SAFETY ASPECTS OF ROCKFILL DAM IN NARROW VALLEY WITH SEISMIC FAULTS IN THE FOUNDATION

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ABSTRACT

Rudbar Lorestan, is an earth core rockfill dam with a height of 156 m, which is located in a narrow canyon in the seismically very active Zagros Mountain Range in the west of Iran. The design and construction of embankment dams in narrow canyons is a challenge for dam engineers and contractors. The special design features include treatment of the abutment rock in the core area, limitation of the abutment slope to 70 degrees, thick filter and transition layers, widening of the downstream fine sand filter towards the abutments and provision of a plastic contact clay layer at the steep abutments. Due to high seismic action and the presence of faults and discontinuities in the footprint of the dam, which could move during a strong earthquake, occurring along a major fault close to the dam site, the shear strength of the clay core is increased by adding sandy gravel. The procedure adopted for the first reservoir impounding, which started in 2017, and the behaviour of the dam during the first years of reservoir operation, is discussed. The results of the microseismic monitoring system installed prior to reservoir impounding are also presented.

1. INTRODUCTION

The Rudbar Lorestan project is one of a series of hydropower development projects in the Dez River catchment upstream of the 203 m high Dez Dam, completed in 1963. The project site is in Lorestan Province in the Zagros Mountains in the west of Iran. The hydropower scheme impounds the Rudbar River, a tributary of the Dez River, with a 156 m high earth core rockfill dam (ECRD), impounding a reservoir with a storage volume of 228 Mm³.

The hydropower project has an installed capacity of 450 MW and provides peaking power to the Iranian National Power System. The powerhouse comprises two 225 MW Francis turbines with vertical axes. The ungated spillway consists of two tunnels each with 11 m diameter, length of 631 m and a total discharge capacity of 3342 m³/s. The dam has two bottom outlets which were used for river diversion during construction and for controlling the rate of reservoir filling during impoundment. The power intake structure is situated at the right bank close to dam body. The head of the plant is 430 m. The pressure system consists of two parallel steel penstocks and two penstock tunnels. The dam with the two tunnel spillways on the left bank is shown in Fig. 1.

Figure 1 : Downstream view of Rudbar Lorestan ECRD and the two tunnel spillways on the left abutment.

The main technical challenges of this project are the location of the dam in a narrow gorge, the very steep abutments, the high seismicity due to nearby active faults, and the presence of discontinuities and faults in the footprint of the dam where seismic movements are possible.

In this paper the seismic design aspects and the special design features of an ECRD located in a narrow canyon and the behaviour of the dam during filling of the reservoir and the first years of operation are discussed. The project was completed in 2017.

2. SEISMIC HAZARD EVALUATION OF DAM SITE

For large storage dam projects, the earthquake hazard is a multiple hazard as besides ground shaking, which is the main hazard considered in seismic design codes and guidelines, earthquakes can cause displacements along potentially active faults in the dam foundation, they can trigger landslides and rockslides, which may cause impulse waves in the reservoir and other site-specific and project-specific hazards. It is also a well-known fact that the earthquake hazard is one of the least known hazards. Especially the estimate of the ground motion at the dam site for the strongest earthquakes with a very low probability of occurrence is difficult and associated with major uncertainties. Therefore, a thorough investigation is needed for the estimate of the ground motion parameters of the different design earthquakes. This investigation includes, on the one hand, the study of the geologic and seismotectonic setting of the dam and reservoir region and, on the other hand, the seismic hazard assessment based on different earthquake scenarios and probabilistic analyses. As the seismic hazard is the most severe hazard from the natural environment to be considered in the design of the Rudbar Lorestan HPP Project, all aforementioned items have to be taken into account in the design, construction and operation of this project.

Although the location of the dam in a narrow canyon would have favored a concrete arch or gravity dam, these options had to be abandoned when the result of the seismotectonic assessment of the dam site with multiple discontinuities in the footprint of the dam, where movements were possible if a strong earthquake would occur at a nearby fault, was obtained. At such locations, following the recommendation by ICOLD (1998), the only feasible dam would be a conservatively designed ECRD, if no other dam site is possible.

The lack of suitable construction materials is used as an argument against certain dam types. This was also the case in Rudbar Lorestan, where an ECRD alternative was discarded because of the apparent lack of core material; however, finally, adequate supplies of core materials were found within a distance of 5 to 15 km from the dam site, making an ECRD economically feasible. River bed material mixed with crushed rocks was used for the production of filter materials.

