Seepage control design of the Arkun dam in Turkey

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The main dam in the Arkun project is a concrete face sand-gravel fill dam (CFSGD). As sand-gravel fill materials, which are not free draining, were used for the major part of the dam body, the owner investigated the seepage behaviour of the dam in detail and considered extreme load cases, which are not usually part of standard dam analyses. The seepage analysis focused on conditions where the cut-off wall shows leakage and/or the face slab suffers from cracking. A simple modelling method determining the steady-state conditions and considering saturated material properties was considered to be sufficient in consideration of the inaccuracy in predicting the location and type of potential leakage. It was proven that the seepage control design of the dam is able to withstand hypothetical extreme load cases, for which the first barrier suffers total failure.

The application of rockfill material for large dams, relying on the high friction and permeability of rockfill material, is common practice. The latter property leads to its characterization as 'free-draining'. In ICOLD [2005[1]] and many other guidelines and corresponding dam engineering books [ANCOLD; 1990[2]; Fell *et al.*, 2005[3]; Cruz *et al.*, 2009[4] ; Hunter & Fell, 2002[5]; Hunter *et al.*, 2003[6]] the design and behaviour of rockfill dams is investigated and discussed, referring to many case studies and documenting a steady development and improvement of the construction and implementation technology over several decades.

The concrete face rockfill dam (CFRD) type is the most competitive in terms of safety and economy, as long as the foundation conditions are suitable and construction materials are reasonably available. The concrete slab controls the seepage, and where the first barrier, consisting of the face slab and the underground treatment, is functioning, porewater pressures will not develop within the dam body. This provides reliable stability and long-term durability. Concerns are mainly directed to the deformation behaviour of the rockfill material, which usually shows a representative elasticity modulus of E_{RC} = 40-80 MPa [Cruz *et al.*, 2009[4]], although higher values can be attained [Fell *et al.* 2005[3]] if material grading, applied compaction work and rock strength effects are supportive. The deformation of the dam body directly affects deformation of the concrete surface slab, which tends to result in cracks and allows seepage intrusion into the dam body. In the case of CFRDs, seepage is usually only an economic impact and does not endanger the stability of the dam. However, when other dam fill materials such as sand-gravel are used, the seepage control design requires special attention. This is because seepage flow caused by cracking or other reasons may lead to the development of porewater pressures in the dam body and affect the stability of the dam with regard to sliding failure or erosion/suffusion. Particular attention to quality control has to be maintained with the use of 'dirty' sand-gravel fills.

In Haselsteiner & Ersoy [2011[7]] the design features of CFRD and CFSGD are summarized and the specific seepage control measures are described with reference to selected case studies. Worldwide case studies show that extreme seepage amounts for CFRDs after first impoundment can reach several cubic metres per second. The largest CFRD dam in the world is Shuibuya dam and its excellent performance during impoundment and operation is the result of elaborate compaction works and intensive site supervision, which resulted in a seepage rate of approximately 40 l/s [Pinto, 2009[8]] at an average elasticity modulus of E_{RC} = 80 MPa. The 187 m-high Aguamilpa dam, which is comparable with Arkun dam with regard to design characteristics, showed 200 l/s seepage after impoundment [Montanez-Cartaxo, 1992[9]] and a horizontal crack close to the crest caused by large deformations within the downstream rockfill zone.

In summary, the design of concrete face sand-gravel fill dams (CFSGD) has to account for the specific seepage control tasks, providing enough drainage capacity to avoid critical porewater pressure conditions in terms of extreme load cases.

1 Project description

Arkun dam is located on the Çoruh river in northeast Turkey at the border of Artvin and Erzurum provinces. The dam is 140 m high from the foundation level. The Arkun project is one of several dam and hydroelectric power projects on the Çoruh that are under construction and are to be completed within the next few years. The highest concrete dam in Turkey, Deriner, is under construction downstream of Arkun and is expected to be completed in less than a year. Several other dam projects, such as Güllübag, are under construction upstream (Fig. 1). The Laleli dam project, has a large reservoir but only small generation potential (100 MW). This makes the project less economically attractive to private investors and so it has not yet moved to the construction phase. However, Laleli reservoir is the key to operational regulation and control for flow regulation and sedimentation processes on the Çoruh river. If constructed it would help to increase peak and overall generation and contribute to sedimentation control of downstream projects including Arkun dam.

Arkun is one of 15 hydropower projects in the portfolio of Enerjisa, a joint venture between Sabanci Group of Turkey and Verbund of Austria, which is targeting an installed capacity of 5000 MW in the coming years, of which approximately half will be covered by hydro projects.

