6TH INTERNATIONAL CONFERENCE ON DAM ENGINEERING
C.Pina, E.Portela, J.Gomes (ed.)
Lisbon, Portugal, February 15-17, 2011

SEEPAGE CONTROL OF CONCRETE FACED DAMS WITH RESPECT TO SURFACE SLAB CRACKING

Ronald Haselsteiner[*] **and Burcu Ersoy**[†]

[*] EnerjiSA Enerji Üretim A.Ş.
Ceyhun Atıf Kansu Cad. Ehlibeyt Mh. Başkent Plaza No: 106 Kat: 8 Balgat/Ankara, Turkey
e-mail: rhaselsteiner@ernjisa.com.tr, webpage: http://www.enerjisa.com.tr

Keywords: CFRD, CFSGD, sand-gravel fill, rockfill, cracks, seepage, erosion

Abstract. *Concrete faced rockfill dams (CFRD) usually show free draining characteristics thanks to the use of very coarse rockfill. This means pore water pressure cannot develop in the dam body where cracking occurs within the face slab. Recent case studies confirm that although long and wide cracks occurred in the surface slab the arising seepage flow did usually not endanger the overall stability of the dam. Of course, seepage conditions always have to be assessed in terms of internal erosion processes in order to guarantee stable long-term conditions.*

A different situation arises where, instead of coarse rockfill material, gravels or sand-gravel soils are applied as main fill materials. In this case, the fill material does not show a free draining character but a permeability of less than $k = 10^{-4}$ m/s. Therefore, a sophisticated dam design which incorporates extra draining zones is required for concrete faced sand-gravel fill dams (CFSGD). This difference is critically dependent on the construction materials used. Where "dirty" sand-gravel fills are used the seepage control/drainage concept and the applied zoning contributes crucially to the long-term stability of the dam.

This paper summarizes the fundamental design principles for CFRD and CFSGD. The results of parameter studies applying 2D FEM seepage analyses for two concrete faced dam case studies assuming cracks in the concrete face sealing are discussed. The case study dams are located in Turkey where earthquake plays an important role. The case studies were investigated in the course of optimization works and technical reviews during tender and/or detailed/final design stage.

1 INTRODUCTION

The application of concrete faced dam types currently competes with RCC dam type all over the world when the general constraints are suitable for both types regarding mainly geology and available materials. Both types reflect the most economical and safe dams considering global failure statistics[1] and their wide application area. When compared with competing dam types the advantages of the RCC dam type are the possibility of combining the concrete dam body and the spillway, overtopping resistance,

---

[†] Fichtner GmbH & Co. KG, Turkey

rapid construction progress and simple construction techniques, Additionally, culvert structures may be favorable for the diversion works avoiding the usually required diversion tunnel(s). Of course, concrete dams show higher resistance against overtopping and, therefore, offer a lower hydrological/hydraulic risk which may be considered by the choice of a shorter recurrence period. Finally, the result of a cost-benefit analysis is decisive assuming that all competing types provide the same safety level.

"*Safety of CFRDs depends in the proper design, construction, and monitoring of actual behaviour during the construction and during the operation of the structure*"[5]. The formation of the concrete face slab is one critical aspect, particularly during first impoundment and earthquake. Concrete faced dams show usually favourable seepage conditions if the sealing and drainage system is fully working and no considerable seepage intrusion from the abutments occurs. Therefore, for the regular load cases the dam body is assumed to stay dry so that the effective stresses are not reduced by the pore water pressure. The calculated factors of safety (FoS) against slope failure usually provides no problem and meets the requirement for a FoS = 1.5-2.0[2,3] for the normal load case. Upstream and downstream slopes are usually dry and the critical slope is usually the downstream slope since the upstream slope is stabilized by the water load for the Normal Operation (NO) load case. For End of Construction (EoC) a lower safety factor is required and the slope stability for both slopes are usually not critical if the foundation is not subject to consolidation or shows low strength sliding layers such as natural interbedded clay or silt layers.

