall and special proposal by BAUER

Besides the above described task of embedding, even the cutting through the alluvia was proposed to be a challenge regarding the performance. Since the soil in the very narrow valley is formed of heterogeneous glacial deposits, it consequently consists of sand and of gravel with stones, but also of blocks and boulders with a size up to 4 m, what had to be taken into account for schedule and prizing.

It is quite consistent that only a few boulders, for instance, of 5 % by volume, can cause a very low performance rate per panel when considering that those 5 % of boulders would make about 45 % of stratigraphical length related to panel section, see Figure 9. Accordingly, a small deviation in boulder content can involve a huge one in cutting performance and, in the case of abrasive components, also in wear and tear.

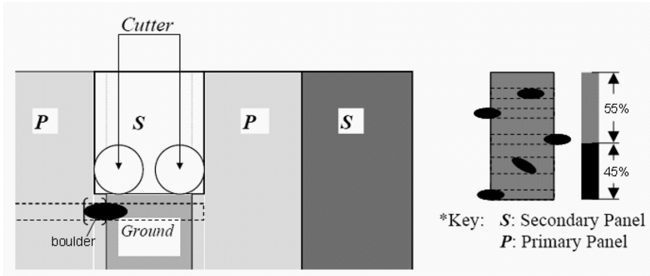

Figure 9: Cutting boulders of a small total volume but, stratigraphically, at a high total panel length

Whereas only a few blocks and boulders can be extracted as complete ones their existence can be proofed easily by evident records of cutting resistance resp. torque and speed of cutting wheels in combination with cutting performance.

At Hinze Dam there was to tear extreme abrasive rock which was also of a very high strength. The most "aggressive" rock was supposed to be the fresh chert (chert 1). But even samples of the rock characterized as slightly to moderately weathered, so-called "chert 2", taken from the de-sanding unit, were identified having a mean unconfined confined compressive strength of 250 MPa, tested with the point load test, and having an extreme abrasivity, in fact meaning a Cerchar Abrasivity Index of 6 (CAI has a scale from 0 to 6). But also fresh greywacke and fresh greenstone were identified as being high strength rock with single values well above 200 MPa, but with a CAI of 4 (greywacke) resp. 3 (greenstone), what is still characterized as very abrasive.

However, further investigations clearly show that the rock type related performance may not be derived only from the compressive strength. Wear and tear does not depend exclusively on rock's abrasivity, either. For instance, specific performance in chert 2 was even better and the wear and tear was even less than in fresh greywacke or fresh greenstone.

Looking at the same specific performance rate in chert 2 and greenstone 3, the wear and tear in extremely abrasive chert was almost 10 times as high as in very abrasive greenstone!

Consequently, these evaluations may lead to the conviction not to consider only compressive strength for any prediction of performance or exclusively abrasivity of wear and tear. Even the combination of strength and abrasivity will fail the prediction, either. According to the main influence of the grain size of alluvia there should be taken into account the fact that of course the rock angularity has an overwhelming influence on both, the performance of the trench cutter as well as on the wear and tear - as proven and therefore included in the drilling prediction tool of BAUER [3]. Therefore, conclusive information on all three of these parameters is required to being able to estimate performance as well as wear and tear reliably in hard rock conditions.

Cold joints and hydraulic reliability

An essential characteristic of another dam project was the installation of a cut-off wall in very dry soil. Executing the 2-

phases COW the secondary panels necessarily cut the primary panels. As a consequence bentonite deposits ("cake") may remain not only between soil and wall but also in the construction joints. This effect has been monitored on the Karkeh-Dam, Iran, where the proper parameters had been analyzed [4]. It had been detected that the following procedures, all alone, were not successful to get completely rid of the bentonite sludge:

- Substitute of the working by concreting suspension (Tab. 1)
- Cleaning the cut concrete surface of the primary panel with brushes
- Placing the soil-cement with the tremie method

But even with these cold joints it has to be declared that nowadays the cut-off wall is the most effective system as a sealing element for dam constructions. Construction joints between primary and secondary panel are dictated by the construction method but may constitute a weaker area in very dry soils [5], see Figure 10.
Joints filled with bentonite are unproblematic with regard to the permeability of the whole cut-off wall. Nevertheless, the erosion stability has to be kept in mind of course which depends on the following aspects:

- Physical characteristics of the bentonite sludge
- Length and thickness of the joint
- Coarseness of the surface and
- Filter stability on the downstream side of the dam

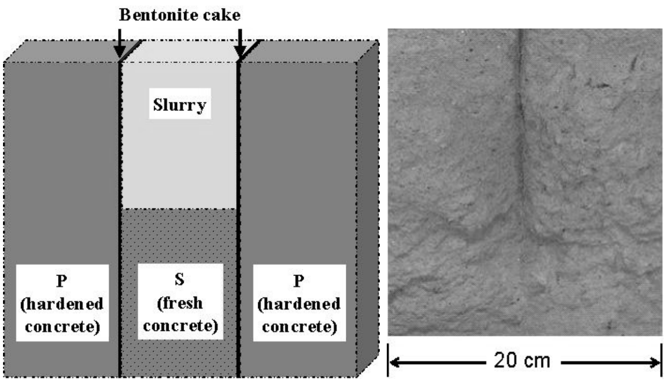

Figure 10: principle of cold bentonite filled joints (left); View of the COW surface and its joint, from which partly material was removed with a knife (right)

However, the following has been stated [4]:

1. Cold joints are inevitable
2. Cutting to be done under supporting fluid
3. Filter cakes consequently remain in joints
4. Numerous parameters influencing thickness of filled joint are, amongst others:

- Rheology of supporting fluid (bentonite)
- Roughness of already hardened concrete (of primary panel)
- Fresh concrete consistency
- Concrete raising velocity
- Hydraulic pressure (panel depth)!