The Arkun dam and hydropower project consists of one diversion tunnel, upstream and downstream cofferdams, a CFSGD with a downstream rockfill zone, a three-gated spillway, a 14 km-long headrace tunnel with an upstream gate shaft, downstream valve chamber and surge tank, a main powerhouse (with three 75 MW vertical Francis turbines) and a powerhouse using environmental flows (2 × 6 MW horizontal Francis

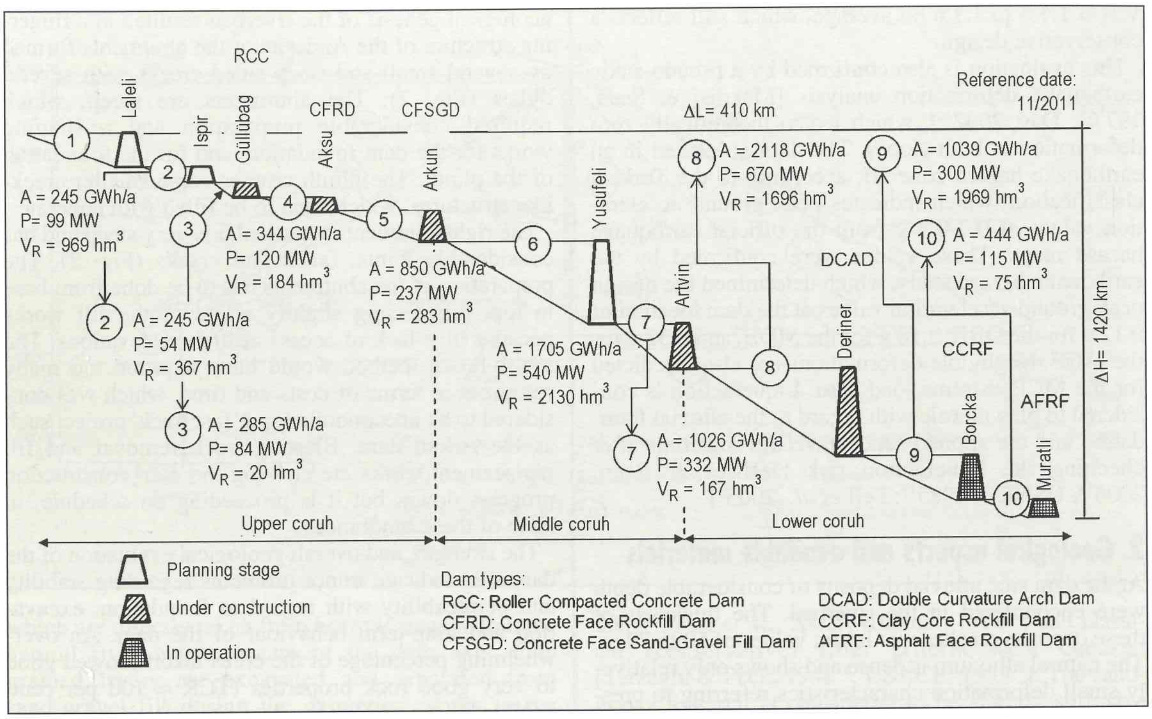


Fig. 1. Development of hydro on the Çoruh river.(after Sezer, 2009).

turbines) and a 380 kV switchyard with a corresponding transmission line. The diversion tunnel will be used for the installation of the bottom outlet.

Approximately 40 km of state and village roads need to be relocated, which will mean the construction of several bridges and tunnels along the new road alignment.

The purpose of the dam is exclusively to generate energy, although it will also provide a contribution to the sediment management and flood control downstream. Annual energy generation will reach a value of 830-850 GWh/year after upstream projects have been fully developed, varying slightly for different operating scenarios and allowing for the inaccuracy of hydrological input data. The electromechanical equipment of the main powerhouse is designed for peak generation, requiring oversizing of the turbines for a mean daily work period of eight hours per day. The small powerhouse will be fed by a bypass pipe from the bottom outlet; the two turbines, which are designed for baseload generation.

Conforming to national regulations, the hydraulic capacity of the spillway is designed for a reservoir inflow with a peak flow (PMF) of about 4701 m³/s resulting in a required hydraulic capacity of the spillway of 4570 m³/s. The diversion works are designed for a recurrence period of 50 years. The design features of the Arkun dam and hydro project are summarized in Table 1.

The dam design was subject to several revisions, including altering the dam fill material and dam body zoning but also changing the crest width. The resulting crest width of 10 m corresponds to international practice [ICOLD, 2005[10]].

To obtain a better understanding of the sand-gravel fill material, large-scale (D = 800 mm) triaxial tests (CD) were carried out at the Karlsruhe Institute of Technology (KIT) in Germany. The test results were considered to be favourable and enabled the owner to redesign the downstream slope and save some resources. The downstream slope was steepened from

Table 1: Main features of the Arkun dam and hydropower project

Item	Value	Unit
Hydrology/reservoir		
River	Coruh river	
Catchment area	6853	km²
Spillway design flood PMF Q_{PMF}	4701	m³/s
Hydraulic capacity spillway $Q_{P\,Sp}$	4570	m³/s
Diversion design discharge	798	m³/s
Maximum flood water level FWL_{max}	938.61	masl
Maximum operation water level OWL_{max}	935	masl
Minimum operation water level OWL_{min}	871.5	masl
Total storage volume V_R	283.24	hm³
Dam characteristics		
Dam type	CFSGD	
Dam height H_D	140	m
Dam crest elevation	940	masl
Crest width W_C	10	m
Max. total dam body fill volume	≈ 6 Mio.	m³
Upstream slope V:H	1:1.6	
Downstream slope V:H	1:1.6	
Hydraulic structures		
Spillway type	Ogee overflow, chute and flip bucket	
Spillway gates	3 radial gates	
Spillway sill elevation	920	masl
Diversion type	Tunnel	
Diameter of diversion tunnel	8.6	m
Length of diversion tunnel	≈ 6640	m
Diameter of energy tunnel	6.4	m
Length of energy tunnel	-	-
Diameter of bottom outlet	2	m
Maximum discharge of bottom outlet	127.5	m³/s
Bottom outlet intake elevation	849	masl
Main (MPH) and environmental powerhouse (EPH)		
MPH turbine type and number	3 vertical Francis	
EPH turbine type and number	2 horizontal Francis	
Total installed capacity P	≈ 237	MW
Total annual energy generation A	≈ 830-850	GWh/year

