The world's largest cutoff wall at Karkheh dam

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The Karkheh dam cutoff wall, with an area of about 190 000 m^2, is the largest plastic concrete cutoff wall in the world to be built as a dam sealing measure. With the new proposal for its extension, its area will be increased to about 350 000 m^2. This article briefly describes the design, construction and the performance of the wall.

Plastic concrete cutoff walls have been used for some three decades following the development of various techniques for constructing underground diaphragms, which can be convenient and economical. Diaphragm walls are generally excavated in panels, with the excavated area supported by bentonite slurry. The first reported application of plastic concrete was for the cutoff of the Santa Luce dam in Italy in 1959 [Xanthakos, *et al.*, 1994[1]]. This cutoff was 354 m long, 1.2 m thick and had maximum depth of 20 m.

The foundation watertightness at the Karkeh dam is mostly achieved by a cutoff wall. The characteristics of the material (plastic concrete) were designed in such a way as to ensure the required impermeability, deformability and strength. At present, the wall surface area is about 190 000 m^2. The depth of the wall in its deepest section is about 80 m, while the average depth is about 50 m. The thickness of the wall is a function of the depth, and was selected to be either 100 or 80 cm.

1. Karkheh dam project

Karkheh, an earth core rockfill dam, is located on the Karkheh river in Iran. The embankment height is 127 m above its foundation, with a 3030 m crest length. The dam is considered to be the largest dam in Iran, with a reservoir capacity of about 7×10^6 m^3 at maximum reservoir water level, and about 33×10^6 m^3 of dam fill. The project includes: the main embankment on the Karkheh river, a powerhouse with a 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 a length of 955 m, located at the right abutment (see Fig. 1).

The Karkheh river is the third largest river in Iran. The average annual discharge is about 180 m^3/s. Karkheh dam provides 3.6×10^6 m^3 of water to irrigate 340 000 ha of downstream farmlands.

The irrigation of these farmlands is the principal purpose for the construction of the dam. Flood control and energy production of about 934 GWh/year are other main reasons for the dam construction.

Fig. 1. General plan of the Karkheh dam project.

2. Geomorphology and geology

The geology of the dam site mainly consists of conglomerate layers. The overall permeability of the conglomerate is estimated to be in the relatively high range of about 4-8 $\times 10^{-4}$ m/s, mainly caused by the zones of discontinuity and open framework gravels. The unconfined strength of the foundation conglomerate has been determined to be in a range of between 1 and 5 MPa.

The conglomerate is stratified by mudstone layers 3 to 9 m thick, and nearly horizontal. The mudstone layers at levels below the river have been given negative numbers (-1, -2 and -3) and those above the river have been attributed positive values (+1, +2, +3 and +4) (Fig. 2). The composition of mudstone layers is also variable between the clay rock and sandy-silty rock. The estimated permeability of the mudstones is between 10^{-7} and 10^{-9} m/s. Geotechnical investigations and observations indicated that these layers are continuous enough at the location of dam to provide dif-

Fig. 2. Dam longitudinal section, where: 1 = mudstone (+4); 2 = mudstone (+3); 3 = mudstone (+2); 4 = mudstone (-1); 5 = mudstone (-2); 6= mudstone (-3); 7 = top of dam crest, el. 234; 8 = top of cutoff wall; 9 = bottom of cutoff wall; 10 = power tunnel; 11 = diversion culvert; 12 = spillway; and, 13 = original ground surface.

Plastic concrete specification for the Karkeh cutoff wall	
Cement content (kg/m^3)	200-220
Water/cement ratio	1.4-2.0
Aggregates (kg/m^3)	1500
Bentonite (kg/m^3)	30-40

ferent strata for each conglomerate layer confined by mudstone layers.

In study phase I of the Karkheh scheme, a series of in-situ tests were conducted to study the effectiveness of a grout curtain as the first option for the foundation treatment. Comprehensive cement-based grouting tests, including single hole and multi-hole tests were carried out. The results of these tests showed that even by using super-fine cement with a Blaine value of about 8000 cm^2/g, a continuous grout curtain as an anti-seepage measure could not be achieved. Only grouting of the highly permeable zones (open framework gravel) could be done satisfactorily. As a result, a decision was made to use a plastic concrete cutoff wall as the main measure for the foundation treatment at Karkheh.

