Durable Embankment Dam Rehabilitation by Concrete Cut-off Walls installed by Hydro Cutters – a safe and economical approach for a durable solution

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ABSTRACT:

The safety of embankment dams, whether zoned dams with clay core or rockfill dams with surface protection, do rely on a reliable foundation. For aging dams improvement of dam-safety and durable seepage control often are the main issues to design the rehabilitation. Such design and planning of dam rehabilitations/remediation lays the basis for durability of the improved structure and for cost effectiveness of the works.
Technological developments and experiences in barrier wall installation, whether in execution techniques or equipment techniques, are used to assist the designs for new hydro-projects, upgrading or rehabilitation of dam projects.

To implement such designs for the rehabilitation of aging dams experienced foundation engineering companies provide the required execution technology for an economical installation of the required seepage control while the reservoir is still impounded. The project-required combination of foundation engineering techniques of different types of concrete barrier walls, the experience of the executing construction company and the latest development of foundation engineering equipment offer the dam owner and their designers the choice to choose from a variety of combinations.

The paper will discuss the advantages of concrete-barrier-walls installed by the latest hydro cutter technology; the requirements of pretreatment in different soil-rock conditions versus the general approach by a drilling and grouting campaign as preliminary measure for the installation of a concrete cut-off wall, considering dam safety being always the main focus.

To illustrate the topic, approach and lessons learned supported by evaluation, matrixes and tables shall form part of the paper. The effective pretreatment of alluvial and colluvial geology or of karst formations as well as the complete closure of gorges is a technique state-of the art in foundation technology. The hydro cutter technology has proven itself both a successful and economical means to install concrete cut-off walls in very hard rock at great depths. The experience to design and install plastic concrete for durable barrier walls combined with this cutter technique is available for the designers of sustainable seepage mitigation structures under dams.

Concrete cut-off walls like the one installed for the Peribonka dam in Quebec, Canada or the Hinze dam in Queensland, Australia are successful evidences for these techniques.

Project experiences and innovative approaches on selected construction sites involving plastic concrete cut-off walls installed by hydro cutters for effective seepage control will supplement the paper and the presentation.

RÉSUMÉ:

Réhabilitation durable des barrages en remblai à l'aide de parois étanches en béton installés par Hydrofraise - une approche sûre et économique pour une solution durable.

La sécurité des barrages en remblai, que ce soit barrages zonés en Argile ou des barrages en enrochement avec protection de surface, depend d'une fondation fiable. Pour les barrages vieillissants, l'amélioration de la sécurité des barrages et le contrôle durable d'écoulements sont souvent les principales questions pour la conception de la réhabilitation.

Le type de conception et de planification de la réhabilitation/restauration du barrage établit la base pour l'amélioration durable de la structure et l'efficacité du coût des travaux.

Les développements technologiques ainsi que l'expérience dans l'installation de murs étanches, que ce soit dans les techniques d'exécution ou des équipements, sont utilisés pour la conception de nouveaux projets hydroelectriques, modernisation ou la réhabilitation des projets de barrages.

Pour mettre en œuvre de telles conceptions pour la réhabilitation des barrages vieillissants, les entreprises de fondations expérimentées fournissent la technologie d'exécution requise pour une installation économique du contrôle des écoulements pendant que le réservoir est fermé.

L’exigence des projets pour combiner les techniques d'ingénierie des fondations des différents types de murs étanches en béton, l'expérience de l'entreprise de construction et les dernières évolutions des équipements de fondation permet au propriétaire du barrage et de leurs designers de choisir parmi une variété de combinaisons.

Cet article abordera les avantages des murs étanches en béton installés par la toute dernière technologie d’hydrofraises, les exigences de prétraitement dans les conditions différentes de sol et de roche par rapport à l'approche générale de forage et injection comme mesure préliminaire à l'installation d'un mur étanche en béton, compte tenu de l'objectif principal qui est toujours la sécurité des barrages.
Afin d’illustrer ce sujet, l'approche et les enseignements tirés par l'évaluation, des matrices et des tableaux feront partie de ce document. Le prétraitement efficace de la géologie alluviale et colluviale ou des formations karstiques ainsi que la fermeture complète de gorges est une technique d'état de l'art dans la technologie de fondations.
La technologie d’hyrdrofraise a prouvé qu’elle constituait à la fois un moyen efficace et économique pour installer des murs étanches en béton dans des roches très dures à grande profondeur. L'expérience pour la conception et installation de béton plastique pour murs étanches durables combinées avec cette technique de coupe avec hydrofraise est disponible pour les designers de structures durables pour l’atténuation d'écoulements sous les barrages.

Des murs étanches en béton comme celui installé pour le barrage de Péribonka au Québec, Canada ou le barrage de Hinze au Queensland, Australie sont des évidences du succès de ces techniques. Les expériences acquises dans ces projets et les approches innovantes sur des chantiers de construction sélectionnés impliquant des murs étanches en béton plastique installés par hydrofraise pour le contrôle d'infiltration efficace vont compléter cet article et la présentation.

1 INTRODUCTION

For the realization of new hydro projects, for the upgrading of dams as well as for remedial works on existing dams durable hydraulic barriers by means of Concrete Cut-off walls (COW) for seepage control are the choice of designers since more than 30 years. These Cut-off walls were installed with cutter technology either from the foundation level or from the crest of the embankment dam through the dam body and through the permeable foundation layers into impermeable strata. Durable plastic concrete cut-off walls have proven to be a reliable solution for all types of projects where a hydraulic barrier is needed. With the latest hydraulic cutter technology and methodologies to successfully install COW's in areas with non-favorable environmental and geological conditions the technique supports dam designs in not only ecologically but often also socio-politically and therefore economically more adequate areas.