Moreover, due to the maximum reservoir depth, the size of the reservoir and its location in a highly tectonically stressed region with several active faults, reservoir-triggered seismicity (RTS) due to the filling and/or operation of the reservoir could not be excluded. Although, RTS may not be a direct concern for the safety of a well-designed and constructed dam, strong RTS events can trigger mass movements into the reservoir, damage buildings and infrastructure in the reservoir region, which have not been designed against earthquakes, and finally RTS and associated noise may create safety concerns among the people in the reservoir region, which have to be taken seriously by the dam owner.

Therefore, two systems for seismic monitoring were installed comprising strong motion instruments (accelerometers) and a microseismic monitoring system with velocity sensors.

The strong motion instruments are composed of seven accelerometers, five of them are located in the dam body and abutments and the remaining two in the powerhouse and in the short penstock tunnel. Since the installation of the accelerometers, no strong motions with peak accelerations exceeding 0.1 g have been recorded.

The microseismic network consists of seven stations, which are distributed in the reservoir area at a distance of 8-25 km from the dam site. The objectives of the microseismic network are as follows: (i) monitoring RTS due to reservoir impoundment and operation of the reservoir, (ii) detecting faults or discontinuities in the vicinity of dam activated due to reservoir impounding, (iii) detecting probable migration of active regions in the vicinity of the dam, (iv) monitoring the effect of water level changes on seismicity, and (v) to establish a record of natural seismicity of the project region prior to impounding of the reservoir, which can be used as a benchmark for assessing any RTS events. If local events with magnitudes exceeding 3.0 are recorded, immediate notification is required. Fortunately, up to now no such events have been recorded.

The issues resulting from the high seismicity and complex seismotectonic conditions have been discussed by Wieland & Fallah (2014) and Wieland & Hajilari (2018).

3. DESIGN AND CONSTRUCTION ASPECTS OF DAM IN NARROW VALLEY

In view of the high seismicity and the complex seismotectonic environment at the Rudbar Lorestan dam site, a conservatively designed ECRD has been selected in accordance with ICOLD (2001). An ECRD has the ability to resist displacements at discontinuities in the footprint of the dam caused by a major earthquake occurring at the Saravand-Baznavid Fault with a distance of 1.6 km from the dam site, and there is extensive experience in the construction of large ECRDs in Iran resulting from the recent construction of the following major rockfill dams in Iran: Upper Gotwand ECRD (182 m high), Karkhe ECRD (127 m high), Masjed-e-Soleyman ECRD (164 m high), Marun ECRD (165 m high), Siah Bishe concrete face rockfill dam (two dams with heights of 82.5 and 102 m), Daryan ECRD (146 m high), Gavoshan ECRD (125 m high), Azad (123 m high) and others.

Some of the important design features of Rudbar Lorestan dam are as follows:

(i) The core excavation is designed such that the core-foundation contact is always in compression.

(ii) The rough rock surface at the abutment is covered by shotcrete and all protruding rock parts are removed.

(iii) The slope of the abutment should not be steeper than 70°, to ensure proper compaction of this zone and to create a contact stress normal to the abutment surface when the core settles and slides along the abutment. This would also prevent any differential settlement especially after impoundment.

(iv) A slight inclination of the core toward upstream is provided, which is favorable in a narrow valley. The inclination is limited to a crushed and highly sheared fault zone, located upstream of the dam axis on the left abutment. The core inclination is selected in such a way to keep placement of the core and the upstream fine filter away from this zone.

(v) The ratio of the core width at the base to the dam height is 0.4, i.e. the maximum core width is 62 m.

(vi) To minimize arching effects in the core a 5 m thick plastic contact clay layer is provided at the abutments, which can be considered as a slip surface.

(vii) High shear strength of the core is necessary in the crest area of the dam, where the largest seismic strains occur. Therefore, the stiffness of the core was increased to at least half of that of the shell material by mixing the clayey material from the borrow area with sandy gravel.

The mixed clayey gravel in the core also helps to reduce the pore pressure in the core. Clayey gravel soils are composed of sticky particles mixed with granular material, and the mechanical behavior is between clay and granular soils. Clay soils have lower resistance and permeability and higher compressibility, while their potential for liquefaction is relatively smaller. Given the importance of studying the dam behavior under seismic loads, cyclic triaxial tests were conducted on the core mixed material, and their behavior parameters for seismic conditions were extracted from these tests.

