Technical Note

Construction of relief wells under artesian flow conditions at dam toes: engineering experiences from Karkheh earth dam, Iran

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Abstract

We report engineering experiences from the critical task of relief well installation under high artesian flow conditions at the downstream toe of the Karkheh earth dam, Iran. Due to the establishment of excessive uplift pressure at the downstream toe of the Karkheh dam, installation of a series of new relief wells was considered to permanently relieve part of these pressures. The mentioned uplift pressure, as high as around 30 m above the ground level, was produced in a confined conglomerate aquifer bounded above and below by relatively impervious mudstone layers which reduced the safety factor of the dam toe to below 1.0. Investigations on the shortcomings of the old relief wells installed at the dam site showed that the main problems were: insufficient well numbers, insufficient well diameters, irregular well screens causing their blockage by time passing, and insufficient total opening area. Despite engineering difficulties and associated risk of downstream toe instability, installation of new relief wells was successfully completed under high artesian flow conditions" was successfully completed. The employed technique for the construction of the new relief wells under flowing artesian conditions was based on: 1) cement grouting and casing of the well, 2) telescopic drilling, 3) application of appropriate drilling fluid, and 4) controlling the artesian flow by adding a long vertical pipe to the top of the relief wells. Numerical modeling of seepage for the Karkheh dam foundation showed that, as a result of the installation of the new relief wells, the safety factor of the downstream toe increased to the safe value of 1.3 for the normal reservoir water level.

Keywords: *Dam engineering, Geotechnical engineering, Karkheh embankment dam, Relief well, Artesian flow, Confined aquifer, Dam toe, Drilling fluid, Numerical simulations.*

1. Introduction

Establishment of excessive pore-water stresses and associated uplift pressures at dam toes has been a common geotechnical difficulty observed in many dam projects throughout the world. As such uplift pressures may destabilize dam toes and consequently endanger the dam safety, monitoring of uplift pressure at dam toes and strengthening the stability of dams against it is of critical importance. The most effective engineering solutions to improve dam safety against uplift pressures at dam toes are: downstream earth-fills (also known as seepage berms) and installation of relief wells". However, for dam sites where permanent high ground water pressures are established at dam toes, construction of relief wells serves

as a useful long-term solution because they relieve regional uplift pressures.

Although relief wells provide many engineering advantages in reducing uplift pressures, their installation is usually associated with technical difficulties mainly because of the presence of artesian water pressure at dam toes which can endanger dam safety. In fact, construction of relief wells under artesian flow conditions has been among complicated engineering problems faced in dam projects both nationwide and worldwide. If an appropriate engineering technique is not applied for the construction of a relief well, the excessive uplift pressure which raise up to 3-4 atm in some dam sites, may cost dam failure in a matter of hours through possible piping from dam foundation. Despite the importance of engineering experiences in this field, very few published works report such experiences. Here, we present experiences from successful installation of relief wells under high-pressure artesian flow conditions at the Karkheh dam site in northwest of Iran.

Karkheh, an earth and rockfill dam with the height and length of 127 and 3030 m respectively, is the largest dam in Iran in view of reservoir capacity (Fig. 1). The capacity of

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the Karkheh dam reservoir is 5600 MCM at the normal reservoir water level (i.e., 220 m above sea level). The main objectives for construction of the dam were: irrigation water supply, hydropower energy generation as well as flood control. The project includes the embankment placed across the Karkheh River, a power house with total capacity of 400 MW at the left abutment and a gate-controlled chute-type spillway (Fig. 1). The Karkheh Dam provides about 4 billion cubic meter of regulated water to irrigate 320,000 hectares of downstream farmlands.

Fig. 1 General plan of the Karkheh dam project. The numbers represent: 1, dam crest; 2, spillway; 3, reservoir; 4, powerhouse; 5, diversion culverts; and 6, the location of the new relief wells at dam toe (the red-dashed polygon)

Karkheh project has been a major engineering project in the country (Iran) and was associated with many engineering challenges among which are: first chemical grouting in the country (Heidarzadeh et al. 2007 [1]), stabilization of coarse material using cement grouting (Heidarzadeh et al. 2013 [2]), and special instrumentation of the dam body and foundation (Mirghasemi 2006 [3]). In the present article, we report another major engineering challenge faced during the construction of new relief wells which led us to develop a safe technique for installation of relief wells under high artesian flow conditions.

