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ABSTRACT

Karkheh dam cut-off wall with an area of about 150000 m^2 is the largest plastic concrete cut-off wall ever built in the world. The wall was designed on the basis of seepage and material behavior analysis. The design and construction of the wall was a great challenge in which in different stages, major design modifications were made based on existing construction facilities, updated geological conditions and cost optimization. The philosophy of "design as you go" was tried to be perfectly accomplished in this project.

The cut-off wall connections to the dam body and other appurtenant structures such as power tunnels; diversion culvert and spillway were designed and constructed to provide a tight and deformable interface.

In this paper, the analysis results are briefly described. The technical specification of execution and material is also summarized.

INTRODUCTION

Dam foundation water tightening is applied to control seepage and to reduce uplift pressure under the dam and appurtenant structures, to prevent sliding of downstream structures on weak ground layers. Grout curtain and cut-off wall are two conventional methods for water tightening of large dam foundations.

The most common method used to seal the rock foundation is grouting. Where the foundation of a dam consists of pervious alluvial layers, grouting methods such as sleeve pipe, jet grouting and chemical grouting are successfully employed. As an alternative cut-off walls can be used in the cases of alluvial or weak porous rock foundations.

Cut-off wall is performed as an underground seepage barrier to control underground water flow. The selection of material is based on the anticipated wall performance, construction facilities and the surrounding ground specifications. The large domain of cut-off wall material includes compacted impervious soil, reinforced soil, soil-bentonite, soil-cement, cement-bentonite, soil-cement-bentonite, plastic concrete, conventional concrete and reinforced concrete. In addition, in some recent cases usage of materials such as geosynthetic, asphalt concrete and mixed soil are reported which are not very common yet. Besides, sheet pile wood, plastic or metal material has been seldom practiced for shallow cut-off walls (Bachy Soletanch, Castle Cement, Rodio,1995).

The need for Cut-off wall to cover a sufficient chemical, physical and mechanical durability for the structure's life time requires that the cut-off wall be adequately non-erodible against impressive water flow. It should be resistible against hydraulic fracturing in during the impoundment and operating period (Shadravan, 1996).

Its stability should be accomplished against subjected loads comes from dam body, other structures, impounding and earthquakes. It should be designed in such away that can tolerate all induced deformations caused by settlement of adjacent foundation. Therefore the material is intended to have similar deformability with respect to surrounding ground and satisfactory strength for stability against exposed loads.

The design and construction of a cut-off wall are mutual, *i.e.* in designing a cut-off wall, the construction method must be considered. There are many methods and related equipment for cut-off wall construction.

The essential reason for progress of the method has been presented as the development of excavation (cutting) equipment with the slurry wall method. There are numerous equipments but the most common practiced equipment has reported as backhoe, Clamshell and Hydromill (Hydrofraise). The last one is a modern cutter that has correspondingly high precision and speed. However, it has been accounted as an expensive technique. It has been used in two phase construction method.

KARKHEH STORAGE DAM

Karkheh dam and hydropower project is constructed on Karkheh River, the third largest river in Iran, located on north of Khuzestan province at southwest of Iran. With a body volume of about 33 Mm^3 and the useful reservoir capacity of 5,600 Mm^3, Karkheh earthfill dam is the largest in Iran. The dam height over foundation is 127 m and the crest length is 3,030 m.

The project includes the embankment placed across the Karkheh River, a power house with total installed capacity of 400 MW, at the left abutment and a gate-controlled chute type spillway with a crest width of 110 m and length of 955 m located at right abutment (Fig. 1).

Iran Water and Power Resources Development Company, IWPC, is the project client. Mahab Ghodss Consulting Engineers was the consultant part in designing and construction period. A variety of contractors were involved in the project. The dam body, spillway and cutoff wall construction was accomplished by Sepasad Engineering Company.

The dam foundation water tightness is mostly achieved by means of a cutoff wall. The characteristics of the cut-off wall material (plastic concrete) were assigned in such a way to ensure the required impermeability, deformability and strength. The final wall surface area is about 150,000 m^2. The depth of the wall in deepest section is about 80 meters while the average of depth is about 50 meters. With a length of 3030 m, it was vertically built in the dam foundation along the dam axis. The wall thickness is 1 meter at valley section and right bank. At some locations of left bank the thickness of the wall is chosen to be 0.8 m. The cut-off wall intersects the major appurtenant structures of the dam *i.e.* hydropower tunnels, spillway, and diversion culvert. Therefore special arrangements and detail design were performed to establish a tight and deformable contact joints.