Later studies [Heidarzadeh *et. al*., 2004[2]], during dam construction, indicated that a combination of initial cement grouting, followed by chemical grouting would be the best procedure for consolidating the foundation of Karkheh dam. In this way, first, the large pores would be blocked by cement grout, and then smaller pores could be blocked using chemical grouts. This procedure would require at least two rows of cement grouting and one row of chemical grout in between. Compared with the cutoff wall, this method would have been more expensive and time-consuming, and also less effective.

3. Cutoff wall design

3.1. Plastic concrete mix design.

The final properties of the plastic concrete mixes were largely determined by the percentage of constituent materials. A comprehensive laboratory investigation was carried out to design the plastic concrete mix [Mirghasemi and Moshashai, 2001[3]]. The first series of tests were carried out at the phase II design stage, in 1995. A total of 12 mixes were investigated in the study. Cylindrical test samples, 150 × 305 mm, were subjected to compressive strength, elastic modulus and permeability tests. Also, a slump test was carried out on the fresh concrete. Between 1996 and 1997, additional mix design tests were done. This series of tests included more than 140 new samples, each one different in specification.

Based on the required specifications, the final decision for the plastic concrete mix was made as summarized in the Table.

The elasticity modulus of the plastic concrete for Karkheh is determined to be between 700 and 2000 MPa. The elasticity modulus of the conglomerate ranges between 500 and 2300 MPa. The compressive strength (at 28 days) of the plastic concrete is measured to be between 2 and 3.5 MPa.

The average unconfined strength of the conglomerate is about 2 to 5 MPa. The permeability test was carried out for different concrete samples, and the results did not vary significantly. The average permeability obtained was estimated to be 5×10^{-8} cm/s. The in situ permeability of the plastic concrete cutoff wall was determined by hydraulic permeability (Lugeon) tests. The field permeability is measured to be 10 times higher than the laboratory results (5×10^{-7} cm/s)

3.2. Dimensions of the wall

Seepage analyses were done to determine the minimum necessary depth for the cutoff wall. The design criteria covered the permissible exit gradient. The extent of the cutoff wall laterally and vertically have been designed based on a balance of the following factors [Shadravan, *et. al.,* 2004[4]]:

- foundation seepage gradient;
- reduce seeping water with respect to economical justification and the dam construction aims; and,
- construction limitation (max. 80 m depth).

In addition to the seepage quantity and gradient reduction, the cutoff wall should not allow for cracking to be induced as a result of imposed loading. This means the material is required to be able to follow the deformations imposed on the soil without breaking up. Deformation could be induced as a result of gravity forces, non-homogeneous or homogenous foundation settlement, reservoir impoundment loading or earthquake loads. As the foundation undergoes the settlement, the wall must be able to tolerate the deformations. Subsequently, the deformability properties of the ground are one of the most important parameters considered to select the appropriate deformability properties of the cutoff wall.

Using a finite difference and non-linear program called CA2 [Fakhimi, 1997[5]], an investigation was carried out to study the interaction of the wall and its surrounding stratified rock (especially at weak rock contacts). The analysis was done at different loading conditions such as at the end of construction, at first impounding and during the operation period. The effect of the material modulus of elasticity, strength and wall-rock contact conditions on the resulting wall stress and strain were investigated in this study.

The main conclusions of this study can be summarized as follows [Shadravan, *et. al*., 2004[4]];

- The cutoff wall strain virtually follows the foundation strain. This means that no significant shear rupture at the wall-foundation contact was anticipated.
- The high strength of the cutoff wall material decreases the wall deformations.

3.3. Wall-core connection

A special detailed design is required for the connection zone between the foundation and the dam body, to facilitate better loading distribution and to prevent the occurrence of incompatible deformations.

Fig. 3. Schematic of the dam body cross section, and details of the connection between the cutoff wall and the dam body.

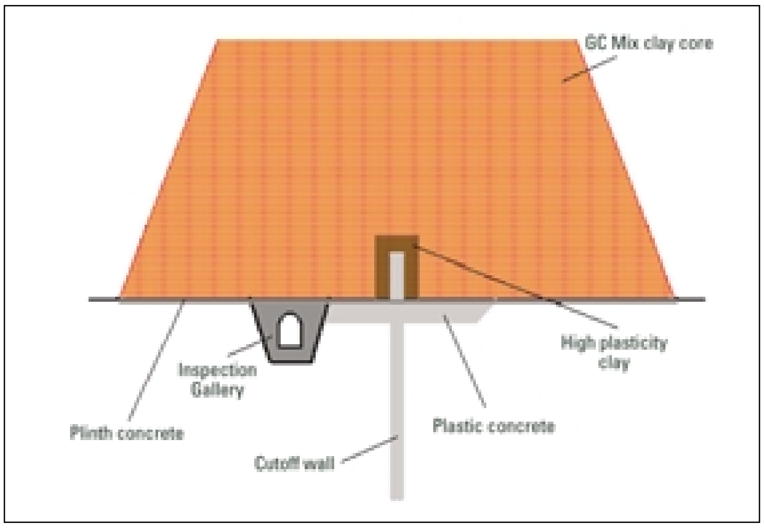

Fig.5.Variation of the water levels in the reservoir and piezometers installed in the dam foundation between mudstones (-1) and (+2).