2. Dam Geology and the Confined Aquifers

Special geological formation at the location of Karkheh

dam is responsible for the establishment of high uplift pressure at the downstream toe of the dam. Karkheh dam is placed on a horizontally-stratified foundation which is a combination of permeable conglomerate and relatively impervious mudstone layers (Fig. 2). The overall permeability of the conglomerate is estimated to be in the relatively high range of about $4\text{-}9\times10^{-4}$ m/s. The impervious horizontal mudstone layers stratify the conglomerate with 3 to 9 m thickness and a permeability of about 10^{-7} to 10^{-10} m/s, which are bedded horizontally in the area of the project (Fig. 2). In Fig. 2, the mudstone layers are numbered due to the river bed level so that the layers located above and below the river bed level are entitled with plus and minus numbers, respectively.
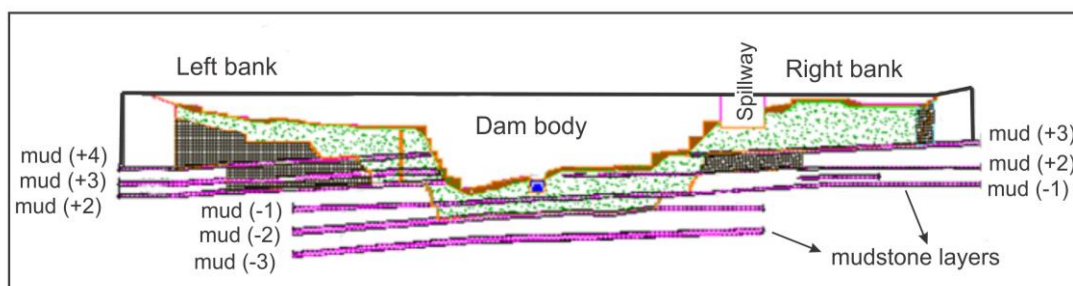

Fig. 2 Karkheh dam longitudinal section showing dam geological layers. Dotted and hatched areas represent the extensions of the dam's old and new plastic-concrete cutoff walls. The figure is exaggerated in the vertical direction

Geotechnical investigations and instrumental observations indicated that these layers are continuous enough at the location of Karkheh dam to provide different strata for each conglomerate layer confined by mudstone layers (Mirghasemi et al. 2004 [4]).

From geological point of view, Karkheh dam and its

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reservoir are located on an unsymmetrical synclinal sloping toward northeast so that all of the underground geological layers of the dam cross the dam reservoir. For example, the mudstone layer (-2) crosses the reservoir at the distance of 4 km from the dam axis. As a result, the conglomerate layers are fed by the reservoir water. The confinement of the permeable conglomerate layers between the impermeable mudstone layers and feeding of the conglomerate layers from the reservoir water are the reasons for development of uplift pressures at the downstream toe of the Karkheh dam. The permeability of the conglomerate aquifer located between mudstones layers (-3) and (-2) is relatively high. After the reservoir impoundment in February 2001, water became trapped between confining mudstone layers and the pressure in this aquifer was increased resulting in the formation of an artesian aquifer. This artesian aquifer produced high uplift pressure at the dam toe and consequently reduced the safety factor of the dam toe to below 1.0.

3. Short Review of Technical Literature

Logani (1983) [6] reported piezometer installation under artesian conditions. A procedure was developed to facilitate the installation of piezometer installation in the abutments of a dam. A manual of Us Army Corps of Engineers (1992) [7] is devoted to design, construction and maintenance of relief wells. However, no information is given about construction of the wells under artesian flows. Rogers and Moore (1997) [8] reported the construction of monitoring wells under artesian conditions in a dam site in the United States. They emphasized that a major item for a successful drilling in flowing artesian conditions is the selection of a properly weighted drilling fluid. Based on their work, the density of drilling fluid, required to offset the artesian head in the aquifer, must be calculated prior to drilling. They performed a series of calculations and proposed the following formula as the drilling fluid density required to control artesian pressure:

$$\rho_w = (D_a + H_a) \times C / D_c \times 1.1 \qquad (1)$$

where D_a is the depth below ground surface to the top of the confined aquifer, H_a is the height of artesian head above ground surface, D_c is the depth below top of drilling fluid filled casing to top of the confined aquifer, the ratio of 1.1 is the safety factor, and C is a constant depending on the different calculation systems.