For unusual load cases such as First Impoundment (FI) and Operational Basis Earthquake (OBE) and extreme load cases considering the Maximum Design Earthquake (MDE) cracking can eventually not be excluded and seepage intrusion into the dam body has to be considered. For the downstream slope appropriate zoning may avoid critical seepage conditions so that usually this load case should not be critical. For the upstream slope the conditions are not critical as long as the reservoir level stabilizes the slope. But, if the reservoir level is drawn down in order to repair damage or decreases due to seepage losses created by the cracks, critical seepage conditions may occur beneath the face slab the unsteady seepage conditions have to be analyzed. This evaluation has to consider the decreasing water table of the reservoir which is simultaneously decreasing the stabilizing water load and the changing pore water pressure within the dam body governed by the applied zoning. An unsteady numerical seepage analysis may shed light on probable critical situations and risks. This analysis can be used for the design of the drainage system and/or for the identification of the most unfavourable pore water pressure conditions at the upstream slope. The pore water pressure is reduced both by back flow through the upstream cracks if these cracks stay open and by the normal drainage outflow directed to downstream.

Internal erosion usually plays no decisive role and should be covered by prudent design work. Assuming constant geohydraulic conditions and parameters which show variability regarding only their un- and saturated behaviour usually steady flow analysis are sufficient for all load cases including cracking. For the load case "Cracking & Drawdown" an unsteady seepage analysis may be required in order to assess the actual seepage conditions and corresponding risks for the upstream slope. In this context, the lower reservoir level may result in a total failure but will not lead to catastrophic downstream flooding if the reservoir is already empty.

Differently to some literature sources, concrete faced rockfill dams (CFRD) and concrete faced sand-gravel fill dams (CFSGD) are distinguished within this paper with regard to the construction material for the main fill within this paper. Rockfill is exploited from rock quarries. Sand-gravel fill material is usually encountered in the form of river deposits (alluvium). The distinguishing of both types is not always clear since almost all CFSGD rockfill material is used within corresponding zones et vice versa.

2 TYPICAL DESIGN OF CONCRETE FACED DAMS / LOAD CASES

Since the CFRD (Figure 1) and CFSGD (Figure 2) dam types described emerged as reliable, economical structures, the number and height of those dams has increased constantly. Also experience and knowledge were gathered both from practice and research. The result is that several design standards, engineering manuals, books and technical bulletins were prepared by national and international dam organizations and engineers[2,34,6]. Also, the dam engineering community was eager to share their experience. Therefore, literature provides helpful recommendations and instructions of how to avoid critical mistakes and cracks and to improve the deformation behavior of the concrete face slab[5,10,12,13,15,16,17].

Concrete faced dams usually have steeper slopes than other embankment dam types since within the main body limited seepage flow and no pore water pressures are assumed to occur for the normal load cases such as "Normal Operation" (NO) and also operational, regular "Rapid Drawdown" (RD) load cases. But, experiences have shown that cracking of the surface slab frequently causes considerable seepage flow through the dam body. This cracking occurs frequently during the load case "First Impoundment" (FI). CFRD are usually designed for withstanding very high seepage flow without allowing the development of high pore water pressures in the dam body and, particularly, beneath the surface slab. This advantage of CFRDs is usually also valid for CFSGDs, but has to be guaranteed by a corresponding adjustment of the zoning/design including an appropriate selection and elaborate specification of the available materials.