Another important factor is the reliability and durability of concrete cut-off walls. The reliability is partly system immanent but requires also considerable experience regarding the execution. The durability of such walls depends on numerous factors like hydraulic gradient, chemical attack by groundwater and or soil/rock conditions but can be individually adapted by developing a project specific plastic concrete mix-design based on the materials available regional.
The wall installation itself is realized with the new generation of hydraulic trench cutters, especially developed for large depths and hard rock (> 180MPa) in order to penetrate through challenging soil/rock formations to more than 150m depth if required.
Pretreatment with an adequate grouting campaign might be required dependent on the specific soil-rock configuration of a project. Advisably the contractor for the barrier wall should be the contractor to execute the grout curtains as required for dam safety and best quality of the permanent concrete wall to be installed. In some occasions for the remediation of existing embankment dams it might be advisable to install an encasement wall prior to the barrier wall installation. It has to be carefully considered during design whether such additional work are is necessary to safely protect the existing embankment.

With professional execution and quality control planning the combination of adequate pre-treatment, the new cutter generations and project specific designed plastic concrete allows the effective and successful treatment of seepage prone foundations even in challenging, extreme soil-rock formations. The upgrade or the remediation of existing dams requires even greater depths to be reached to cut-off the destructive water seepage.

With the technology to install durable concrete walls through alluvium/colluvium boulders the execution of projects in mountainous, greatly uninhabited areas are now feasible. Already end of the last century techniques have been developed to successfully cut through such geology and into fresh rock even in lateral rock structures in forms of slopes, cliffs and even overhangs. Technological developments and experiences in barrier wall installation are used to assist in the designs for hydro-projects to enhance planning in the newly developing hydroelectric market.

The requirement for more carbon free renewable energy, the increase in flood control due to impacts of the climate change or more fresh water for an ever increasing world-population on the one hand, and the increasing public awareness and resistance regarding new hydro projects in populated areas on the other, increases the requirement for the upgrade of dams of existing hydro projects and pushes new projects into areas which might be socio-political acceptable but geologically less suitable, hence more challenging for the installation of barrier walls.

The new generation of hydraulic trench cutters, developed for hard rock penetration in ever greater depths, extends the possibility of concrete cut-off wall installation in challenging soil/rock formations in combination with new and existing dams significantly. Installation of lasting continuous seepage barriers into very hard rock, through boulders in gorges, along cliffs and to depths of 150m and beyond are within reach of the new trench cutters. Discussed below in more detail.

Plastic concrete cut-off walls prove to be a reliable solution for all types of the projects mentioned above. Since the 1980's installation of plastic concrete cut-off walls have been used as well defined and durable structural barriers.
The durability of these walls depend on a number of factors. Not only proper design, mixing and installation of the concrete but factors such as environmental conditions or chemical attacks from groundwater and/or soil/rock will govern the decision for the concrete mix. Individual project specific mix-designs from available materials are being developed, tested and used.

The combination of cut-off wall installation using suitable, project specific designed plastic concrete together with the new cutter generation allows the effective and successful treatment of seepage prone foundations for existing dams and for the execution of new projects in remote, greatly uninhabited areas. Solutions out of innovative technological developments and proven experiences in barrier wall installation are used to assist the designs for new hydro projects, for the upgrading of projects as well as for remedial works at aging dams and are ready to augment planning opportunities in the newly developing hydroelectric market.

2 The hydro cutter – a proven trenching system for challenging geology

New dams are accepted best by the indigenous communities if built in modest populated or even unpopulated areas. Following this principle new dams like the Dhauliganga hydroelectric project in Tehri Garhwal District of Uttarakhand, India or the Peribonka hydroelectric project in Quebec, Canada, had been planned with concrete COW's installed by hydro cutters to tackle the challenging and experience-wise as well as equipment-technology-wise demanding geology. The availability of such solutions often proves to be the key for the realization of such hydro projects.

2.1 History of the equipment for cut-off walls

During the 60s the first generation of hydro trenching equipment with reverse circulation methodology was introduced to the market. Companies like Tone Boring and Okumura, Japan developed and used hydraulic trenching equipment already end of the 60s of the last century for slurry walls.

Figure 1. Hydraulic trenching machine from Okumura, Japan

Since end of the 70s beginning of the 80s a new type of trenching equipment, the hydro cutters (Hydrofraises, Trench Cutters), are available.

Figure 2. Trench Cutter at Brombach Main Dam, Germany 1984

With the availability of the hydro cutter technique the design for barrier walls for dam project changed. The barrier walls for seepage mitigation in the foundation of dams executed as concrete cut-off wall (COW) was introduced to more and more projects.

Defined positive barrier walls as Concrete Cut-off walls excavated by hydro cutters are installed since the early 1980's. At that time hydro cutters reached depths of up to 50m. Refer also to 'Deep Cut-Off Walls constructed under Dams with Trench Cutters - K. Beckhaus, S. Schmitz and W. Schwarz – 2009'.

Since the 90s concrete cut-off wall depths beyond 100m are achievable. Concrete Cut-off walls are being installed for embankment dam rehabilitation in the USA by companies like Soletanche and BAUER.