Interim Water Well Drilling Advisory Committee for the Province of British Columbia (1994) [9] discussed construction and maintenance of wells and provided information for construction of relief wells under artesian flow conditions. According to this manual, the history of flowing wells or artesian conditions needs to be studied and all reasonable precautions needs to be taken to prevent any well from flowing out of control [9].

In general, our literature review suggests that few works are published on the construction of relief wells under artesian flow conditions. Despite all of the associated difficulties, installation of relief wells is an

ideal solution for permanent and safe reduction of uplift pressures, and hence is favored by dam engineers. Due to the extremely large reservoir water volume (i.e., 5600 MCM) and associated relative high artesian pressures at the dam toe, Karkheh dam's relief well installation work was an opportunity to obtain invaluable experiences for the installation of relief wells under extremely difficult conditions.

4. History of Artesian Flow at the Karkheh Dam and Existing Relief Wells

As discussed above, the first step towards installation of relief wells is to study the history of artesian flow conditions at the dam site and to obtain information about the previous experiences of this kind at the dam site.

Considering the presence of an artesian aquifer in the foundation of the Karkheh dam and associated probable uplift pressure in the future, some relief wells were constructed in the downstream toe of the dam during its construction (1995-2001) (red-dashed polygon in Fig. 1). These well penetrated from 10 to 20 m into the artesian aquifer with spacing of about 20 m from each other. In total, 19 relief wells with the diameter of 2 or 3 inches were constructed to relieve part of the excess uplift pressure of the artesian aquifer and consequently to improve the safety factor of the area against instability (Mahab Ghodss Engineers 1998 [10]). After the reservoir impoundment in February 2001, these wells discharged water from the confined aquifer and relieved the existing hydrostatic pressure. Due to some shortcomings in the installation of these wells, and improper estimation of the foundation permeability (Mirghasemi and Pakzad 2005 [11]), they were not able to effectively discharge water from the confined aquifer. At the highest reservoir level, the total amount of water discharge from 19 relief wells was about 35 lit/sec which was a disappointing record.

To monitor the performance of these relief wells and to determine their precise effect on the reduction of the uplift pressure, some observational wells were installed in the artesian aquifer. Figure 3 presents fluctuations of water level in the conglomerate layer between mud (-3) and mud (-2) at 5 observational wells, installed at the downstream of the dam. These observational wells were installed at the dam toe in the area shown with the red-dashed polygon in Fig. 1. As can be seen, for the reservoir water level of around 200 m (in September 2004, Fig. 3), the water level in the observational wells was around 140 m. Since the elevation of the dam toe is around 120 m, the water levels in the observational wells produce an uplift pressure of around 20 m (i.e., 2 atm) to the dam toe. For the reservoir water level of 210 m (in April 2004, Fig. 3), the hydrostatic pressure to the dam toe is about 30 m above the ground level (Fig. 3). Such high uplift pressures decrease the safety factor of the dam toe to the unsafe value of 0.95 (Mahab Ghodss Engineers 2004 [5]). Therefore, installation of new relief wells was necessary to relieve part of these excessive uplift pressures and to assure the stability of the dam toe.
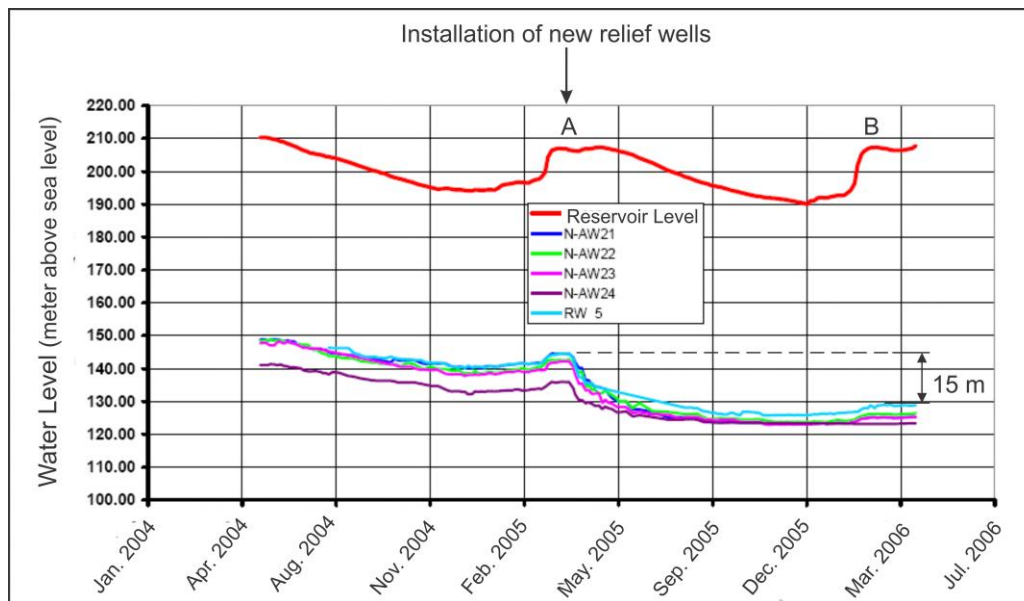
Fig. 3 Water level fluctuations for the conglomerate layer between mudstone layers (-3) and (-2) in some observational wells, installed in the downstream of the Karkheh dam. The thick-red line at the top of the figure shows reservoir water level