V:H = 1:1.8 to 1:1.6 on average, which still reflects a conservative design.

This evaluation is also confirmed by a pseudo-static earthquake deformation analysis [Makdisi & Seed, 1977[11]; Day, 2002[12]], which led to theoretically zero deformation at both slopes. The dam is located in an earthquake hazard zone III, according to the Turkish classification, which indicates peak ground acceleration values of 0.2-0.3 g from the official earthquake hazard maps. These values were confirmed by the earthquake hazard study, which determined the design peak ground acceleration values at the dam location of 0.12 g for the OBE, 0.18 g for the MDE, and 0.32 g for the MCE. Negligible deformations are also predicted for the MCE extreme load case. Liquefaction is considered to play no role with regard to the alluvial foundation and the applied sand-gravel fill materials after checking the liquefaction risk [Jeffries & Been, 2006[14]; USNRC, 1985[15]; Fell *et al.*, 2005[3]].

2. Geological aspects and available materials

At the dam site, alluvial deposits of considerable depth were encountered in the riverbed. The thickness of these deposits reaches maximum values of 50 to 70 m. The natural alluvium is dense and shows only relatively small deformation characteristics referring to pressure meter and plate load tests. The grain size of blocks reaches more than 1500 mm. The average grain size is approximately 5-20 mm. Extensive testing of the sand-gravel fill was done beforehand mainly focusing on the obtainable grading and moduli of elasticity. Test results and back-analysis of the material indicate favourable engineering properties of the sand-gravel material when used as fill. For shear strength and deformation, this material is considered to be strong. The elasticity modulus during construction is expected to be higher than the specified value of $E_{RC} >$ 200 MPa (Table 2). Sand-gravel fill is usually not free-draining, but has a hydraulic conductivity of $k < 2 \cdot 10^{-3}$ m/s on average, depending on the percentage of fines and sand. The unit weight shows generally high values depending on the amount of fines.

The bedrock at the dam site is Andesite, which is classified as a good and strong rock, showing maximum strength values of UCS > 100 MPa. The specific geological genesis of the riverbed resulted in a fingering structure of the Andesite at the abutments formed by several small and steep sided creeks with several dykes (Fig. 2). The abutments are steep, which required considerable preparation and re-shaping works for the dam foundation, and for the foundation of the plinth. The plinth crosses some smaller creek-like structures, which need to be filled with concrete.

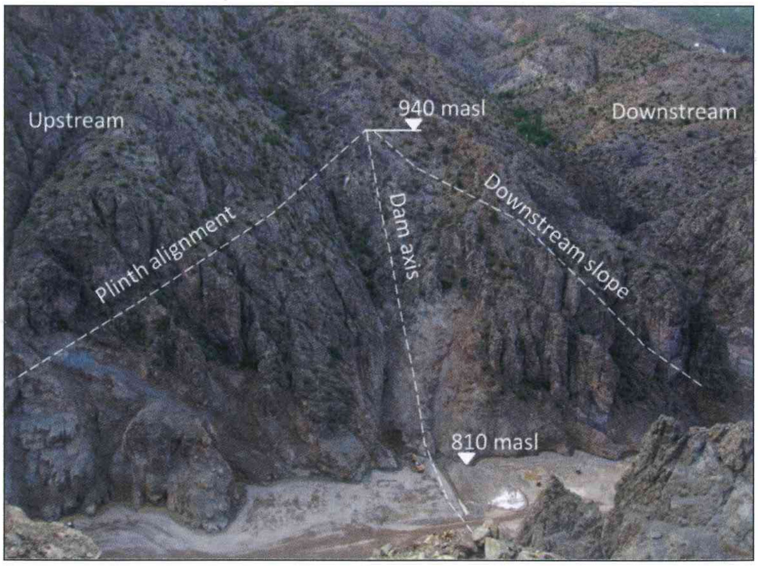


Fig. 2. Left abutment of Arkun main dam site during the initial phase of dam body fill works.

The right abutment in particular is very steep and has considerable joints, faults and cracks (Fig. 2). The preparation of the abutments has to be done from base to top, progressing slightly ahead of the fill works because of a lack of access at higher elevations. The top-to-down method would have required too many resources in terms of costs and time, which was considered to be uneconomic for a 'fast track' project such as the Arkun dam. Blasting, rock removal and fill replacement works are slowing the dam construction progress down, but it is proceeding on schedule, in spite of these hindrances.