Figure 3. Hodges Village Dam – Oxford, Massachusetts; USA

2.2 Rock strength and boulders

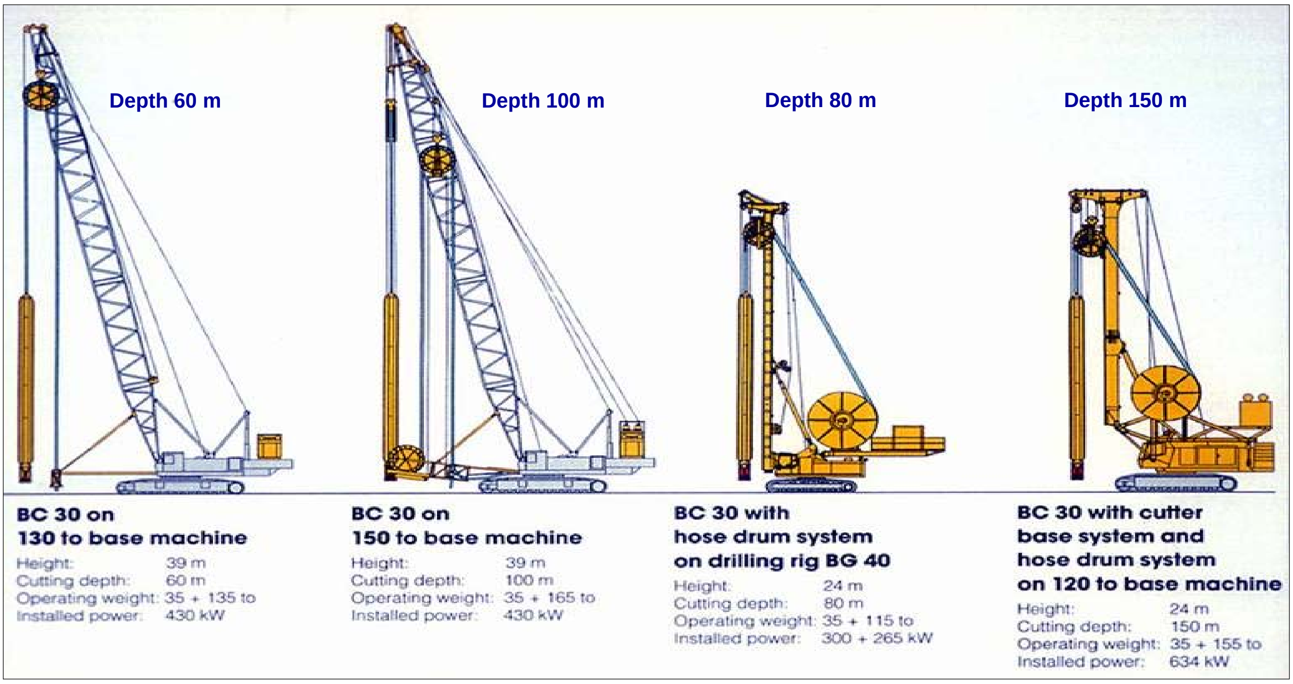
Apart from the wall depth, the strength of the rock, in which the design of wall asked for embedment, was the challenge. The capacity of the base machines to provide hydraulic power was improved to carry heavier cutters and to provide more power to the gearboxes of the cutter wheels. Whereas in the nineties rock strengths of 100 MPa unconfined compressive strength (UCS) was almost the limit for the available cutters, hard rock with UCS of more than 150MPa is being cut by these equipment's since beginning of the new millennium. Ways to successfully and effectively treat and cut cobbles and boulders was developed by BAUER in the last 10 years.

Figure 4. Cutting of cobbles and boulders

2.3 Demand lead to development

With concrete cut-off walls required for dam rehabilitations or upgrading of hydro projects the equipment was modified to reach greater depths.

The development of trench cutters over the last 25 years, with several innovative steps and patents by the leading companies, led to equipment, which today is able to excavate to depths of more than 150m and with individual wheel-sets to cut rock of strengths of more than UCS 180 MPa.



2.4 Wall depths reached

Trench cutters installed the concrete cut-off walls at the Peribonka Dam project, Quebec, Canada for Hydro Quebec and had to reach down to a depth of 116m at the main dam. The deep wall was installed with a BAUER Trench Cutter CBS CBC 135 designed for depths up to 150m.

Figure 5. Trench Cutter at Peribonka Dam Project, Canada 2005

2.5 Rock strengths successfully cut

With innovative developments over the past 15 years the equipment available is cutting rock with unconfined compressive strengths of 180 MPa and more. The installed power permits rock cutting under a cutter weight of more than 50 tons. Rock cutting wheel-sets have been developed for medium to very hard rock.

Figure 6. Wheel-sets (BAUER) for rock-cutting (soft-medium-hard)

Table 1. Rock strengths and sections of cutting through rock

Project, Location	**Rock type**	**max. Unconfined compressive strength (UCS in MPa)**	**Max. depth thru rock cutting**
Hinze Dam, Queensland, Australia	Greenstone-Basalt, Greywacke, Chert	up to 150+	~33m
Peribonka Dam, Quebec, Canada	Granite, Anorthosite	up to 180+	bed rock: ~26m
Dhauliganga Dam, India	Biotite Gneiss, Augen Gneiss	up to 160+	boulders and bed rock: ~24m
Hodges Village Dam, Massachusetts, USA	Gneiss, Quarz mica schist	up to 127+	boulders and ~1,5m bed rock

2.6 Challenging soil-rock formations successfully cut

Installation cut-off walls in mountainous valleys often ask for treatment and cutting of cobbles and boulders. With the experiences from the Dhauliganga Hydro Electric Power project (HEP) and the Peribonka HEP cut-off wall installation in such valleys or even gorges with overhangs and cliffs is now experience-wise and equipment-technological-wise possible.