Investigations on the shortcomings of these relief wells through field survey and revisiting of the technical drawings showed that the main shortcomings were: 1) insufficient well numbers, 2) insufficient well diameters, 3) irregular well screens causing their blockage by time passing, and 4) insufficient total opening area, e.g., the ratio of opening area to the total are of the well casing was 4 to 5 percent which is too small.

5. Installation of New Relief Wells

Due to the above-mentioned situations and in order to permanently release part of the existing uplift pressures, the installation of new relief wells was considered. The other measure employed in this context was earth-filling of the dam toe to an appropriate elevation. Since the dam reservoir was not impounded at the time of the installation of old relief wells, there were no artesian conditions in the downstream of the dam. However, installation of new relief wells was a major technical challenge because a hydrostatic pressure of up to around 20-30 m above the ground level (Fig. 3) was present at the dam toe. The engineers involved in this process were well aware of this challenge because an uncontrolled artesian flow occurred during the installation of the first observational well some months before the installation of new relief wells. It costed a considerable amount of time and money to stop it. Details of the installation method for the new relief wells are followed.

5.1. Cement grouting and casing of the well is a must

Learning from the problems encountered during the installation of the first observational well into the artesian aquifer, construction of the new relief wells was based on the water tightening and stabilization of the upper aquifers using cement grouting and installation of casing in the wells. Using such a technique, the artesian flows were guided out of the well safely without washing out the soil particles and causing piping.

5.2. Application of appropriate drilling fluid

Due to the relatively large diameter (14-22 in) and depth (~ 50 m) of the wells, collapse of the excavated walls was possible. Hence, a drilling fluid consisting of bentonite, barite, and water was used throughout the drilling process to stabilize the excavated walls. The mix ratio was: bentonite, 25 kg; barite, 5 kg; and water, 200 lit.

5.3. Telescopic drilling method

The method used in Karkheh dam is based on a telescopic drilling technique in which drilling diameter decreases by depth. This method, which is pretty old and is popular in oil industry, presented various advantages in our practice which is discussed later in the article. Figure 4 shows the details of the telescopic well used for the installation of new relief wells at the Karkheh dam toe.

In this technique, first, using the direct rotary method, the well was drilled down to a few meters below the top of the mudstone layer No. (-1) with a diameter of 22 inches. Then, a 20-inche diameter casing was installed to 1 meter below the top of the mudstone layer No. (-1) (Fig. 4). Sand backfill having grade size in the range of 0-5 mm was placed in the space between the borehole wall and the casing. It can be noted that a one-inch narrow pipe was attached to the casing during its installation. This narrow pipe was used later to inject grouting materials to the sand backfill using low pressures in the range of 1-5 kg/cm^2. The grouting materials were a combination of water, cement with the water/cement ratio of 1/2, and conbex-100 to the amount of 0.5 percent by volume of cement. Then, the well construction was stopped for about 3 days to

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guarantee the water tightening of the conglomerate layer above mud layer (-1), and also for strength gaining of the previously injected sand backfill.