The strength, and overall geological evaluation of the dam site, indicate minor problems regarding stability and permeability with regard to foundation, excavation and long-term behaviour of the dam. An overwhelming percentage of the cores taken showed good to very good rock properties (TCR ≈ 100 per cent, RQD ≈ 80 per cent) at the dam site, according to standard rock classification systems. At fault and joint zones, the rock surfaces exhibited less strong characteristics, showing GSI = 30-50 and UCS < 60 MPa.

The Lugeon tests at the dam site resulted mainly in values lower than 1-5 Lu, but locally gave high values of 50 Lu for greater depths (> 50 m). The alluvium portion of the foundation will be sealed by a cutoff wall and the rock will be treated by conventional grouting.

The plinth is placed on artificial fill, 25 m deep, to avoid placing the foundation directly onto the natural alluvium, which shows heterogeneous stratification. Also, the total deformation at the perimeter joint could be reduced by partially replacing the natural fill with compacted sand-gravel fill and by raising the perimeter joint elevation by 25 m. Taking these advantages into consideration, it was decided to increase the total depth of the cut-off wall creating savings by the reduction of the area of concrete face sealing.

3. Seepage control design of the Arkun main dam

3.1 General layout and zoning

Originally, Arkun main dam was designed as a classical CFRD with corresponding zoning, using only rockfill materials for the main sections (3B, 3C, 3D). Later, the rockfill material was largely replaced by sand-gravel fill material to be dredged from the upstream river bed. Since a considerable amount (≈ 1×10^6 m^3) of rockfill material is to be obtained from the spillway excavations, the zoning results in a free-draining downstream slope. The application of this downstream rockfill slope is economic and favourable in terms of seepage control and slope stability. Because of the less favourable elasticity modulus of rockfill compared with sand-gravel fill, the deformation behaviour is still under investigation and will be finally reviewed when first deformation measurement results are available.

A typical section of the dam design is shown in Fig. 3. Zones 3E and 3F are sand-gravel fill materials,

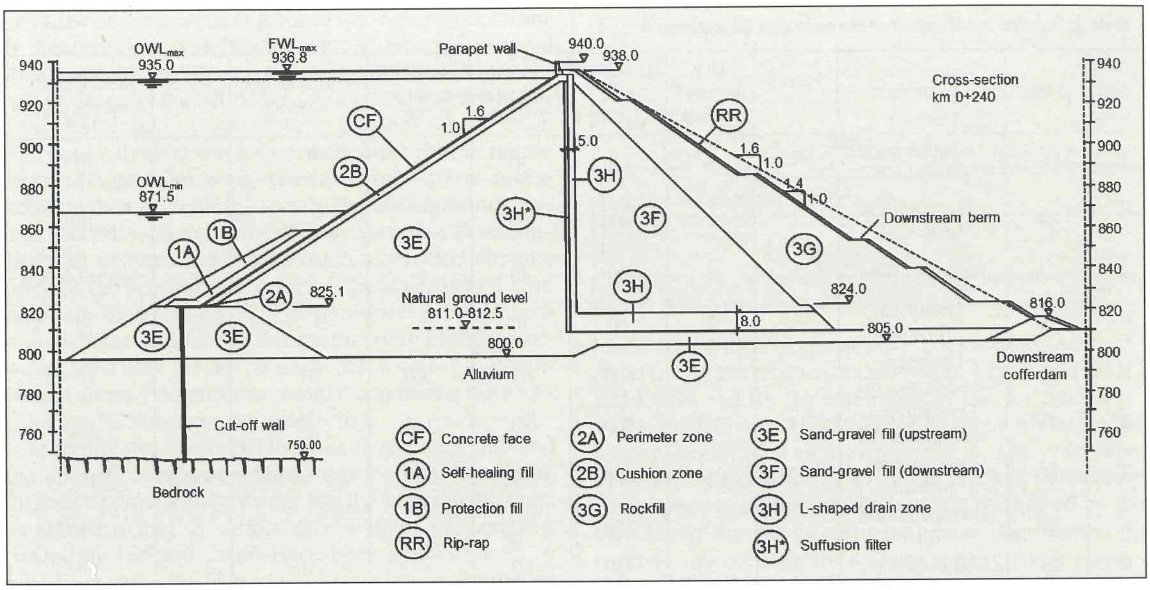


Fig. 3. Typical dam cross section (maximum height).

which are directly taken from borrow areas within the natural river bed upstream of the dam axis. Fine grained layers are excavated and separated from sand-gravel fill during the extraction works in the riverbed. Boulders larger than 600 mm were sorted manually at the borrow area and at the dam site. More details of the applied zoning are given in the next section.

3.2 Zone functions, filter design and technical specifications

Gradings according to the technical specifications for some of the fill materials are shown in Figs. 4 and 5. For zones 1A/B and 2A/B standard materials are applied as specified in ICOLD [2005[10]]. These materials are not shown in the subsequent figures.

Again, zones 3E and 3F are sand-gravel fills, which will provide both a high elasticity modulus and strong shear strength, confirmed by field and laboratory test results. The rockfill is considered to be free draining with a minimum hydraulic conductivity of $k = 10^{-2}$ m/s or higher [Sherard *et al.*, 1992[15]] and also strong shear strength behaviour resulting partly from the medium to high strength.