In the dam body design, besides the clay core, a fine sand and coarse sand filter and transition zone, all of them 5 m thick, were provided to eliminate the risk of internal erosion, and to cope with possible foundation movements and seismic slope movements. In order to reduce the risk of seepage erosion along the steep core-abutment contact the width of the downstream fine sand filters in contact with the abutments was increased to 10 m (Fig. 2).

Figure 2 : View of core, 5 m wide plastic contact clay zone at the abutments, 5 m thick fine sand filter widened to 10 m at the downstream contact with the abutment, 5m thick coarse sand filter, 5 m thick transition zone, and rockfill (view from downstream).

Because large differential settlement near the abutments may result in transversal cracking within the embankment, a 5 m wide plastic clay zone at the interface with the rock abutment is provided. This would minimize the seepage and erosion hazard along the abutments, minimize arching effects in the core, and increase compressive stresses in the core. The contact clay, which was compacted with special equipment, had a water content of 1-2 percent above the optimum water content.

The gradation envelopes of the rockfill were selected based on trial fill placement results and trial blasting operations at quarries with the objective to ensure good compaction and high stiffness.

The highest cross-section with material zonation is shown in Figure 3.

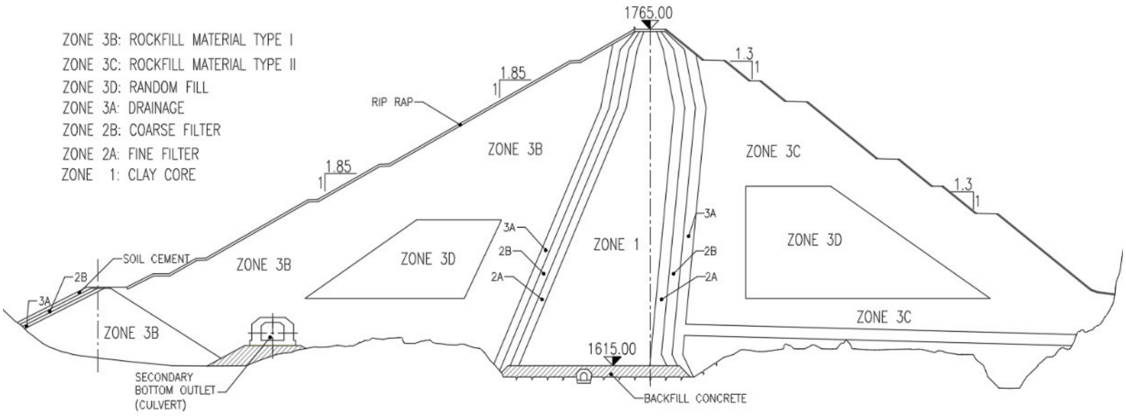

Figure 3 : Highest cross-section of Rudbar Lorestan ECRD with material zonation.

4. DAM INSTRUMENTATION AND MICROSEISMIC MONITORING

4.1 Overview

The dam monitoring instruments are located at three transversal and one longitudinal sections on five levels from the bottom to the top of the dam. The instruments comprise of piezometers (electric and stand pipe), total pressure cells, inclinometers, surface displacement (benchmarks), measuring weirs (v-notch), extensometers, time domain reflectometry, strong motion instruments detecting instruments (accelerometers) and a microseismic network (velocity sensors).

Most of the installed instruments are in operation. However, a few stopped functioning during construction, while a few stopped working after reservoir impounding. Generally, the damaged instruments did not cause problems for the dam safety monitoring during construction and reservoir impounding. The dam monitoring was done according to the initial plan.

Construction of the dam body was completed in December 2015, while reservoir filling started in May 2016, which is the dry season for the project region and reservoir catchment. After about 10 months the reservoir elevation reached the normal water level at elevation 1756 m asl.

The issues resulting from the dam body monitoring results including, deformation, seepage and pore water pressure measurements during and at the end of impounding have been discussed by Wieland & Roshanomid (2019). In this paper the instrumentation results which directly deal with seismic aspects and dam deformation close to the steep abutments are discussed in more in detail.

4.2 Time-Domain Reflectometer

In the case of Rudbar Lorestan dam, located in a narrow gorge with steep abutments, monitoring of the displacements of the clay core in the contact with abutments is important. For that purpose, time-domain reflectometers (TDR) installed on both abutments (Fig. 4). A TDR is a relative slip gauge measuring device.