The next step was installation of a 14-inch casing down to 1 meter below the top of mud (-2) (Fig. 4). The boring diameter for this casing was 18 inches (Fig. 4). Similar to the first step, the conglomerate layer confined between mud layers (-1) and (-2) was water proofed using grouting. This stage of water proofing was more challenging because the aquifer located in the bottom of mud (-2) was artesian.

The last step in telescopic drilling method was drilling through the mud (-2) and installation of the 6-in casing. This was the most challenging part of the process because the conglomerate layer confined between mudstone layers (-2) and (-3) was under high artesian pressure. Hence, this step needed to be handled with a cautious approach discussed in the following section.
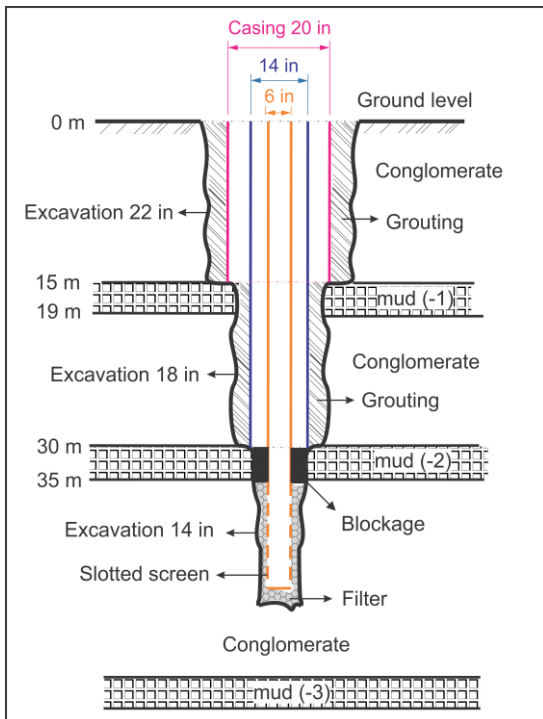

Fig. 4 Sketch showing the details of the telescopic well used for the installation of new relief wells at the toe of the Karkheh dam

5.4. Controlling the artesian flow by adding vertical pipes at the top of the relief wells

The most challenging task during the installation of new relief wells was cutting of the mudstone no. (-2) in order to penetrate into the artesian aquifer (Fig. 4). As mentioned above, the conglomerate layer confined between mudstone layers (-3) and (-2) was under extreme artesian pressure of around 20-30 m above the ground level. Therefore, it was necessary to control the existing artesian conditions in order to be able to block the aquifer and to place the filter material (Fig. 4). Before proceeding this step, we needed to estimate the amount of existing uplift pressure in the artesian aquifer and consequently to calculate the potentiometric head of the water. For this, information obtained from observational

wells was used (Fig. 3). Based on these observational wells, the water surface was estimated about 15-20 m above the ground surface at different locations in the region shown by dashed-red polygon in Fig. 1. For controlling artesian flow, a 20-inch diameter vertical pipe with a length of 15-20 m was attached to the top of the 20-inch casing (Fig. 5). The artesian water flow was stopped by adding this long vertical pipe to the top of the well. After the artesian water flow was stopped, filter materials were placed and the interface of the mudstone layer (-2) was blocked (Figs. 4-5).

Using this technique, 33 new relief wells were installed at the toe of the dam which are shown in Fig. 6. As shown in Fig. 6, new relief wells are of two types: 10 wells with small diameter and 23 wells with a larger diameter of 6 in. The small-diameter wells are installed at the northern part of the dam toe (Fig. 6) where construction of larger-diameter wells was not possible due to some limitations. In addition to relief well installation, back filing of the dam toe also was considered to increase the safety factor of the area which is shown in Fig. 6.