Before filling works were started, a considerable number of trial tests were carried out simultaneously with laboratory tests, to determine the grading limits for zone 3E and 3F, as shown in Figs. 4 and 5. The processing of the materials for 3E and 3F focused on the limitation of the maximum grain size. The fine content was generally in the allowable range.

The technical specification of the fill materials are shown in Table 2, including basic conductivity values considered for the seepage analysis. The number of passes was defined conservatively, mainly referring to local experience and extensive plate loading tests. In international practice, a lower number of passes would be enough to obtain satisfactory fill properties according to documented experience gained on international projects [Fell *et al.*, 2005[3]; Cruz *et al.*, 2009[4]; ICOLD, 2005[10]]. However, this conservative approach results in very favourable engineering properties and decreases the inherent risks.

For the checking of the filter functionality of the present interfacing materials, modern [USACE, 2004[16]; Fell *et al.*, 2005[3], Kutzner, 1996[17]] and classical (conservative) filter criteria were checked [Terzaghi & Peck, 1948[18]; USACE, 1953[19]]. The sand-gravel material is considered to be slightly suffusive after analysis of the material, according to the approach of Wan & Fell [2005[20]], which is again based on works of Kenney & Lau [1986[21]] and Burenkova [1993[22]]. Erosion and suffusion processes in the dam body and underground are generally limited to condi-

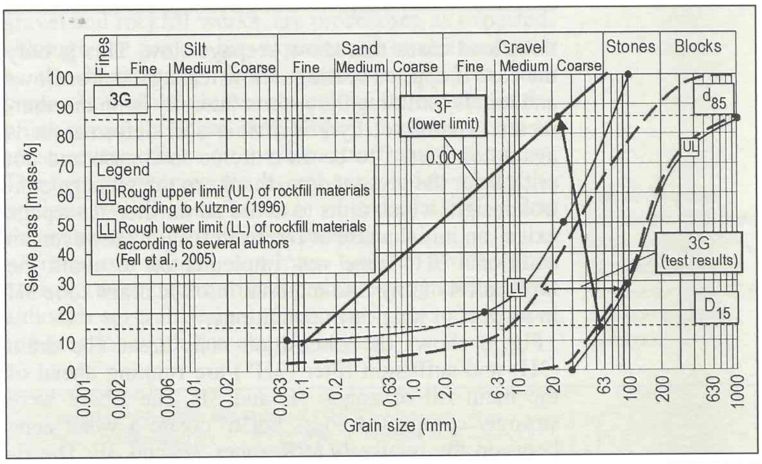


Fig. 4. Gradation of the rockfill material 3G quarried from spillway excavations and lower border of 3F sand-gravel fill material (interface).

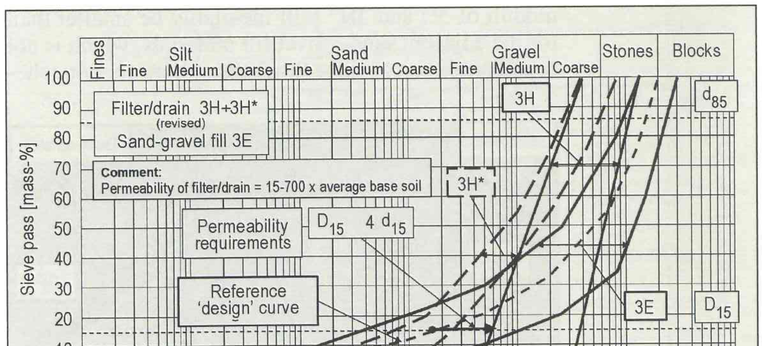


Fig. 5. Sand-gravel 3E, drain 3H and suffusion filter 3H gradations.*

Table 2: Technical specifications of the main dam fill materials[1)]

No.	Name	Description	Passes (-)	Dry density[4)] S_d (g/cm³)	Max. grain size d_{max} (mm)	Layer thickness T (cm)	Elasticity modulus E (MPa)	Permeability k (m/s)	Water (l/m³)	Model 'Set0' k-values (m/s)[6)]
1	1A[3)]	Cohesionless fine grained soil	-	-	63	30	-	-	-	10^{-5}
2	1B[3)]	Fill, protection material	-	-	400	60	-	-	-	10^{-4}
3	2A	Perimeter filter	8	2	40	40	-	-	-	Not modelled
4	2B	Transition filter 1	8	2	80	40	-	-	-	10^{-5}
5	3E	Upstream sand-gravel fill	12	2.5	400	60	200	10^{-4}	5)	10^{-4}
6	3F	Downstream sand-gravel fill	12	2.5	600	80	200	10^{-4}	5)	10^{-4}
7	3G	Downstream rockfill	12	2.2	600	80	80[2)]	10^{-1} to 10^{-2}	250-500	10^{-1}
8	3H	L-shaped drain /filter	8	1.9	150	60	-	10^{-2}	-	$5\text{-}10^{-2}$
9	3H*	Suffusion filter	8	2	150	60	-	10^{-3}	-	10^{-3}
10	RR	Rip-rap	-	-	1500	150	-	10^{-1}	-	Not modelled