Figure 4 : View of 5 m wide plastic contact clay zone at the abutment, treatment of rock surface in the core and filter zones by shotcrete and slip measuring devices (TDR) installed on abutment.

Time domain reflectometry is based on the transmission of an electric pulse as a waveform within a medium and watching for reflection of this transmission. As the ground displaces, the installed cable is sheared or displaced. This causes a change in the material property of the cable. This change in property is detectable and allows us to locate the actual location of displacement. If the cable is deformed and altered due to displacement of the contact clay in the vicinity of abutment, then the characteristic impedance is altered and a transmitted pulse will be reflected showing the location of deformation.

The TDRs recorded the location where deformations took place in the contact clay zone near the abutments; however, they do not provide the value of the deformation. This can be obtained, for example, by extensometers. Rudbar Lorestan is the first dam in Iran where these instruments were used. The sensors are not in use anymore.

4.3 Horizontal Embankment Extensometer

The horizontal embankment extensometers are used to measure horizontal deformations in large earth structures. They are incorporated in the filling material, chained together by means of extension rods. The system consists of several measuring units connected by extension rods to the anchor plates. The measuring unit is a telescopic section equipped with displacement transducer. In the Rudbar Lorestan project, extensometers were installed in the rockfill shell, filters, and the clay core (Fig. 5).

Figure 5 : Installation of horizontal extensometers in dam body.

As shown in Fig. 6, the sensors installed close to rock slope (3 m from abutment) and in the contact clay show the maximum deformations. This behavior also approved the positive performance of the contact clay composed of highly plastic material which could resist toward this deformation and decrease the arching effect on the abutments. Worth noting, most sensors shows deformation during and at the end of construction and (except one) do not show special change during impounding.

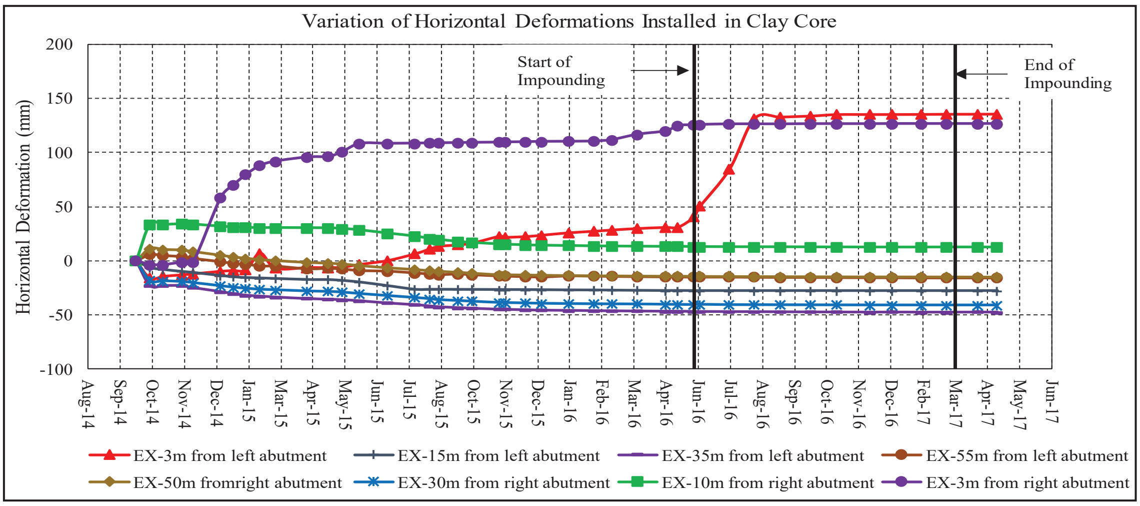

Figure 6 : Time histories of horizontal deformations recorded by extensometers in the clay core located 40 m below the dam crest.

4.4 Microseismic monitoring network

In highly seismically active regions, such as the Zagros Mountain Range in Iran, most of the faults could be potentially active or could experience some movements.