Fig. 5 (Left): controlling the artesian flows by adding long vertical pipes at the top of the relief wells at the Karkheh dam site. (Right): placing filter materials after controlling of the artesian flow
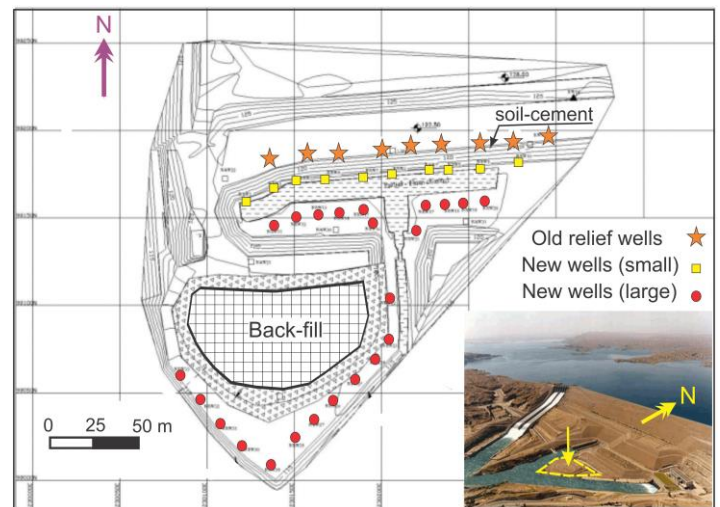

Fig. 6 Location and arrangement of the old and new relief wells installed at the downstream toe of the Karkheh dam

6. Performance of New Relief Wells in Reducing Uplift Pressures

The best way to evaluate the performance of new relief wells in reducing the regional uplift pressure is measurements from downstream observational wells (Fig. 3). As shown by an arrow in Fig. 3, new relief wells started to be installed around March 2005 (point A in Fig. 3) where the water elevation in the observational wells was about 145 m. Reservoir water level was at 208 m above sea level at this time. It is clear that to evaluate the performance of new relief wells, different water elevations in the observational wells should be compared with each other at the same reservoir water level. Around one year after the installation of new relief wells (i.e., February 2006), the reservoir water level reached the same level of 208 m (point B in Fig. 3). It can be seen that at point B, the water elevation in observational wells decreased to the value of 130 m suggesting a 15-m decrease in regional uplift pressure. This shows that the new relief wells were successful in releasing part of the extreme uplift pressures. Table 1 presents the amount of water discharge of each of the newly-installed large-diameter relief wells. The discharge from each newly-installed small-diameter well was around 10 lit/s. From Table 1 and taking into consideration the discharge from small-diameter wells, the total water discharge of the new relief wells is about 900 lit/s. The drainage discharge from all old relief wells (9 wells- Fig. 6) was around 35 lit/s.

Table 1 Water discharges from the new relief wells installed at the downstream toe of the Karkheh dam recorded on 16 July 2005. The reservoir water level was at 201.25 m above the sea level at this time

Relief well name	Discharge (lit/s)	Relief well name	Discharge (lit/s)
N-RW-11	23	N-RW-22	34
N-RW-12	36	N-RW-23	44
N-RW-13	28	N-RW-24	30
N-RW-14	23	N-RW-25	20
N-RW-15	31	N-RW-26	35
N-RW-16	28	N-RW-27	65
N-RW-17	48	N-RW-28	35
N-RW-18	48	N-RW-29	75
N-RW-19	15	N-RW-30	85
N-RW-20	31	N-RW-31	55
Total discharge (lit/s)			**789**

From engineering point of view, relative decrease in the regional uplift pressure or increasing the drainage discharge from the artesian aquifer may not give information about the level of safety of the dam toe which is the most important piece of information for dam engineers. In this context, we need to calculate the safety factor of the dam toe against uplift pressure. To evaluate this safety factor, the 3D seepage model FEFLOW-3D was used to model part of the dam foundation confined between mudstone layers (-3) and (-2). The thickness of this aquifer is around 30 m and is extended from the elevation 50 up to the elevation 80 m above the sea level.