1) For all materials, a smooth drum vibrator compacter (SDVC) with a static weight of 15-16 tons will be used. The speed is limited to 2.5-3.5 km/h.
2) This value reflects the target value which was not included in the TechSpecs and the civil contract.
3) For fill materials upstream of the face slab (1A, 1B) no or only slight compaction work is required.
4) The given values reflect check values which are controlled during construction.
5) The sand-gravel fill needs no watering since the residual moisture content is close to the optimum moisture content. If too dry, the material should be watered before compaction by pressureless water. The material must not be completely saturated.
6) 'Set0' reflects the standard set of applied conductivity values for the seepage analysis. For 'Set1' the seepage relevant zones were increased by a factor of 10, and for 'Set2', decreased by this factor. For 'Set3', only the sand-gravel materials (3F, 3E, alluvium) were assumed to show a permeability of $k = 10^{-3}$ m/s.

tions/load cases that show seepage flow. This is only the case if applied sealings show leakage and/or flows and rain is intruding the system laterally from the abutments. Therefore, hydrodynamic soil deformation is again considered to be an extreme load case and not critical for the present dam, thanks to the seepage control design, which aims to avoid an unfiltered seepage exit as an initial phase of internal erosion. However, an additional 3H* zone was implemented to avoid the infiltration of any fine material into the drain zone 3H in respect of long-term conditions.

Fig. 6 shows the filter/drain zone area. The drain (3H) and suffusion filter (3H*) are running ahead of the main fill of zones 3E and 3F. The filters were strongly compacted so as not to create a weak zone between the relatively stiff zones 3E and 3F. The E-moduli of 3H and 3H* will inevitably be smaller than for the adjacent sand-gravel fill materials, which is not considered critical since the drains/filters are not cohesive and in the case of larger deformation will result in only a higher permeability, which is appreciated while keeping the filter stable.

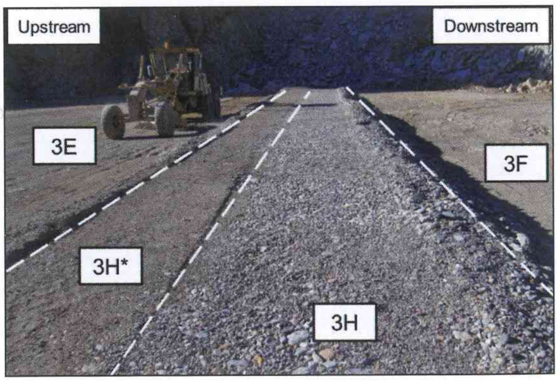


Fig. 6. Compacted zones 3E, 3H, 3H and 3G.*

In this context it should be mentioned that erosion/suffusion processes through the alluvial foundation are governed by the functionality of the cutoff wall. The construction of a 50-70 m-deep cutoff wall in alluvial soils with large blocks is likely to face some difficulties, which can be covered by the specific methodology and control works. The interface between rock and alluvium is steep and also requires special treatment so as not to leave unsealed joints/gaps.

The valley shape coefficient indicates more than a negligible influence of the geometry of the valley on the deformation behaviour in terms of stress relocation. For this purpose, a 3D static deformation model will be developed, which will generate more accurate predictions of the total deformation, particularly for the impoundment case. This will also help to give a better understanding of the required joint design of the face slab and at the plinth including the slab connection to the upstream cut-off wall.

3.3 Seepage analysis and results

The seepage control design of Arkun dam shows three lines of defence: upstream sealing (face slab, cut-off wall, grout curtain); L-shaped filter; and, rockfill zone (see Fig. 3). The main materials 3H, 3H*, 3F and 3G control the seepage conditions. In addition, leakage in the form of cracks in the face and imperfections in the cut-off wall were investigated applying leakage zones of different widths and different permeability values at critical points along the face slab as shown in the dam sketch in Fig. 8.

For the risk assessment prior to the dam slope stability analysis, investigations were done on potential steady seepage conditions caused by three sorts of leakage in the cut-off wall (CWL, 775 m), at the perimeter joint (FSC1, 825 m) and close to the crest level (FSC2, 922 masl), the last crack in consideration of the failure mode at Aguamilpa dam. Also, the situation was investigated when no sealing, or only the underground sealing, was not working. All the load cases have to be classified as extreme load cases (LCX). Selected phreatic lines of the seepage for some of the investigated load cases are shown in Fig. 7. The porewater pressure conditions in the dam body confirm that only limited porewater pressures are to be expected within the downstream slope. For extreme seepage conditions the rockfill zone 3G stays almost unaffected.

Generally, for the imperfections in the face slab and the cut-off, 10 cm openings were modelled applying different permeability values for the specific leakage, as shown in Fig. 8. Alternatively, other methods for modelling leakage could have been applied, such as pipe flow using the Hagen-Poiseuille law or similar, as was done by the author for previous case studies [Haselsteiner, 2007[23]; Haselsteiner & Ersoy, 2011[7]]. Since the inaccuracy is related not to the modelling of the imperfection, leakage or crack but to the geometry, size and type of the imperfection and surrounding zones, the simple approach applied is considered to be suitable for purpose.