GEOLOGY

The dam is placed on poor to fair permeable conglomerate beds, which are slightly-moderately cemented. The overall permeability of the conglomerate is estimated to be in the relatively high range of about $4\text{-}9*10^{-4}$ m/s mainly caused by the zones of discontinuity and open frame work gravels. The impervious horizontal mudstone layers stratify the conglomerate with 3 to 9 m thickness, estimated permeability of about 10^{-7} to 10^{-9} m/s, which are bedded horizontally in area of the project. Geotechnical investigations and observations were indicated that these layers are enough continuous at the location of dam to provide different strata for each conglomerate layer confined by mudstone layers. Site investigations determined that the lower mudstone layers can be regarded as an impermeable layer. So the natural extensive and continuous layers act as an upstream impervious blanket.

The unconfined strength of the foundation conglomerate has been determined to be in a range of between 10 to 100 kg/cm^2 (1 to 10 Mpa)

BACKGROUND AND CRITERIA

In different stages, major design modifications were made based on existing construction facilities, updated geological conditions and cost optimization. In Karkheh Dam project, the designer of the dam was responsible for supervision of the construction. Therefore, the philosophy of “design as you go” was tried to be perfectly accomplished.

Due to the high permeability of conglomerate layers, a vertical foundation water-tightness system is required to control water flow to downstream, to reduce exit hydraulic gradient, to prevent high measure of leakage, to decrease the uplift pressure, and finally to provide associate stability of the dam body and hydraulic structures (Shadravan , 2003).

Phase I Investigations

In phase I study of Karkheh Dam project, a grout curtain was considered as the main anti-seepage measure of the dam foundation for several reasons, such as the availability of the technology, lack of other suitable technique in the country, anticipating higher speed, and lower cost of the method than the other methods.

As it is necessary for large projects to perform a field grouting test to determine the groutability, borehole spacing and suitable grout pressure. A series of comprehensive cement based grouting test including single hole and multi-hole test was carried out. Results of these tests showed even by using super-fine cement with Blaine value of about 8000 cm^2/g a continuous grouting curtain as an anti-seepage measure could not be achieved. Only the grouting of highly permeable zones (open framework gravel) was satisfactorily done.

As a result, a plastic concrete cut-off wall was used as the main measure for the foundation treatment of Karkheh dam project.

The Preliminary Cutoff wall Design

In common, cutoff walls are usually considered in soft soils, while Karkheh dam foundation is highly permeable weak rock and contains different layers and properties of materials.

In order to design the Karkheh Dam project cut-off wall, various construction methods were studied. Inquiry in design phase showed that the most suitable construction method is two-phase panel excavation method executed by Hydromill equipment. This method was preferred because of the special situation and configuration of the stratified weak rock foundation of Karkheh

Dam, the need for rapid and precise excavation procedure and required high depth of the wall. The first design was planned based on the maximum depth of 60 meters because of the limitation of the only available Hydrofraise machine in the country. The design included the execution of wall at right and left abutment by clamshells to a maximum depth of 20 meters.

The presence of conglomerate with relatively high permeability between mudstone layers, suggests that the reservoir water will seep downstream through the conglomerate. The cut-off wall construction across the water path will reduce seepage and prevent the increase of hydraulic gradient. Thus, the preferred water path will be longer and lead to reduction of water pressure downstream from the wall.

At different locations of dam, the depth of wall is determined with respect to seepage analysis, construction ability and economical factors (Fig. 3). Site investigations have indicated that mudstone (-2) with thickness of 3 to 9 m can be regarded as an impermeable layer. On the basis of these information, the outcrop of this layer is estimated at a distance of 4 km upstream and downstream of dam axis. So the 8 km natural extensive and continuous layer acts as an upstream impervious blanket. Therefore, along the dam axis at critical section (river valley), section, cut-off wall is proposed to be connected to impermeable mudstone (-2) in order to have a positive cut-off wall.

Finally, the cut-off wall was designed to be connected to the highest mudstone layers (mudstone No. [+3]) at the most part of right abutment. At the left abutment mostly the cut-off wall is suspended in conglomerate above mudstone No. [+4] (Fig. 3.).

Top of the cut-off wall was planned to insert 2 to 8 meters into the dam core. The insertion height is designed based on the existing hydraulic gradient and minimum required seepage path at the core-wall contact.

The inspection gallery was constructed in the dam foundation, downstream of the cutoff wall, parallel to the dam axis to install instrumentation and drainage holes and to enable necessary remedial measures of the dam and foundation during dam operation(Pakzad, 2001).

The Cutoff Wall Connection to the Dam Body

Special detailed design is required in the connection zone between the foundation and the dam body in order to facilitate better loading distribution and to prevent occurrence of incompatible deformation.