In the original design, it was assumed that the pure clay (mudstone) material would be used in the impervious core. The design was then revised and it was decided to place a mixture of mudstone (60 per cent) and conglomerate (40 per cent) in the impervious core. Compared with pure clay, the mixed material provides a slightly higher permeability coefficient, higher shear strength and higher deformability modules (lower deformability). More details of the core design are given in the article on p00 At the contact of impervious core with the foundation and the plastic concrete cutoff wall, still pure plastic clay material (wet side of optimum) with a minimum thickness of 1 m was used (Fig. 3). This was done to ensure adequate sealing, and proper load transferral and to decrease the possibility of cracking. Furthermore, a 1.5 m-deep horizontal plastic concrete layer was placed in the connecting zone between the core and foundation. This creates a plastic concrete pad in the critical part of the cutoff wall connecting to the clay core. By increasing the seepage path, the induced hydraulic gradient is brought to the allowable limit. In case of probable cracking in the wall at the part where it enters the core, it is designed to act as a second line of defence against the existing hydraulic gradient.

An inspection gallery was designed in the dam foundation, downstream of the cutoff wall, and parallel with the dam axis, to install instrumentation and to provide for necessary remedial grouting of the dam and foundation.

Excavation of the cutoff wall in the riverbed by a BC30 Cutter.

4. Cutoff wall construction

The hydromill (or hydrofraise) excavation precedure which is a two-phase, panel-by-panel method, was used for the construction of the Karkheh dam cutoff wall (Fig. 4). The primary panels, with a length of 2.8 m and appropriate depths and thicknesses were constructed. After cutting and concreting of a number of primary panels, the intermediate secondary panels were excavated while the vertical edge of two adjacent existing primary panels were cut. The excavated trench was stabilized by bentonite slurry. After the final depth had been reached, the excavated panel was filled with plastic concrete from bottom to top.

4.1 Material

The physical and chemical properties of the components of the plastic concrete (including water, bentonite, cement and aggregates) were specified according to the API and ASTM standards. The allowable weighting error for the components was considered less than conventional concrete. Portland cement type V was specified to be applied to avoid the destructive effects of sulphate compounds of the water and soil.

The maximum size for aggregates of 20 mm was selected to prevent separation and segregation of the plastic concrete, when placed by the tremie tube method.

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

4.2. Platform

A temporary compacted soil platform with a minimum thickness of 1.5 m was made for each construction stage of the wall in the dam body area. The main reason was to prevent quality problems in the dam core, such as undesired high compaction or contamination with slurry and plastic concrete. The cutoff wall guide walls had to be constructed within the platform layer.

To avoid water entering into the trench and the plastic concrete during when construction, the underground water level was limited to be 2.5 m lower than the top level of the platform.

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

4.3. Excavation

An overlap between the panels was provided, to avoid separation of the adjoining panels at depth. The allowable deviation was considered to be less than 0.2 per cent according to the technical specification of the cutoff wall.

Where the cutoff wall was connected to the mudstone layers, the depth of this insertion was designed to be at least 2 m, to block the water flow during operation of the dam.

Limitations were specified for the excavation slurry properties in its fresh condition, during and after excavation, to ensure adequate behaviour and to minimize the joint thickness.

To facilitate its application, the slurry was mixed more than 10 hours before excavation.

It was determined that if the trench demonstrated a high slurry loss, it had to be backfilled with soil or plastic concrete, to avoid the trench wall dropping or collapsing. After a minimum of three days, the cutoff wall was allowed to be excavated again.

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

4.4. Concreting

The concreting duration was planned to be minimal, to avoid concrete hardening during its application. In addition, the tremie tube method for concreting required special care. For instance, the tube bottom had to be more than 3 m within the concrete during concreting to prevent mixing slurry with the concrete.