The extreme load case LCX4 (leakage in the cut-off wall) was investigated for material parameters 'Set0', 'Set1' and 'Set2' as shown and explained in Table 2. 'Set1' and 'Set2' represent the variation of the permeability values applying a factor of 1/10 and 10, respectively. The basic set of parameters 'Set0' is the best guess based on both test results and analytical determination of the permeability values applying three different formulae [Reddi, 2003[24]; Beyer, 1964[25]; Sherard et al., 1992[26]].

For the load case LCX4, the line of seepage does not practically change after applying 'Set0,1,2' parameters. But the seepage flow increases by a factor of 100 from q_{tot} = 0.33 l/s to 32 l/s, which confirms the theoretical quotient of k_{Set1}/k_{Set2} = 100. This shows that the porewater pressures can be controlled allowing corresponding seepage amounts.

In Fig. 8 the total seepage flow and the pressure head in the drain and beneath the face slab are shown for the three types of leakages investigated. The results show that a leakage zone in the foundation is more critical than in the face slab, as in the face slab adjacent zones contribute to seepage control, whereas the cut-off directly interfaces with the natural alluvial foundation, which shows a high permeability and allows a corresponding pressure head development in the dam body. For the three investigated leakage conditions, the L-shaped filter (3H) is considered to be effective and could decrease the porewater pressure to a maximum of 813 m at the drain.

Only for very unrealistic and low probability system conditions (LCX1 'Complete sealing is not working', LCX2 'Underground sealing not working') is the L-shaped filter capacity not sufficient to control the seepage in the dam and the phreatic line of seepage develops in zone 3F before it is controlled by the rockfill zone 3G (see Fig. 7, LCX1). For the usual load cases, the seepage control system fully controls the porewater pressure conditions. This is also typical for extreme load cases with leakage at different locations and with different characteristics as shown in Fig. 7 for LCX3 and LCX4 and for the conditions in Fig. 8 ('Set3').

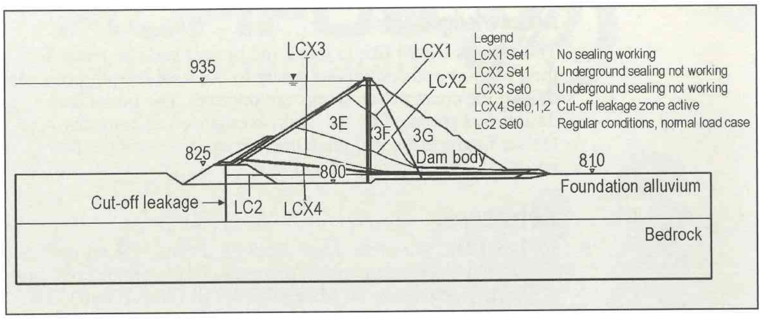


Fig. 7. Phreatic line of seepage in the dam body of Arkun main dam for selected load cases.

The crack characteristics have a crucial effect on the seepage conditions as shown in Fig. 8. The graph also illustrates the conditions when the crack is controlling the seepage conditions and when it is controlled by the dam body. For the investigated cases, the dam body controls the seepage for a characteristic crack permeability of k > 10^{-3} m/s, the crack is the control for a permeability of k < 10^{-6} m/s.

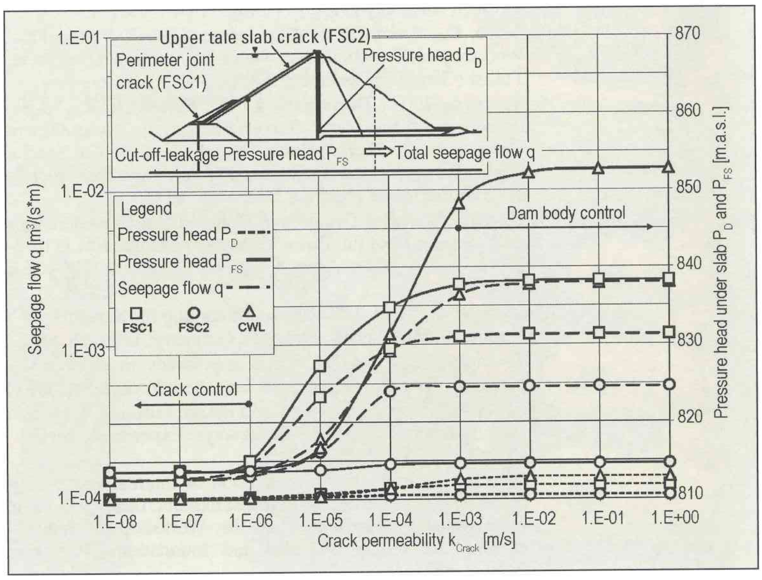
4. Project status and perspective

The dam body filling works were 30 per cent complete at the end of October 2011, reaching a level of 840 m, and the expected completion date is January 2013. All of the dam works will be completed in mid-2013. The completion of the whole project is scheduled for the beginning of 2014.

The works at the main dam, especially the sand-gravel and rockfill works, are proceeding as expected, although the project has experienced hindrances such as the installation of the monitoring system. The preparation of the abutments and the foundation of the plinth along the steep side slopes is not expected to cause severe effects on the dam construction progress. The first monitoring results are expected to verify the preliminary test data in terms of compressibility and shear strength of the applied materials.