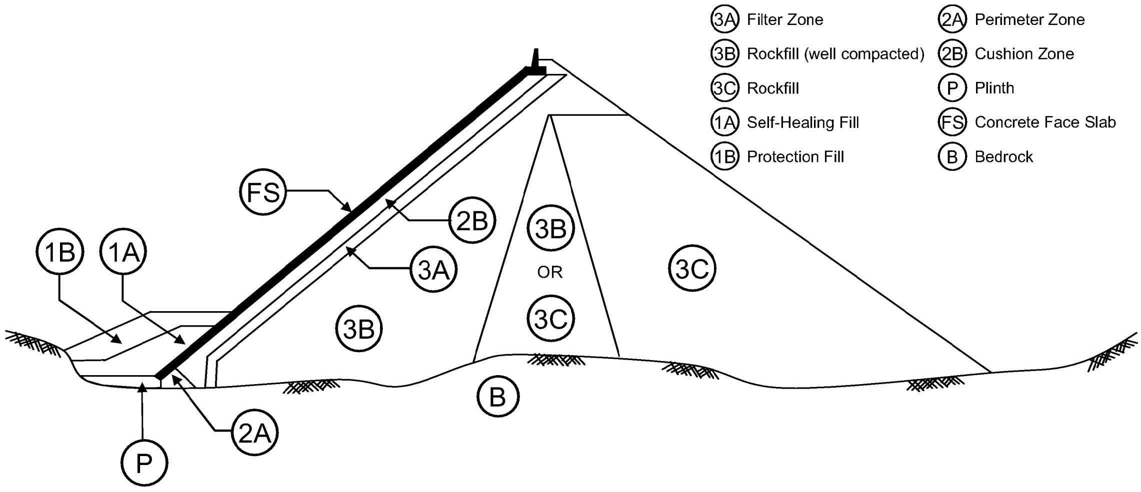

Figure 1: Standard CFRD section/zoning (adapted from ICOLD, 2005[6])

To avoid strong seepage intrusion through cracks in the concrete slab several "defence lines" are usually applied. These means shall avoid the occurrence of persisting cracks, limit the amount of seepage and shall enable self-healing effects. Both zoning/materials and the joint design may offer elaborate structural precautionary measures which are explained and discussed in detail in literature[3,6].

The nomination/classification of the zoning of concrete faced dams has to be specified for each project in consideration of the available materials, applied zonings and other constraints. In Figure 1 a typical section of a CFRD is shown. A uniform classification is not available, but Fell et al. (2005)[3] the most common classification is shown which corresponds approximately to the approach of ICOLD[6].

In general, CFSGD types are handled as CFRD as the general approach for the design and construction of CFRDs and CFSGDs correspond to each other. But as shown later in this paper some aspects have to be evaluated and handled differently. In Figure 2 a principle sketch of a CFSGD section is shown. The different applied fill materials are separated by a L-shaped drain/filter to control the seepage flow and flow resulting from the occurrence of cracks. As discussed below, if dirty rockfill or dirty sand-gravel fill is explicitly used only within zones 3C and/or 3D where seepage flow is unlikely to occur.

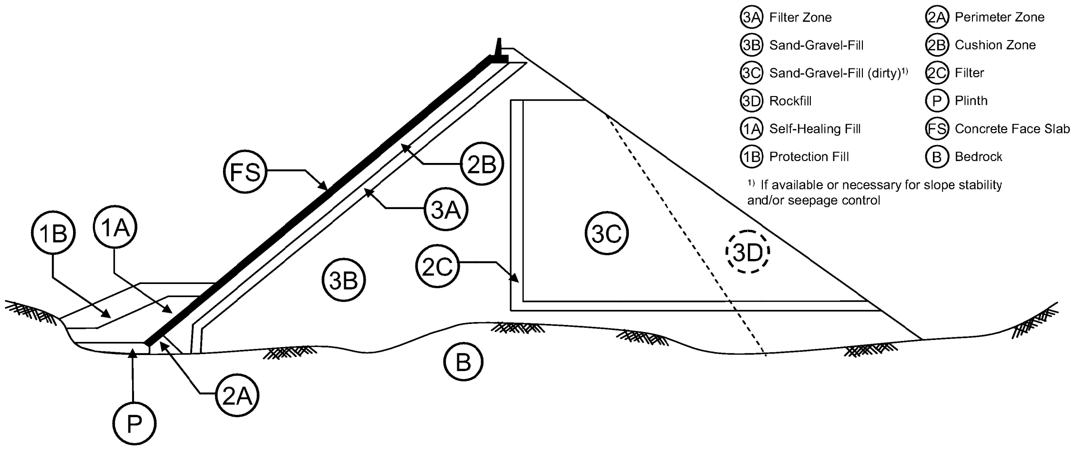

Figure 2: Standard CFSGD section/zoning (adapted from Fell et al., 2005[3])