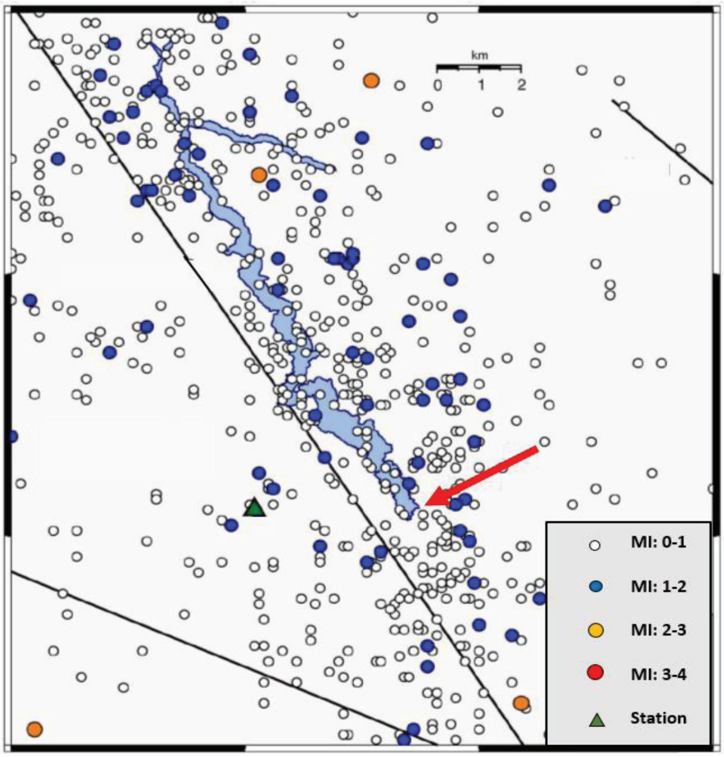

Figure 7 : Seismic events recorded from 2015-2018 by the microseismic network of Rudbar Lorestan pro-ject (the red arrow indicates the dam site, and the fault parallel to the reservoir is the Saravand-Boznavid Fault, which has an estimated upper bound magnitude of 7.5).

The microseismic network installed in 2014 consists of seven stations with velocity sensors with 24-bit resolution. The system is capable of recording and localizing seismic events with magnitudes down to zero. In Fig. 7 the seismic events recorded in the project area from 2015-2018 are shown together with the Saravand-Boznavid fault. The great majority of local events had magnitudes of less than 1, which cannot be felt by people. There are four events with magnitudes in the range of 2 to 3. There is no clear indication that these events are RTS events. However, it is recommended to continue operation of the microseismic network for some time so that the first few years of reservoir operation can also be covered. Afterwards monitoring by the national seismic network of Iran may be sufficient

5. CONCLUSIONS

The following conclusions may be drawn from the design and the first impoundment of the reservoir of the 156 m high Rudbar Lorestan ECRD:

1. The main safety concern of the dam design was the risk of internal erosion due to cracking of the core due to arching effects in the narrow canyon and seismic actions, and erosion due to seepage along the core-abutment contact. For the protection against internal erosion a 5 m wide fine sand filter was provided at both dam faces. Towards the abutments the downstream fine sand filter was widened to 10 m to prevent erosion due to seepage at the core-abutment contact. Arching effects in the core and the formation of cavities at the core-abutment contact was minimized by a 5 m wide plastic contact clay zone, which acts as a sliding surface. Rock surface treatment was required and the maximum abutment slope was limited to 70° to facilitate proper compaction of the dam materials in the dam-abutment contact zone.
2. Standard instrumentation with an automatic data acquisition system is provided for the rockfill dam. The total number of sensors installed in Rudbar Lorestan dam body is 1288 whereof 90 sensors are out of service. Time-domain reflectometers were installed in both abutments to monitor slip movements of the clay core in the contact with the abutment. This was the first time that such instruments were installed in a dam. They are no longer in use.
3. Reservoir-triggered seismicity is monitored by a sensitive microseismic network comprising seven stations. The network was installed prior to reservoir impounding in order to record the natural seismicity of the project region. No unusual seismic activity has been recorded since the start of reservoir impounding in 2016.

4. The horizontal extensometers installed in the contact clay in the vicinity of the abutments show maximum horizontal deformations of 130 mm, whereas the other extensometers recorded maximum values of up to -50 mm and have not shown any remarkable deformations from the start to the end of impounding.

The Rudbar Lorestan dam, located in a very difficult topographical and seismotectonic environment, has performed well during the first impoundment and since the start of operation of the reservoir until today. Among the large embankment dams in Iran, the Rudbar Lorestan ECRD is technically the most challenging rockfill dam project built in Iran and can serve as a template for other projects in difficult topographic and seismotectonic environment.

Although the dam is safe, hopefully, the extreme seismic actions for which the dam has been designed will never occur as such events would still cause significant damage to the project.

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