Figure 7. Boulders at Punatsangchhu, Bhutan

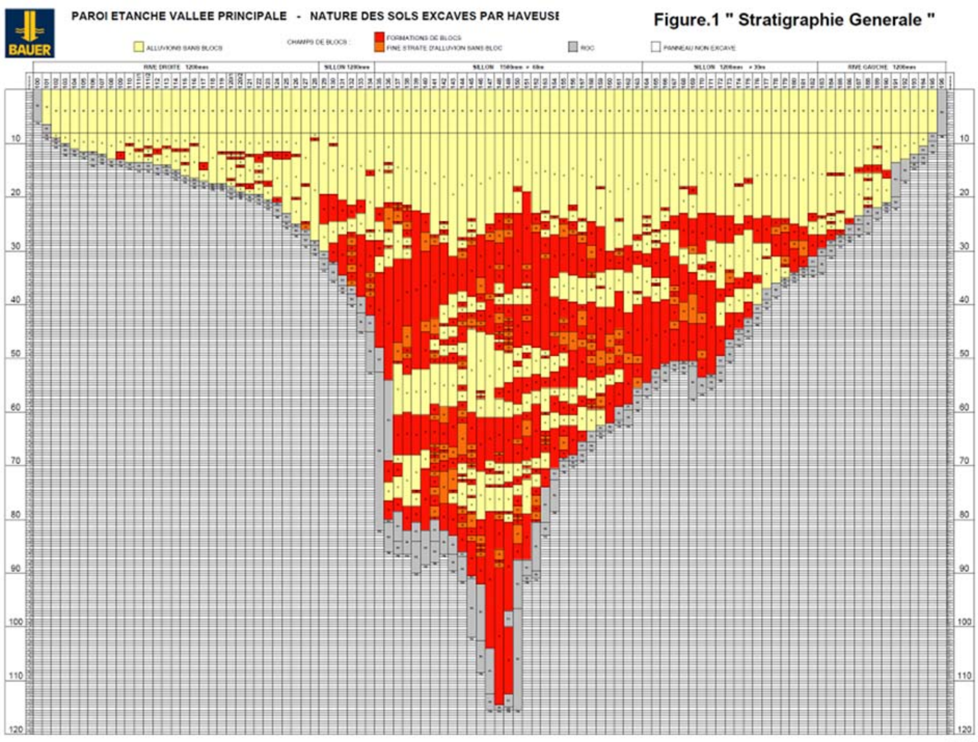


Figure 8. Distribution of **boulders and cobbles** at Peribonka HEP, main valley

For more regarding the successful execution of the cut-off wall at Peribonka HEP please refer to the relevant papers and articles.

2.7 Boulders / cobbles / hard and soft rock next to each other

Not only are boulders and cobbles challenging for execution and for the equipment, similarly are complex geologies with fresh rock and adjacent completely weathered rock in the area of a cut-off wall. The example of the Hinze Dam Project, Australia shows such demanding geological conditions. After proper design and planning, the wall was executed successfully by skilled and well trained staff. Refer also to the paper of Steve O'Brien et al CONSTRUCTION OF THE PLASTIC CONCRETE CUT-OFF WALL AT HINZE DAM .

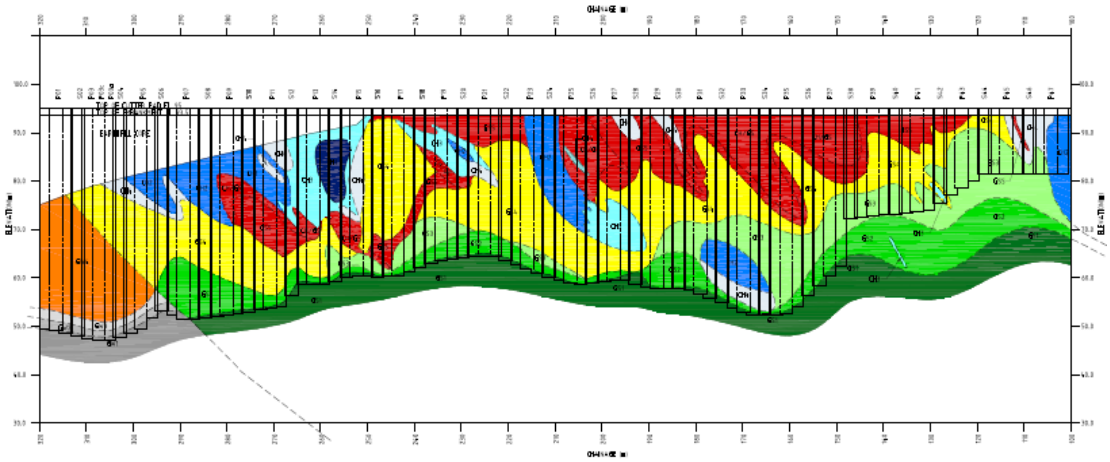


Figure 9. Hinze dam, Australia - geological profile and panel layout at the right abutment (see legend below)

Legend to Figure 9.:

- Basalt/Greenstone – extremely weathered to fresh
- Greywacke – extremely weathered to fresh
- Chert – weathered to extremely high strength

3 Technical requirements originating out of the demand to build at remote locations

3.1 Equipment for remote areas

Challenging geologies and wall depths is one side of the demand for the latest generations of hydro trench cutters. The other side is the location of the project sites. Projects in remote areas are asking for equipment which modularly is able to be dismantled for transportation.