Works on the 14 km-long tunnel, which were assumed to be on the critical path, are progressing well, although several design adjustments were made after construction work had already begun. ◊

Fig. 8. Seepage conditions (pressure head, seepage flow) for 'Set3' material parameters and three different types of leakages.



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References

1. **ICOLD,** "Concrete Face Rockfill Dams – Concepts for Design and Construction", International Committee on Large Dams, Committee on Materials for Fill Dams (Draft), 2005.
2. **ANCOLD,** "Ancold Guidelines on Concrete-Faced Rockfill Dams", Australian National Committee on Large Dams (ANCOLD), Tasmania; 1991.
3. **Fell, R., MacGregor, P., Stapledon, D., Bell, G.,** "Geotechnical Engineering of Dams", A. A. Balkema Publishers, Leiden London New York Philadelphia Singapore; 2005.
4. **Cruz, P. T., Materon, B., Freitas, M.,** "Concrete Face Rockfill dams", Dados Interncaionais de Catalogacao na Publicacao (CIP), Brazil; 2009.
5. **Hunter, G., Fell, R.,** "The deformation behaviour of rockfill", UNICIV Report No. R-405, ISBN: 85841 372 8, The University of New South Wales, Sydney, Australia, 2002.
6. **Hunter, G., Glastonbury, J., Ang, D., Fell, R.,** "The Performance of Concrete Face Rockfill Dams", UNICIV Report No. R-413, ISBN: 85841 380 9, The University of New South Wales, Sydney, Australia; 2003.
7. **Haselsteiner, R., Ersoy, B.** "Seepage control of concrete faced dams with respect to the surface slab cracking", *Proceedings,* 6th International Conference on Dam Engineering, Lisbon, Portugal; 2011.
8. **Pinto, N. L. de S.,** "The design and construction of extra high CFRDs, *Hydropower & Dams*; Issue 3, 2009.
9. **Montanez-Cartaxo, L. E.,** "The Perimetric Joint Design for Aguamilpa Dam", *International Water Power & Dam Construction*, April Issue, pp 22-28, 1992.
10. **ICOLD,** "Concrete Face Rockfill Dams – Concepts for Design and Construction", International Commission on Large Dams, Committee on Materials for Fill Dams (Draft); 2005.
11. **Makdisi, F. I., Seed, H. B.,** "A simplified Procedure for estimating earthquake-induced deformations in dams and embankments", Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, California, USA; 1997.
12. **Day, R. W.,** "Geotechnical Earthquake Engineering Handbook", McCraw-Hill; 2002.
13. **Jeffries, M., Been, B.,** "Soil liquefaction", Taylor & Francis Group; London New York; 2006.
14. **USNRC,** "Liquefaction of soils during earthquakes", National Academy Press; Washington DC, USA; 1985.
15. **Sezer, U.,** "Çoruh River Development Plan", International Workshop on Transboundary Water Resources Management; Tbilisi (Georgia); December 2009.
16. **Sherard, J. L., Dunnigan, L. P., Talbot, J. R.,** "Basic Properties of Sand and Gravel Filters", In: Embankment Dams: James L. Sherard Contributions (Geotechnical Special Publication), Sherard & Singh (Editors), American Society of Civil Engineers (ASCE); December 1992.
17. **USACE,** "General Design and Construction Considerations for Earth and RockFill Dams", Engineer Manual EM 1110-2-2300, United States Army Corps of Engineers (USACE); 2004.
18. **Kutzner C.,** "Erd- und Steinschüttdämme für Stauanlagen", Ferdinand Enke Verlag, Stuttgart, Germany; 1996.
19. **Terzaghi, K., Peck, R.,** "Soil mechanics in engineering practice", John Wiley and Sons Inc.; New York, USA; 1948.
20. **USACE,** "Filter experiments and design criteria", Technical Memorandum No. 3-360, Waterways Experiment Station, Vicksburg, USA; 1953.
21. **Wan, C. F., Fell, R.,** "Investigation of Internal Erosion by the Process of Suffusion in Embankment Dams and their foundations", Contribution to the Workshop of internal erosion and piping of dams and foundations. Aussoise, France; 2005.
22. **Kenney, T. C., Lau, D.,** "Internal stability of granular filters", *Canadian Geotechnical Journal*, Vol. 22, No. 2, 1985.
23. **Burenkova, V. V.,** "Assessment of suffusion in non-cohesive and graded soils. In: Brauns, Heibaum & Schuler (Editors): Filters in Geotechnical and Hydraulic Engineering, Balkema, The Netherlands; 1993.
24. **Haselsteiner, R.,** "Hochwasserschutzdeiche an Fließgewässern und ihre Durchsickerung", PhD-thesis, Lehrstuhl und Versuchsanstalt für Wasserbau und Wasserwirtschaft, Mitteilungsheft Nr. 111, Technische Universität München; Munich, Germany; 2007.
25. **Reddi, L. N.,** "Seepage in Soils", John Wiley & Sons; New Jersey 2003.
26. **Beyer, W.,** " Zur Bestimmung der Wasserdurchlässigkeit von Kiesen und Sanden aus der Kornverteilung", WWT, Vol. 14, No. 6; 1964.

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