In the original design, it was assumed that the pure clay (mudstone) material would be used in the impervious core. The design was revised and it was decided to place a mixture of mudstone (60%) and conglomerate (40%) in impervious core. Comparing to pure clay, the mixed material provides slightly higher permeability coefficient, higher shear strength and higher deformability modules (lower deformability). At the contact of impervious core with the foundation and plastic concrete cut-off wall still pure plastic clay material (wet side of optimum) with a minimum thickness of 1 m was used (Fig. 2.). This has been done to ensure adequate seal, proper load transferring and decreasing the possibility of cracking.

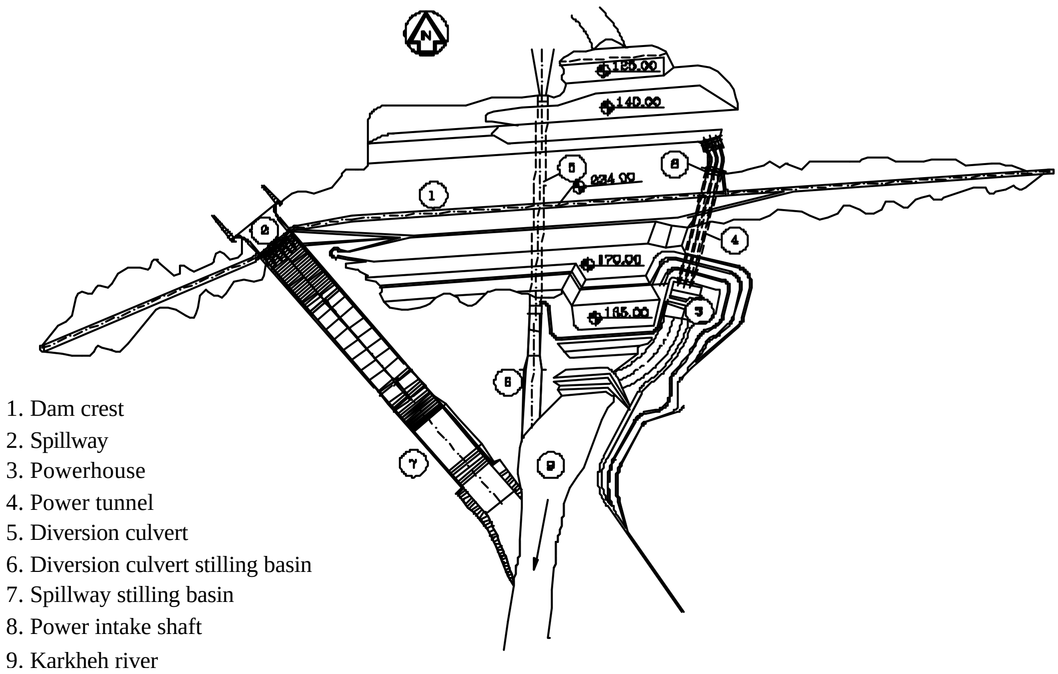
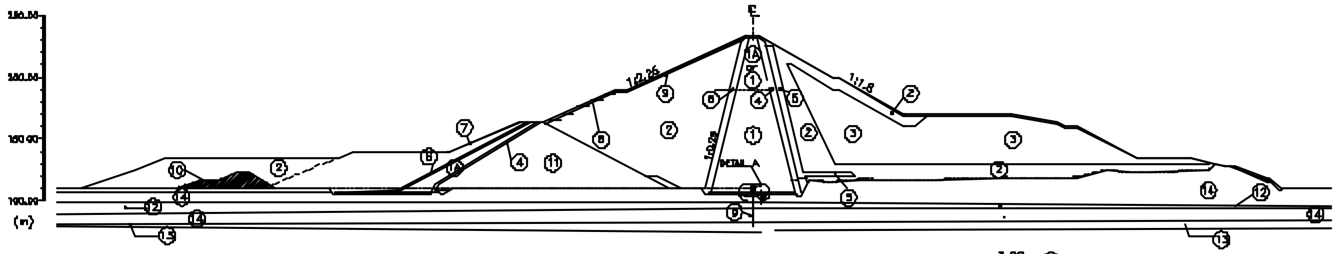
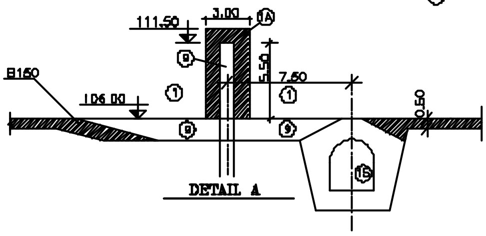