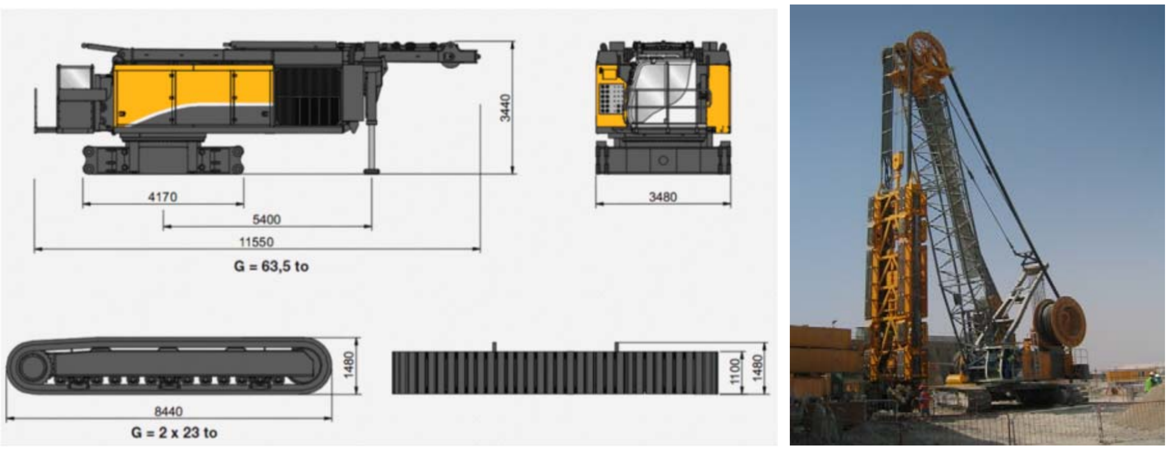


Figure 10. Base machine dismantled for transportation and erected Trench Cutter

The modular character of the main equipment allows access to remote areas, whether it is via small winding roads in the Himalayas or via ice-roads to the Diavik project in northern Canada.

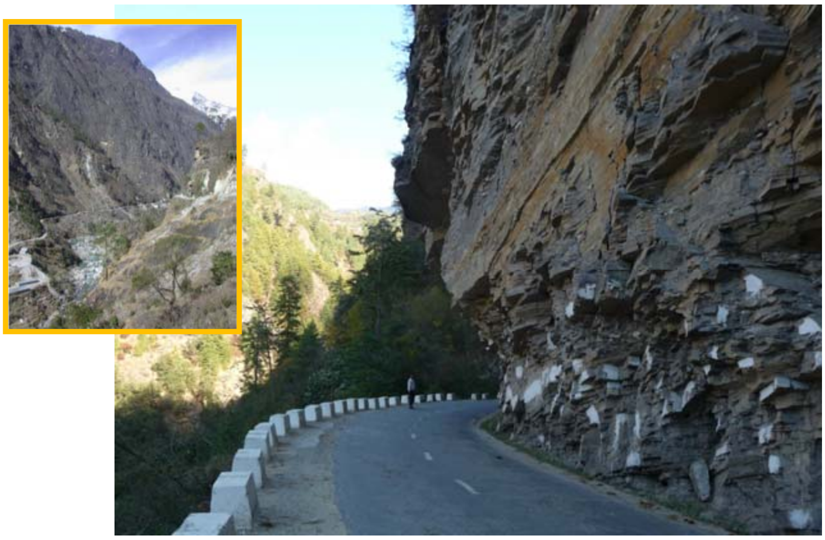


Figure 11. Challenging transportation routes for heavy equipment – Himalaya

Figure 12. Challenging transportation routes for heavy equipment – Canada

The actual generation of hydro trench cutters allows cutting depths of 200m with an improved cutting performance utilizing 60 metric tons cutter weight. Measurement and survey for such depths are being developed as well as control features for wall continuation and successful embedment at the designed depth. The available concrete technology regarding material and installation technique will be improved further with innovative ideas.

3.2 The latest Trench Cutter developments – beyond existing limits

At the BAUMA 2010, Munich the next generation of trench cutter was exhibited, the BAUER Trench Cutter HDS 150 on MC128 with excavation depths of 150m and designed for excavations well beyond this depths.

Figure 13. Trench Cutter at BAUMA exhibition, Munich 2010

4 Concrete for permanent Cut-off walls

Plastic concrete is being installed in cut-off walls by BAUER since 1984. Plastic concrete cut-off walls are designed to provide a defined (shape-wise and material-wise) ductile barrier element for durable seepage mitigation in the foundation of dams. Qualitatywise guiding properties for the design of a suitable plastic concrete mix might be:

- very low Young's modulus (E-modulus)
- moderately low compressive strength
- high strain at failure in confined compressive strength test– low permeability
- definite erosion stability.
- Characteristics of the Plastic concrete could be in the following ranges:
- $E \leq 1000$ MPa (MN/m²) (assessed from the UCS stress-strain graph)
- Unconfined compressive strength of approx. 2 MPa (UCS)
- Permeability (k_f-value) $\leq 10^{-9}$ m/s in the laboratory
- Erosion stability at a hydraulic gradient of $i \leq 50$
- Adequate workability over the required time of installation, not limited to, but at least characterized by consistency, demanding a slump value of 180 to 250 mm, where the target value can be defined more precise after conduction of trial tests with actual ingredients and required composition.

4.1 Plastic concrete for highly ductile walls

The characteristics of plastic concrete in cut-off walls shall meet the requirements of the design for the ductile wall, in particular, as asymmetrical deformations of the COW are to be expected and as open cracks should be avoided which could cause hydraulic instability.
Based on specific design / loading conditions the required properties of plastic concrete differ from project to project but, as a rule of thumb, are quite similar due to given recommendations of the International Committee On Large Dams (ICOLD). For the Hinze Dam Upgrade project, Australia, the following requirements for the plastic concrete have been defined:

- Slump: 190 mm $\leq s \leq$ 250 mm
- Strength: 2 MPa $\leq$ UCS $\leq$ 4 MPa
- Axial strain at maximum compressive strength > 0.6 %, and > 7 % at 50 % of peak
- Permeability: $k_f \leq 1 \times 10^{-8}$ m/sec

A mix design enabling such properties is given in Table 2.