In our model, a rectangular domain having dimension of 8 km × 8 km was modeled using 70876 nodes and 105516 6-noded triangular-prismatic 3D elements. We assumed the steady state seepage condition for our modeling (Fig. 7). The domain length of 8 km seems enough because the mudstone layer (-2) crosses the reservoir at the distance of 4 km from dam axis.
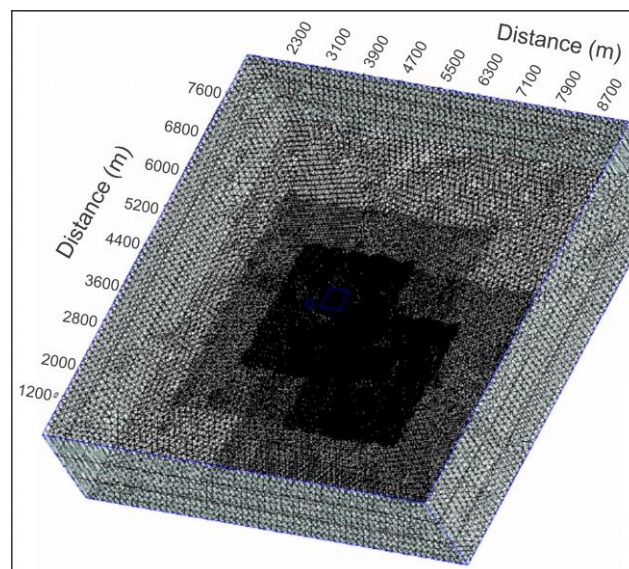

Fig. 7 Computational 3D mesh used for modeling the artesian aquifer confined between mudstone layers (-3) and (-2) at the Karkheh dam toe

The model was calibrated using instrumentation data. We tried to reproduce the water levels observed in some observational wells installed in the downstream toe (Table 2). According to Table 2, the average water level recorded at 7 observational wells was 124.17 m above sea level on 16 July 2005.

Table 2 Comparison of the modeled and the observed water levels at some observational wells at the downstream toe of the Karkheh dam on 16 July 2005. The reservoir water level was at 201.25 m above the sea level at this time

Observational well no.	Observed water level (m)	Modeled water level (m)
1	126.12	~ 125
2	126.60	~ 125
3	126.55	~ 125
4	124.79	~ 125
5	120.19	~ 125
6	122.14	~ 125
7	123.77	~ 125
Average	**124.16**	**125**

This calibration resulted in the horizontal permeability of 1.6×10^{-3} m/s. Figure 8 shows the iso-potential lines for the modeled region indicating that the water head significantly decreased at the dam toe (red-rectangle in Fig. 8) due to the installation of the new relief wells. According to Fig. 8, the modeled water level at the downstream toe is around 125 m which is close to the observed values (Fig. 8 and Table 2). In other words, the

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seepage model was able to successfully reproduce the observed water levels. Therefore, the model is valid for further analysis.
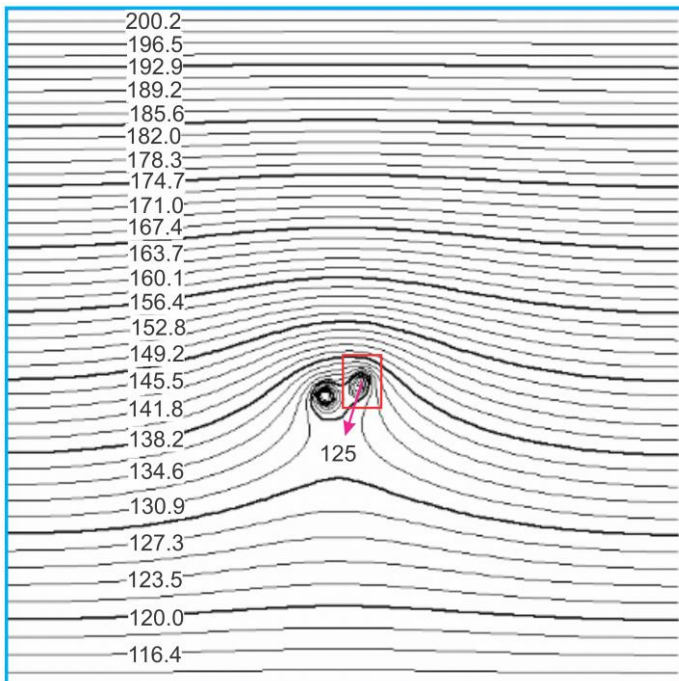