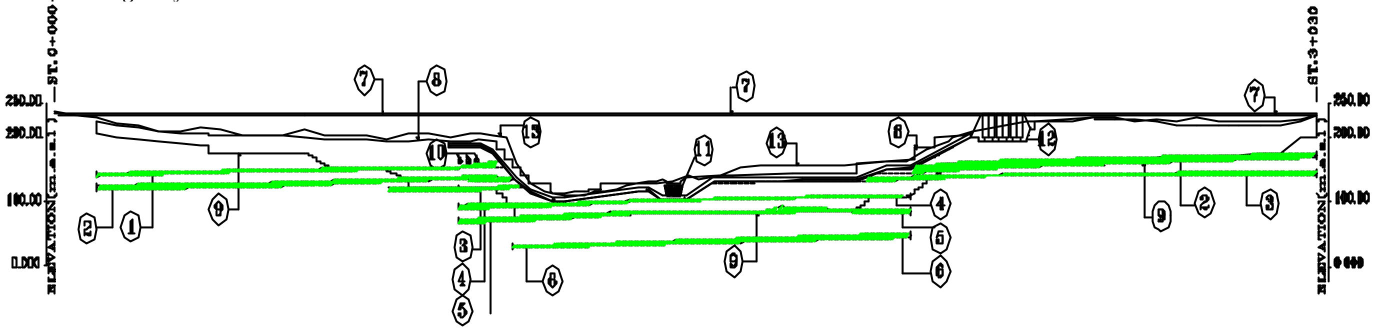
Fig. 1. General plan of Karkheh dam project





1. Impervious core (mudstone mixed with sandy gravel)
1A. Impervious core (mudstone)
2. Sandy gravel
3. Conglomerate or sandy gravel
4. Sand filter
5. Gravel filter and drain
6. Sand-gravel filter
7. U/S slope protection using limestone riprap
8. U/S slope protection using soil cement
9. Plastic concrete cut off wall
10. Pre-coffer dam
11. Main cofferdam
12. Mudstone no. (-1)
13. Mudstone no. (-2)
14. Conglomerate
15. Inspection gallery

Fig. 2. Dam cross section in river channel



1. Mudstone no. (+4)
2. Mudstone no. (+3)
3. Mudstone no. (+2)
4. Mudstone no. (-1)
5. Mudstone no. (-2)
6. Mudstone no. (-3)
7. Top of dam crest el. 234
8. Top of cut-off wall
9. Bottom of cut-off wall
10. Power tunnel
11. Diversion culvert
12. Spillway
13. Original ground surface

Fig. 3. Dam longitudinal section

Furthermore, a 1.5 meters depth horizontal plastic concrete layer was placed in the connecting zone between the core and foundation. It creates a plastic concrete pad in the critical part of the cut-off wall connecting to the clay core. By increasing the seepage path, the induced hydraulic gradient is brought to the allowable limit. In case of any probable crack in the wall at the insertion part into the core, it is designed to act as a second line of defense against the existing hydraulic gradient.

Increasing Depth of The Cutoff wall

The first part of the cut-off wall was completed under the diversion culvert. After successful construction of this part, it was determined to accelerate the cut-off wall construction. Hence, another hydromill machine was required. Since the completion of the cut-off wall was in the critical path of dam body construction activities, it was decided to prepare an equipment with higher capability of cutting speed and depth. The selected hydromill machine (BAUER BC30) was able to execute the wall up to 80 meter in depth. Therefore, with this new facilities the cut-off wall was extended in some areas in left and right abutments according to the new obtained geological information.

<u>The cutoff wall connection to other structures</u>

The cutoff wall connection to appurtenant structures, such as diversion culvert, spillway and power tunnels, required particular considerations. The connection zone is considered as a transition between the soft plastic concrete of cut-off wall and the relatively rigid conventional concrete of the structure.

The contact joint was designed in such a way to prevent cracking and to provide enough sealing using concrete keys and plastic watertight material (Fig.4.).

The neighboring cut-off wall at contact with spillway and diversion culvert was strengthened by steel reinforcement. At the contact zone with waterpower tunnels, the surrounding rock was consolidated using contact grouting to achieve appropriate connection.