Table 2: Mix Design of Plastic Concrete, example

	mass
Plastic Concrete Mix Design	[kg]
coarse aggregate 5/10 mm	437
sand 0/5 mm	1013
cement	155
added water	172
added Bentonite slurry of …	
- dry Bentonite	46
- water	222
sum computational	2045
dry mass	1651
total water	395
retarding agent (optional)	1.55
water/cement ratio	2.55
moisture content by dry mass	23.9%

4.2 Particular mixing of the concrete on the Hinze Dam project

The Bentonite was premixed as slurry before mixing with dry concrete in truck mixers.
Despite the methodology of concreting a COW does not differ much from the concreting of a Diaphragm Wall in general, still minor effects by special COW conditions like different depth of individual panels in unlevelled rock surface, usually no reinforcement, particular locally available material or the assurance of wall continuity might influence the particular mix.
As the over-cutting instead of working with stop ends and water-stop rubbers should not influence the concreting itself, there is a significant design based difference in construction having no steel reinforcement cage in the trench to be considered.

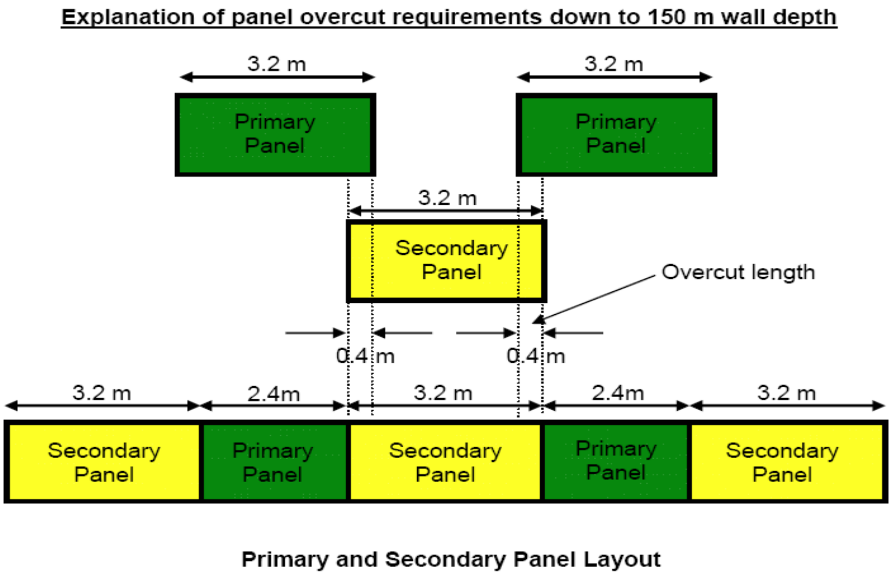


Figure 14. Continuous wall by over-cutting

Not consciously proven, the lack of any obstacles inside the trench may cause a different concrete flow upwards than maybe observed in diaphragm walls. However, at Hinze Dam an obviously too cohesive concrete appeared at the surface of an un-reinforced wall – see Figure 15. This concrete still at the top of the ready installed panel was confirmed to have been from the very first poured batches of concrete in about 50 m depth, proven by using dyed concrete, leading to the hypothesis shown in Figures 16.
Although the plastic concrete was produced using a retarding agent at a lab-tested dosage supposed to ensure slump retardation of several hours, the plastic concrete poured at the very beginning had initially started setting before having risen to the surface.

Figure 15. Up-rising cohesive plastic concrete

A simple and practical test to determine the initial setting of concrete was then carried out on site. The so called 'Knead-bag Test' consists of filling some fresh concrete into a plastic bag and sealing it. With such test the setting behavior can be observed simply 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 as well as the plastic stage which indicates the initial setting when the concrete still 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 not being the main influence for the described occurrence at COW operation at Hinze dam. Dosing more retarding agent up to 2.5 %, related to cement, but less with progressing pouring time (down to zero for the last batch), the concrete rose up still workable.
Primary panels already installed with early setting concrete were proven to be of proper quality by investigating intensively before pouring the secondary panels.

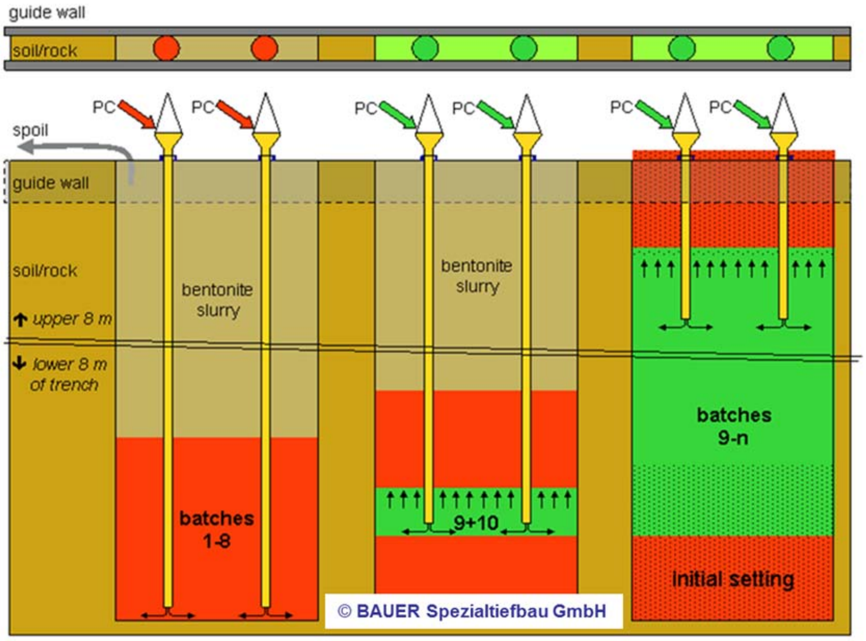


Figure 16. Course of up-rising plastic concrete in relation to batching numbers as found at Hinze Dam

Figure 17. Dyed concrete for testing and confirmation of assumptions. Perfect quality of joints was proven.