5. Cutoff wall performance

5.1. Construction joints

As mentioned above, the construction of the cutoff wall was done panel by panel. A question was raised about the quality of the joints between two adjacent panels, and whether the cutoff wall could form a watertight curtain or not. One part of the wall at the left bank encounters the hydroplant tunnels (Fig. 2). For this part, the wall had to be completed before excavation of the tunnels. During the tunnel excavation, the quality of the placed wall, and particularly the quality of the joints between panels, could be examined. Six joints were found in the form of a film of thickened bentonite slurry, with different thicknesses ,being less than 5 mm. In two joints, the average thickness was more than 5 mm, varying between a few mm and in some parts up to 1.5 cm. There are always cold joints between the primary and secondary panels of a diaphragm wall. After this observation, efforts were made to limit the thickness of the joints to less than 1 mm. Preventing the contamination of bentonite slurry by agents such as sulphate or calcium, quality control of fresh slurry by specified tests and recycling it and brushing and cleaning the contact surface of the primary panels prior to concreting the secondary panels were among the steps taken. Furthermore, the dented shape of the joints and the penetration of slurry into the permeable zones avoided any defect concerning the overall performance of the cutoff wall, as will be discussed further in the next section.

5.2. Overall performance

To monitor the performance of the Karkheh dam, geotechnical instruments are installed in the embankment and foundation. Impounding of the dam affected the piezometers installed in the rock foundation. As discussed earlier, each horizontally extended conglomerate layer (confined with the impervious mudstones) had to be considered separately with respect to the pore pressure.

Fig. 5 shows the reservoir water level along with the measured pore pressure at RP5-3 and RP5-4, which are located at the upstream and downstream sides of the cutoff wall respectively, in the conglomerate between mudstones (+2) and (-1) (Fig. 2).

Fig.6.The water levels in the reservoir and piezometers installed in the foundation along the dam axis between mudstones (-1) and (+2) on 21 December, 2004.

The upstream piezometer (RP6-3) is directly affected by the water level of reservoir. While the pore pressure measured in the rock foundation below the downstream shell (RP6-4) downstream of the cutoff wall is practically influenced by the hydrostatic free water pressure downstream. Fig. 2 shows that the existing plastic concrete cutoff wall causes a considerably large drop in the foundation water pressure. This accounts for the impervious performance of the cutoff wall.

The measured porewater pressure of the standpipe and vibrating wire rock piezometers located at the downstream and upstream sides of the cutoff wall is plotted versus their location along dam axis in Fig. 6. As can be seen, at the left and right end points of the wall, minimal differences exists between the piezometric levels at the two sides of the wall. This Figure also shows the good performance of cutoff wall.

6. Cutoff wall extension

When the Karkheh project was designed, information on the permeability of the conglomerate foundation, especially in the part above the groundwater table, was contradictory. At the design stage, a comprehensive study was carried out to estimate the permeability of the conglomerate, which was a difficult engineering task. Different methods, such as Lugeon and pumping tests, were used in this investigation. Also pumping tests were carried out on two lower conglomerates. Because of the complexity of the conglomerate formation, the measured permeability varied greatly (about two orders of magnitude). Thus, with data obtained from feasible methods of investigation and testing, there remained significant uncertainty.

Furthermore, most of the dam foundation was above the natural groundwater level, and therefore, reliable large-scale hydogeological testing had not been possible. In the circumstances, an accurate and reliable prediction could not be taken. Instead, the decision was taken to install a comprehensive monitoring system and to start the reservoir filling slowly. Remedial actions were taken in response to data detected by the monitoring system.

In consideration of the observed response of the foundation to the reservoir impounding, a series of measures are being implemented to increase the length of the seepage path and to collect the seepage flow safely. Among these new measures is an exten-

Karkheh dam, Andimeshk, Iran (in the Spring of 2004).

sion of the cutoff wall at the left and right abutments (Fig. 1). With this new proposed extension, the total area of the cutoff wall will be increased to about 350 000 m^2. Most of this extension will be executed with a new machine with a capacity of 120 m to a depth which was not possible before. The capacity at the design stage was 60 m, and during the construction stage it was increased to 80 m.

7. Conclusion

The Karkheh dam cutoff wall, with an area of about 190 000 m^2 is the largest plastic concrete cutoff wall ever to be built as a dam sealing measure. With the new proposal for its extension, its area will be increased to about 350 000 m^2.

At the Karkheh site, the cutoff wall was found to be preferable to a grout curtain for economic and technical reasons, as well as to meet the construction schedule for the whole project. The dam cutoff wall has shown satisfactory performance after five years of impounding, according to information provided by the instrumentation installed. ◊

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