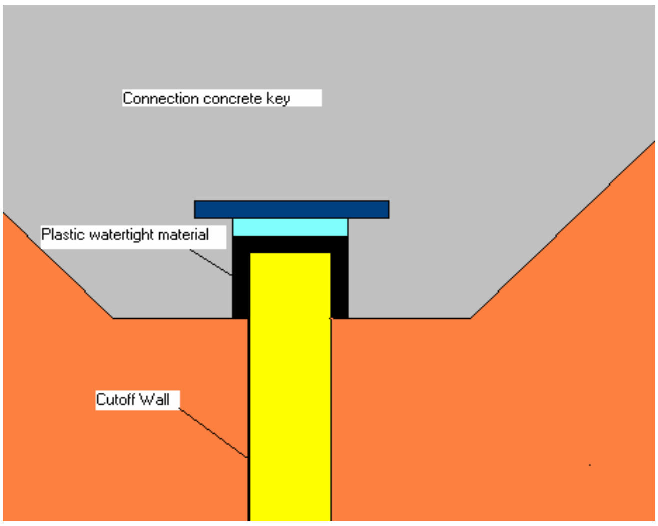


Fig. 4. Schematic picture of the connection between the cut-off wall and other dam structures such as diversion culvert, spillway and power tunnels

SEEPAGE ANALYSIS

The cut-off wall material controls leakage of the dam foundation in an acceptable measure. The dam body and foundation seepage analysis were carried out by the SEEP program prepared based on FEM. The liquid phase continuity, following of the water flow by Darcy law and anisotropic soil media were among the assump tions employed in the seepage analysis.

The entire permeability of the cutoff wall is dependent to the material specifications. The plastic concrete material was suggested to have a permeability of less than 10^{-9} m/s. The practical net permeability in other projects has been reported to be 10 times of the produced material. Thus the calculated net permeability was assumed to be 10^{-8} m/s.

For left and right banks, seepage analysis was made to determine the minimum necessary depth of cut-off wall. The design criteria were to achieve permissible exit gradient. The extent of the cut-off wall laterally and vertically has been designed with a balance among the following factors:

a. foundation seepage gradient in every where lower than 0.2
b. construction limitation (max. 80 m depth)
c. reduce seeping water with respect to economical justification and the dam construction aims

Totally nine two-dimensional vertical sections at various locations of dam body at river valley, left and right abutments were selected and analyzed. Figure 5 describes the results of seepage analysis of critical vertical section at station 1+200.

The presence of conglomerate with relatively high permeability between mudstone layers, suggests that the reservoir water will seep downstream through the different conglomerate layers by rounding the cut-off wall. Therefore seepage analysis was carried out using two dimensional horizontal sections at various conglomerate aquifers. Figure 6 shows the result of seepage analysis including the velocity vectors and equi-potential lines for conglomerate layer between mudstone (+2) and (-1) at right abutment.

The result of seepage analysis showed that this measure is able to reduce remarkably the seepage quantity and exit hydraulic gradient.

MECHANICAL DESIGN SPECIFICATION

The detail mechanical specifications of Karkheh dam plastic concrete cut-off wall are reported by Mirghasemi and Moshashai (2001).

<u>Deformability</u>

In addition to seepage quantity and gradient reduction, the cut-off wall should behave in such manner that no crack is induced as a result of imposed loading. It means a material is required that is able to follow the deformation imposed on the soil without breaking up. The deformation can be induced as a result of dam gravity force, non-homogeneous or homogenous foundation settlement, reservoir impoundment loading and the earthquake loads. As the foundation undergoes the settlement, the wall should be able to tolerate the deformation. Subsequently, the deformability properties of the ground are one of the most important parameters considered to select the proper deformability properties of the cut-off wall.