5 Project Examples

5.1 Peribonka Dam, Canada

Owner Hydro-Quebec and designer SNC-Lavalin faced problems with water seepage at the 80-m-high dam along the Peribonka River in Québec, Canada. The successfully completed plastic concrete cut-off wall with the exceptional depth of up to 116 m was the solution, but stretched the limits of at the time possible geotechnical construction techniques.

Figure 18. Set-up for cut-off wall at Peribonka dam, Canada

The bedrock underlies coarse highly permeable alluvial deposits, and formed a buried valley with steeply sloped flanks. Granite and anorthosite at the site had measured strengths in the range of 120 to 180 MPa, and occasionally in excess of 200 MPa[1].

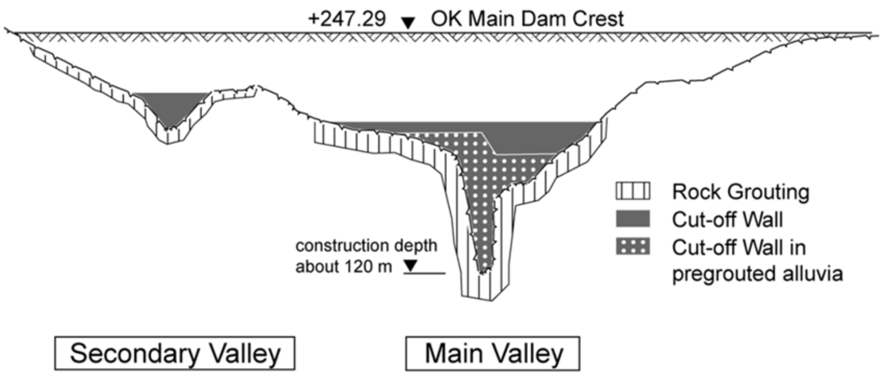


Figure 19. Cut-off wall layout Peribonka

BAUER completed the plastic concrete cut-off wall in October 2006.

5.2 Dhauliganga HPP, India

The key structure of the 280 MW Dhauliganga-1 hydroelectric project (owner: NHPC) in Uttar Pradesh, India is a concrete face rock-fill dam (CFRD). A design was developed for the sealing of these alluvia by means of a very deep diaphragm (plastic concrete) cut-off wall. The head of the cut-off wall is connected to the dam face by an articulated plinth.[2]

[1] Deep Foundations _DFI Spring 2010 Cover story, Peribonka Dam Cut-Off Wall Plunges 116 m Deep at Canadian Site; Sebouh Balian and Mazin Adnan; Spring 2010

[2] Pöyry, Dhauliganga Hydro Electric Scheme, project sheet

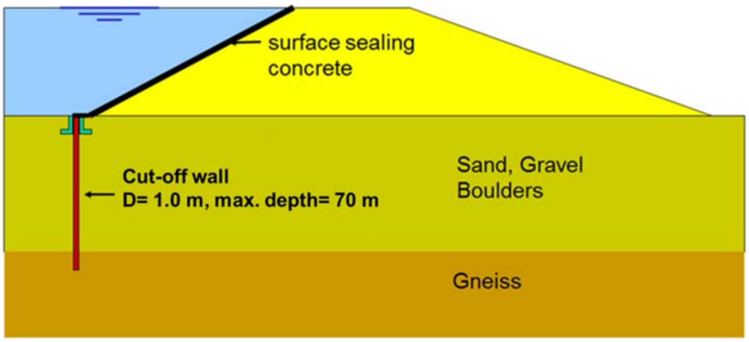


Figure 20. Dhaulingana-1 HEP; schematic dam design

The 7,500 m² plastic concrete cut-off wall of 1,000 mm thickness has a depth of up to 75 m and is embedded into the granite and gneiss bedrock. The works have been executed with a BAUER cutter BC40 in 2003.


Figure 21. Site set-up for cut-off wall at Dhauliganga-1, India

5.3 Center Hill Dam Foundation Remediation, USA

In September 2011 the U.S. Army Corps of Engineers (USACE), Nashville District awarded the installation of a barrier wall.
"This important construction will provide a barrier to protect the earthen portion of the main dam from seepage problems. The barrier will significantly improve the long-term reliability of the dam and public safety" said USACE-Project Manager Linda Adcock.


Figure 22. Center Hill Dam - aerial view

A concrete cut-off wall will be built within the entire length of the embankment dam. The wall will extend up to 95 m depth into the limestone foundation to cut off seepage and stop erosion.
The USACE design asks for an encasement wall with a thickness of 2.25 m in the upper part and a barrier wall 800 mm into the lower part and final depth.