Fig. 8 Results of 3D seepage simulations for the artesian aquifer confined between mudstone layers (-3) and (-2) at the Karkheh dam toe. The lines represent iso-potential lines. The numbers are water head in meter above sea level. The red rectangle shows the dam toe where the new relief wells were installed

Using our 3D-calibrated seepage model, it was found that the safety factor would reduce to the unsafe value of about 1.0 without relieving the uplift pressure exerting to the bottom of the mud layer (-2). However, this factor was improved 40% after installation of 23 new relief wells. The new safety factor of the dam toe against uplift pressure is 1.5 at the reservoir water level of 201.25 m above the sea level by taking into account the weight of the newly-placed earth-fill at the dam toe. By running the model for the normal reservoir water level (i.e., 220 m above sea level), it was found that the safety factor of the downstream toe will be around 1.3 which is a safe value.

7. Discussions

The installation of new relief wells at the Karkheh dam toe was a unique experience in several ways. First, the artesian pressure at the dam toe was relatively high because the Karkheh reservoir is extremely large and is among the world's largest artificial lakes. Second, due to the confinement of the conglomerate aquifer between two impervious mudstone layers, we were facing a concentrated artesian flow. Third, we experienced an uncontrolled artesian flow conditions during the installation of the first observational well which endangered dam's safety and washed out soil particles from the dam foundation before its blockage. Regarding above considerations, our experience from Karkheh dam

may be considered as a realistic engineering solution for an extreme case.

To stop uncontrolled artesian flow encountered during the installation of the first observational well, at first, the well was filled with a large amount of surcharge consisting of concrete, gravel and clay. However, it was not successful after two days of filling and artesian flow continued to wash out soil particles. At this stage, we noticed that the artesian pressure for the conglomerate layer between mudstones (-3) and (-2) is far more than our previous expectations. In fact, this incident was an opportunity to have a realistic understanding of the concentrated and high uplift pressure at the Karkheh dam toe. Finally, we reached the idea that the well needs to be re-drilled and its walls should be grouted down to the mudstone (-2). In this process, about 20 tons of cement was grouted along with the placement of 10 m^3 of sand (0-20 mm). In fact, the idea for the installation of new relief wells using the method shown in Fig. 4 was the outcome of our challenges with the failure of this observational well.

Our experience suggests that the arrangement of the openings and their size are of vital importance for the proper function of the wells. As discussed above, one of the main shortcomings of the old wells was inappropriate opening arrangement and size. For the new wells, we changed the arrangement of the screens and used a regular shape for them (Fig. 9). In addition, we significantly increased the ratio of opening area to the total well area. In fact, there is no limit for the maximum screen area as long as the filter materials are prevented from entering the well. Therefore, we maximized the opening area of the wells (Fig. 9).

Fig. 9 Picture showing the arrangement and size of the well screens used for the new relief wells at the Karkheh dam

8. Conclusions

We reported engineering experiences from installation of relief wells under flowing artesian conditions in the downstream toe of the Karkheh dam. It was a unique experience for several reasons: I) the artesian pressure was relatively high compared to normal dam sites, II) we were facing a concentrated artesian flow, and III) we experienced an uncontrolled artesian flow during the installation of the first observational well which endangered dam's safety and washed out soil particles before its blockage. The main findings are:

1- Main shortcomings of the old relief wells were: insufficient well numbers, insufficient well diameters, irregular well screens causing their blockage by time passing, and insufficient total opening area.

2- Our technique for the construction of new relief wells under flowing artesian conditions were based on: a) cement grouting and casing of the well, b) telescopic drilling method, c) application of appropriate drilling fluid, and d) controlling the artesian flow by adding vertical pipes at the top of the relief wells.

3- A regular shape was used for the well screens and the well opening area was maximized. As a result of these actions, the drainage discharge from the wells significantly increased.

4- Numerical modeling of seepage for the Karkheh dam foundation showed that as a result of the installation of the new relief wells, the safety factor for the downstream toe was improved to the safe value of 1.3 at the reservoir normal water level.

5- After the installation of the new relief wells, the drainage discharge from the conglomerate layer confined between mudstone layers (-3) and (-2) increased from 35 lit/s to around 900 lit/s.

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