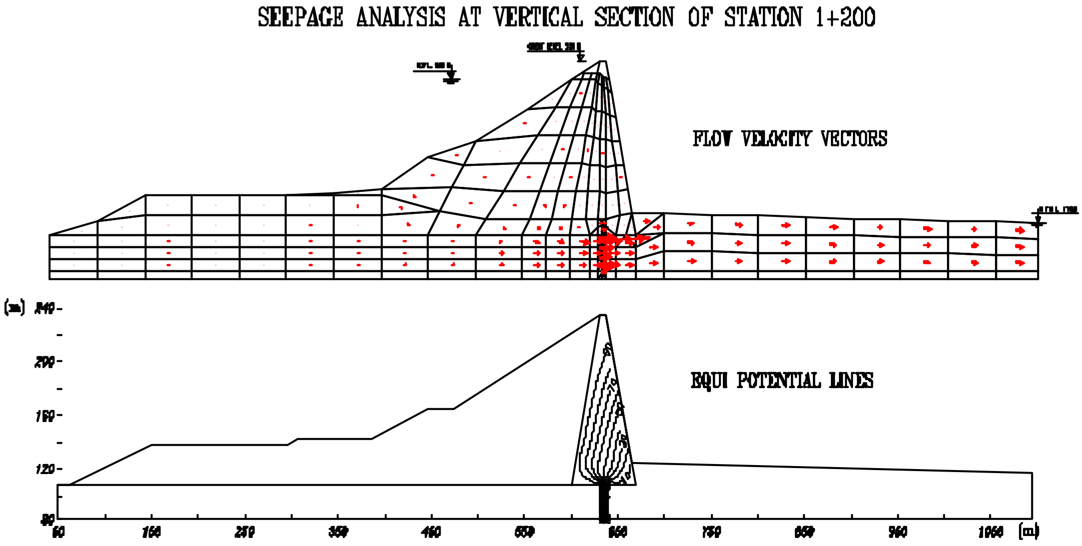


Fig. 5. Velocity vectors and equ-potential lines derived from seepage analysis at critical section (Station 1+200).

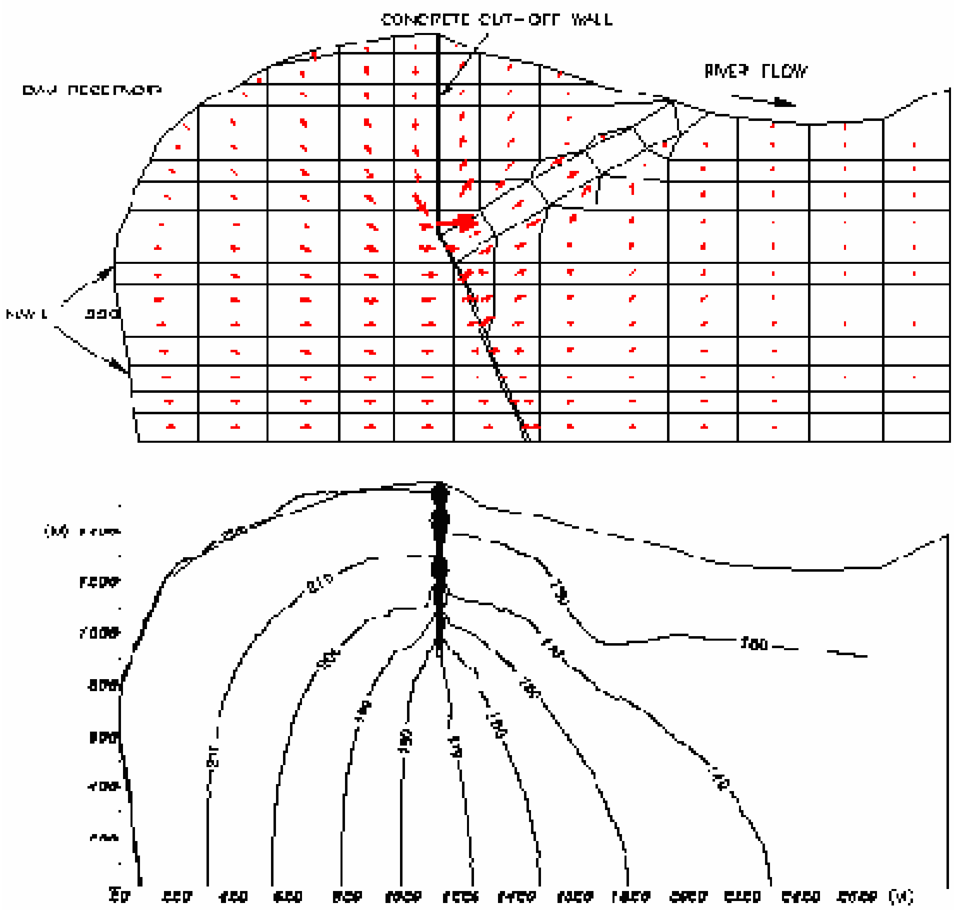


Fig. 6. Result of seepage analysis including the velocity vectors and equi-potential lines for conglomerate layer between mudstone (+2) and (-1) at right abutment.

The plastic concrete has a significant deformability to withstand the different loading conditions. The ideal condition is that all mechanical properties of plastic concrete, except the permeability should be very similar to those of foundation material. Due to broad variation of foundation properties, this criterion can not be always satisfied. ICOLD (Bulletin 51, 1985) indicate that a material having a deformability modulus 4 to 5 times greater than the surrounding soil is suitable.

Based on above considerations, the elasticity modulus of plastic concrete for Karkheh Dam project is determined to be between 20,000 to 50,000 kg/cm^2. The elasticity modulus of conglomerate is ranging between 5,000 to 23,000 kg/cm^2.