Finding the best site procedure to minimize the thickness of the joints is recommended to be done empirically on site, for example by monitoring different testing panels, because all parameters and interactions can't be foreseen before the start of the project.
Precious experiences showed that bentonite sludge with a significant thickness arise only in dry conditions. Since effective procedures can't be preplanned without having tested various measures on site, consequently, necessary procedures can not be known in advance and hence can not be calculated.
Normally, the standardized criteria that are highlighted in Tab. 1 are enough effective, next to the criteria of the quality plan, to create high quality joints.

TABLE 1: SPECIFICATION OF BENTONITE (SUSPENSION)

slurry	pH [-]	Density [g/cm³]	Marsh flow [s]	Sand content [%]	filtration loss [cm³]	cake thickness [mm]
fresh	7-10	1.015	32-50	0	<30	<3
working	7-12	1.200	32-60	<6	<50	<6
concret-ing	7-12	1.100	32-50	<4	<30	<3

Besides the actual existing of cold joints at all, favourably their course is uneven and of a specific graininess due to the sand content as residual soil or concrete fines, Figure 11.

Figure 11: Traces of the cutter wheels give the joint's profile

Plastic concrete for highly ductile walls

The requirement for plastic concrete in cut-off walls meets the demand on ductile walls, in particular, if unequal deformations of the COW are expected and open cracks should be avoided which could cause hydraulic instability.

Based on specific design resp. loading conditions the required properties of plastic concrete are different but, as a rule, are quite similar due to given recommendations of the international committee on large dams (ICOLD). For Hinze Dam project, Australia, there have been following requirements for the plastic concrete.

- Slump: 190 mm ≤ s ≤ 250 mm
- Strength: 2 MPa ≤ UCS ≤ 4 MPa
- Permeability: k ≤ 1 · 10-9 m/s

Bentonite was premixed as slurry before mixing with dry concrete in truck mixers or in the mixing drum of the plant.

Despite the proceeding of concreting COW can not differ much from concreting Diaphragm Walls in general, there might be still little effects by special COW conditions. For example, there might be steps at the COW base when sufficient substratum quality had reached at different depths to embed the COW - due to the cutting procedure, usually three single bites will be executed in a primary panel. Depending on the level difference there can be needed three points of pouring concrete to ensure constant concrete flow from the deepest point upwards using three tremie pipes. When an equal concrete level is reached and a proper immersion of outer tremie pipes is guaranteed the middle tremie can be removed.

As the over-cutting instead of working with stop ends and water-stop rubbers should not influence the concreting itself, there is supposed to be a huge, design based difference in construction having no steel reinforcement cage in the trench. Not consciously proven, the lack of any obstacles inside the trench may cause a different concrete flow upwards as it is known for self compacting concrete.

However, at Hinze Dam an obviously stiff concrete came out of the not reinforced wall section up to the surface. This obviously stiff concrete was verified to having been the very first poured concrete, using coloured concrete.

Although the plastic concrete was produced using a retarding agent at a dosage supposed to ensure slump retention of several hours, the plastic concrete poured in the very beginning was initially set before having risen to the top.

A simple and practical test to determine the initial setting on concrete was carried out on site. The so called knead-bag test consists of filling some fresh concrete into a plastic bag and sealing it. With time the setting behaviour can be observed by hand. The stages of initial setting and final setting are based on the consistency limits acc. to "Atterberg" starting with the fluid stage, then passing the smooth and the plastic stage which indicates the initial setting when the concrete can be kneaded. After the semi-firm and firm consistency phases, the stiff consistency indicates that the final setting has occurred when the concrete can no longer be indented by thumb.

The knead bag test was suitable to figure out the correlation of retarding agent dosage and resulting workability period in a very simple but practicable way. Other possible effects as a thixotropic effect or an effect due to filtration have been investigated as maybe intensifying the setting effect but had been come out as not being the main influence.

Dosing more retarding agent up to 2.5 %, related to cement content, but less with progressing pouring time (down to zero for the last batch), the concrete rose up still workable. Even when retarded sufficiently, the proceeding as described above was proven as valid for long-term workable concrete as well.

Primaries already produced with early setting concrete were proven to be of proper quality by investigating intensively before pouring the secondary panels.

Conclusion

For many potential water storage areas new dams' construction or upgrading of existing dams is only feasible if the dam foundation in permeable soils or rock is sealed efficiently.

A new generation of hydraulic cutters allows excavating cut-off walls at depths in excess of 100 m, in hard rock and difficult ground conditions. Hence extreme geological conditions where only few years ago dam projects were deemed not feasible are no more a hindrance today.

Regarding specific tasks as embedding into extremely hard rock, cold joints between primary and secondary panels or quality assurance for plastic concrete it can be concluded, that combination of preplanning and finding suitable measures on site is effective to ensure proper executing of cut-off walls even under critical conditions serving a good long-term behaviour of dams.

Hence the use of cut-off walls as a sealing in dam foundations proves to be a safer design practice, in comparison to alternative construction solutions such as grout curtains.

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