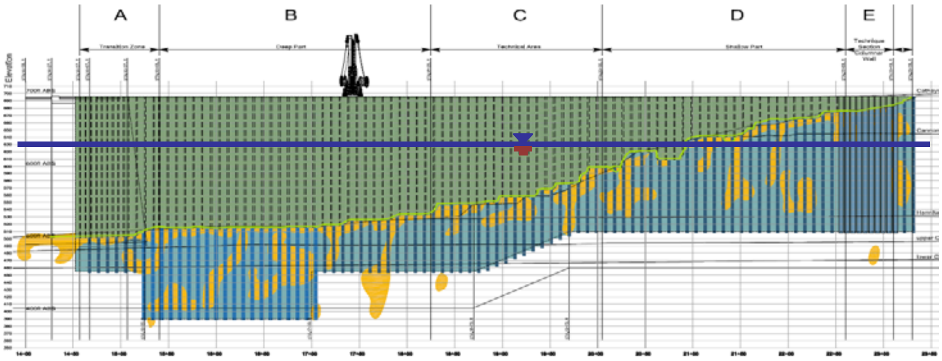


Figure 23. Center Hill Dam - barrier wall

5.4 *Punatsangchhu-1 HPP, Bhutan*

In order to enable the works for the roller compacted concrete main dam for the Punatsangchhu-1 hydroelectric project the main contractor Larsen&Toubro had to divert the river into two tunnels. Coffer dams at up- and downstream of the location for the main dam are under construction.
The seepage under the upstream coffer dam will be stopped by a plastic concrete cut-off wall. Because of the difficult colluvial material in the deep valley and the nearly 100 m deep excavation pit, which will be required for the main dam, the owner Punatsangchhu Hydropower Authority (PHPA) decided to replace the initially tendered Jet Grouting curtain by a positive cut-off wall executed with a trench cutter.

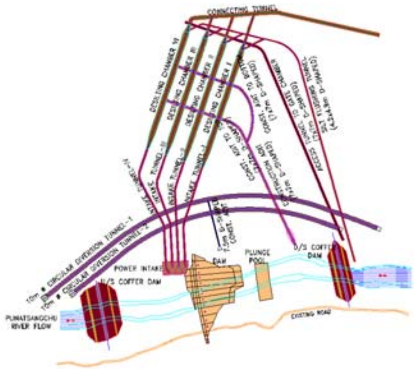


Figure 24. Punatsangchhu-1 HEP, concept design, PHPA

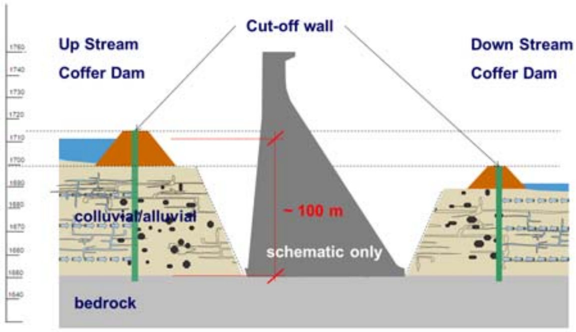


Figure 25. Schematic design Punatsangchu-1 dam

All equipment including a MC128/BC50 BAUER cutter unit has been mobilized and execution of the works will be completed in 2012.
The wall will extend from the working platform up to the alluvium/bedrock with a minimum of 500 mm into the bedrock to ensure proper sealing of the contact zone between cut-off wall and bedrock. The length of the cut-off wall is approximately 170 m and its nominal wall-thickness will be 1200 mm. The maximum depth will be approximately 75 m.

6 Conclusions

With experience developed over 25 years in barrier wall and more particular concrete cut-off wall execution by trench cutters and with the latest generation of hydro trench cutters, concrete cut-off wall installation for seepage-mitigation and -control by such barrier walls is available for the demand of deeper walls through existing embankment dams and pervious foundations into impervious rock as required out of dam-heightening for the upgrade of dams.

A cut off wall, consisting of a defined plastic concrete element, is an economical and reliable solution as seepage barrier wall both for temporary and permanent requirements.
Today available trench cutters are both modular transportable, capable to cut very hard rock and reaching practically any required depth.
Likewise installation of the required barrier wall for new dams, whether under the dam or for the cofferdams, is available – if required also for walls installed through boulders, in gorges along cliffs and overhangs and into fresh bedrock, all with rock strengths of UCS of 180+ MPa.

Regarding specific tasks like embedding into extremely hard rock, cold joints between primary and secondary panels or quality assurance for plastic concrete, the combination of preplanning and finding suitable project designed measures is effective to ensure proper executing of cut-off walls even under critical conditions.
A cut-off wall is a defined geometric body with high erosion stability and therefore very low overall system permeability in the order of $10^{-8}\ {}^{m}/_{s}$ can be assumed.
Eventually the use of cut-off walls (COW) as a sealing wall in dam foundations proves to be a safer design practice, in comparison to alternative construction solutions such as grout curtains. The experiences and the techniques are at hand to increase reservoir capacity environment- / nature- and sociopolitical-friendly. It's up to the planning engineers to use this experience best.

The time required for the installation of a cut-off wall can be reliably determined. With a cut-off wall all voids and fissures in the soil are intersected and such a wall is acting as a continuous sealing membrane.

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Author's introduction

Peter Banzhaf, Diploma Civil Engineer studied in Munich, Germany. He is a Project Director in BAUER Spezialtiefbau, Germany working for the company since more than 25 years. He is primarily focused on barrier wall construction and management. As a director Peter Banzhaf has managed specialists department in BAUER Spezialtiefbau GmbH (BST) executing more than 2,000,000 m² of diaphragm and Cut-off walls until 2001. Peter Banzhaf is Head of Dam services in the BST. In the past 20 years his job responsibilities have required him to work for BAUER on projects in many parts of the world. In 2007 e.g. Peter Banzhaf provided high quality consultancy services to URS for barrier wall construction at Hinze Dam Upgrade, Australia. At present Peter Banzhaf is the Project Superintendent on the USACE Project Center Hill Dam Remediation.
Peter Banzhaf is a Member of ASDSO since 2008, a Member of USSD since 2009 and member of the German ICOLD member DTK.