Strength

Generally, great strength is not required because the wall does not have a load-carrying role. On the other hand, strength and deformability are closely related. Therefore, to obtain a high deformable material, the possible lowest compressive strength is desired. However, the material should sustain the different loading conditions during construction, first impounding and reservoir operation. Besides that, the resistance to erosion due to high hydraulic gradient is directly related to compressive strength (Mirghasemi, 1999). To satisfy above criteria, the minimum compressive strength (28 day) of plastic concrete is recommended to be 30 kg/cm^2.

Mechanical Analysis and Specification

As mentioned before, the dam has a non-homogeneous and complex foundation. The dam foundation consists of horizontally stratified layers of conglomerate and mudstone.

The conglomerate itself is a non-homogeneous material. The average unconfined strength of the conglomerate is about 2-5 Mpa and the average modulus of elasticity of 500-2300 Mpa.

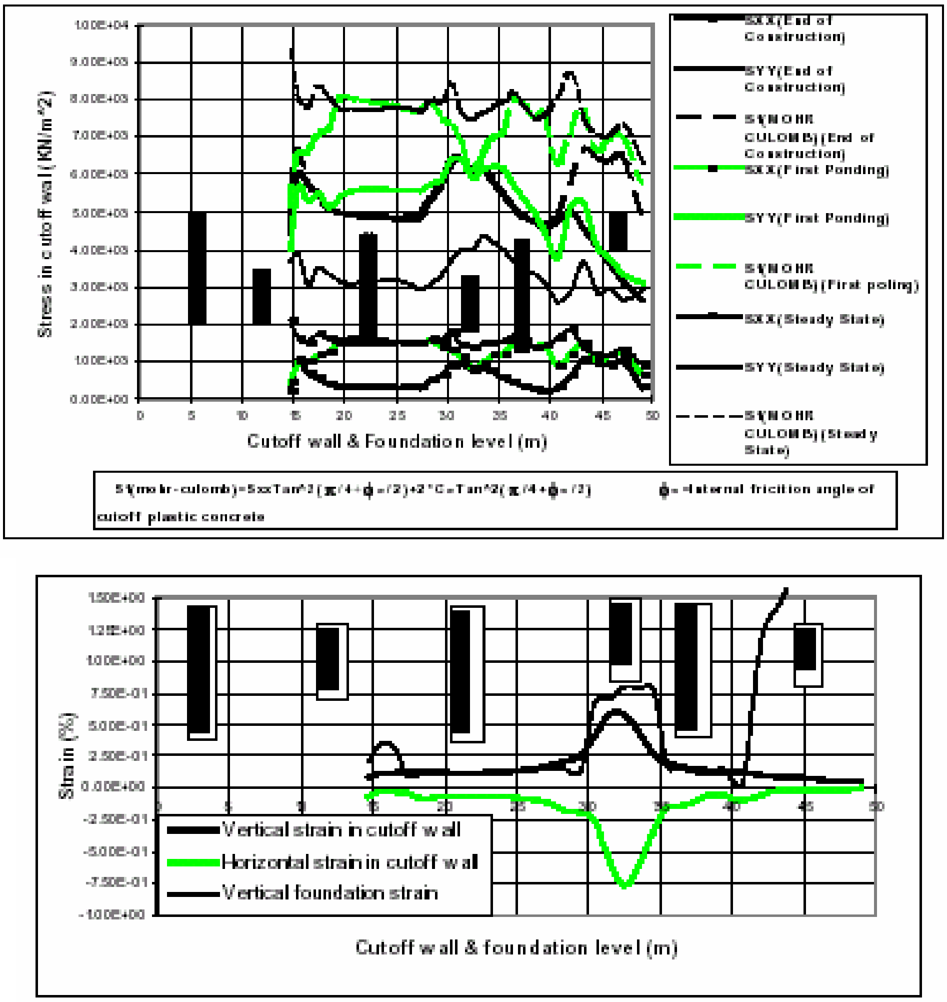


Figure 7: Result of wall–foundation numerical analysis
(a) Predicted wall stresses under different loading conditions.
(b) Predicted wall strains at wall-foundation contact at different levels.

The conglomerate itself is a non-homogeneous material. The average unconfined strength of the conglomerate is about 2-5 Mpa and the average modulus of elasticity of 500-2300 Mpa.

Using a finite difference and nonlinear program called CA 2 (Fakhimi, 1998), an investigation was made to study the interaction of the wall and its surrounding stratified rock (especially at weak rock contacts). The analysis was performed at different loading conditions such as end of construction, first impounding and operation period. The effect of material modulus of elasticity, strength and wall-rock contact conditions on resulting wall stress and strain were investigated in this study.

The main conclusions derived from this study are summarized as follows (Shahbazian Ahari, 1999):

- The cutoff wall strain relatively follows the foundation strain. It means no significant shear rupture at the wall-foundation contact was anticipated (Fig. 7).
- In case of shear rupture at the contact, the induced wall strain was reduced.
- The high strength of cut-off wall material decreases the wall deformations.
- High shear rupture occurrence at the contact leads to nailing of core by cut-off wall. Therefore, in this case, it was suggested to use alternative methods for lengthening the seepage path instead of wall insertion into the core.

DETAIL CONSTRUCTION SPECIFICATION

The cutoff wall construction has a repeating process panel by panel and needs continuous precise inspection. An overview on the construction specifications is summarized here for the Karkheh dam cutoff wall (Shadravan, 1999).

Material

Plastic Concrete mixture was predicted to be bentonite or other special additives added to the usual mix materials of concrete.

The plastic concrete was specified for both upper and lower limitations of deformability and strength. As the plastic concrete properties are very sensitive to its components quality, some specifications were measured for components quality and quantity.

Physical and chemical properties of components of plastic concrete (including water, bentonite, cement and aggregates) were specified as the API and ASTM standards. The repetition of the tests was anticipated for the construction period.

Allowable weighting error for the components was considered less than conventional concrete.

Portland cement type V was noticed to be applied to avoid the destructive effects of sulfate compounds of the water and ground.

The limitation for aggregates maximum size of 2 cm was selected to prevent separation and segregation of plastic concrete, when placed by tremmie tube method.

The fresh plastic concrete is specified with a high slump of 16 to 22 cm just before concreting to achieve high workability. Because of tropical climate, maximum temperature of 30^o C was specified for pouring fresh concrete.

Platform

A temporary compacted soil platform with minimum 1.5 meters thickness was made for each construction stage of the wall in the dam body area. The main reason was to prevent dam core quality problem, undesired high compaction (via transporting of heavy excavators and truck mixers and backhoes and …), contamination with slurry, machine oils and plastic concrete. The cutoff wall guide walls had to be constructed in the platform layer.

To avoid entering water into trench and plastic concrete when constructing, the underground water level limited to be minimally 2.5 meters lower than platform top level.

After completion of the cut-off wall, the whole constructed platform, the upper part of the core (0.5 m in thickness) and upper part of the wall were removed. This was done to ensure appropriate core specification and remove the part of the wall that might be contaminated by the excavation slurry. Besides, other construction facilities were also provided to avoid contamination of the dam body and other structures.

Excavation

Special precision was anticipated for construction of the high depth panels.

Overlap between panels was created to avoid separation of the adjoining panels in the depth. The allowable deviation was considered to be less than 0.2% according to the cutoff wall technical specification.

Where the cut-off wall was connected to the mudstone layers, the depth of insertion was designed to be at least 2 meters to block the water flow during the dam operation.

Limitations were dictated for the excavation slurry properties in fresh condition, during excavating and after-excavating stages to accomplish adequate function and minimize the joints thickness.

For enhanced appliance, the slurry was mentioned to be mixed more than 10 hours before excavation.

The slurry requires low viscosity (for high workability), certain density (to overcome trench collapse and underground water flow), low sedimentation (to decrease thickness), suitable cake (to make trench wall diaphragm), sufficient stability and proper alkali (ph).

It is determined that If the trench demonstrates a high slurry loss, the trench had to be backfilled with soil or plastic concrete to avoid trench wall drop or collapse. After a minimum of three days, the cutoff wall was allowed to excavate again.

The time between excavation and concreting was limited to avoid trench wall drop or collapse. Also there was a time limitation between completion of primary panels and excavation of secondary panels to decrease the joints thickness. Before and during concreting, the depth of the trench was checked repeatedly to control the slurry sedimentation or possible flocculation and trench wall collapse.

Concreting

The concreting duration was expected to be minimal to pass up concrete hardening during concreting. Additionally, tremie tube method for concreting needed special care. For instance, the tube bottom must be in concrete more than three meters during concreting for preventing mixing slurry with the concrete.

CONCLUSION

The Karkheh dam cut-off wall design and construction procedure was based on performed analysis, compatibility with the most important standards and codes (ASTM, API, DIN, BS, EUROCODE), recommendations (USBR, ICOLD, PCA), experiences published in the papers and updated conditions of the site project.

The design and construction experience was discussed in technical national and international workshops and panels.

The dam cutoff wall showed satisfactory performance after four years of impounding according to information provided by the installed instrumentation.

The successful design and construction of the Karkheh dam cutoff wall convinced the cutoff wall via cost, construction, period and e ngineering specification. This means that cutoff wall can be assumed as an alternative for seepage control of weak rock foundations of large dam (Mirghasemi, 2002).

ACKNOWLEDGEMENT

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