Due to economic aspects, the application of sand-gravel fill materials, mostly alluvial deposits, is gaining more and more relevance for the selection of the dam fill materials. Since processing (sieving, washing, etc.) is cost intensive also “dirty” sand-gravel fill material is sometimes used with a percentage of fines exceeding more than 10-12 % which reflects more or less the specified limit for the percentage of fines for “clean” rockfill or sand-gravel fill. Seepage flow through zones consisting of “dirty” sand-gravel fill should be only allowed if internal erosion can be excluded. Otherwise, the draining system/zoning has to be designed such that, if crack induced seepage flow or other seepage intrusion occurs the “dirty” zones stay unaffected. In this context, the authors recommend a high factor of safety (FoS) for the layout of the drainage bodies/layers of about FoS = 5[7]. Unspecified materials always are an invitation to use materials randomly that is strictly refused by the authors.

As shown and proven in literature[8,9] a considerable pore water pressure reduction is obtained by applying sealing and/or drainage layers with a permeability difference of at least 1,000 times. But, the maximum permeability difference of interfacing layers should not exceed the factor of 100 as a rule of thumb in order to meet filter requirements. This simultaneously leads to difficulties in meeting filter criteria if less than two are applied.

3 CRACKING OF CONCRETE SURFACE SLABS OF CFRD AND CFSGD – EXPERIENCES, REASONS, CONSEQUENCES & RISKS

3.1 General

Rockfill material in dams and landfills was placed by dumping before modern machinery and techniques were invented and introduced in dam practice. This "old" approach led to enormous deformations which made it risky to apply a deformation sensitive concrete face slab. After the implementation of modern machinery and techniques and the formulation of technical specifications for the different zones the application of concrete faces turned out to show strong advantages regarding seepage, slope stability and, therefore, economical aspects for dam structures.

For high CFRD the Brazilian Foz do Areia Dam with H = 160 m was considered as milestone for the CFRD technique in 1990. Ten years later the Tianshengqiao CFRD with H = 178 m was completed in China in 2000. Afterwards in 2007, the Shuibuya CFRD was built to a height of H = 233 m which was the highest CFRD at the time[10]. The trend heads towards CFRDs with heights of over 300 m[11].

3.2 Experiences with Cracks and Leakage in Concrete Faced Dams

Mendez & Perez (2007)[12] compiled the leakage experiences of selected high CFRD all over the world and compared these benchmark values with the Mexican El Cajon CFRD with H = 188 m. With a total seepage flow of only 150 l/s the El Cajon Dam showed relatively favourable results. Therefore, for El Cajon CFRD no measures were taken to reduce seepage flow after impoundment. Other projects showed more difficulties. For example, the initial seepage flow reached values up to 1,700 l/s at the Ita Dam in Brazil.

For Shuibuya Dam in China a total seepage flow of 40 l/s was recorded[13] which is considered to be an acceptable and favorable value for this high dam. Also Kutzner (1996)[14] and Hunter et al. (2003)[18] discussed CFRD projects worldwide with regard to observed seepage flow data. Worth mentioning is the Shiroro CFRD in Nigeria with H = 125 m which showed a seepage flow of 1,700 l/s after first impoundment. This value was reduced to only 100 l/s by simply flushing silty sand into the joints/cracks. Extreme values were recorded at Fades CFRD in France where 2,000 l/s seepage flow occurred, including abutments and precipitation[14]. Fell et al. (2005)[3] referred to more CFRD case studies which showed even higher leakages such as Scofield Dam with a maximum of 5,600 l/s. Scofield Dam also suffered from erosion processes.

The 202 m high Campos Novos Dam sustained huge vertical and horizontal cracks which occurred before 90 % of the reservoir level was reached in 2007. The maximum observed seepage flow was 1,400 l/s which made the responsible engineers perform a complete drawdown. The critical stability situation never occurred[15]. By applying a rockfill material with an elasticity modulus of 50-60 MPa the deformation behaviour was within the expected range and corresponds to the experiences gained for other projects with high CFRD structures. Similar results could be observed for the Barra Grande CFRD (H = 185 m) which also showed strong seepage flows of 1,300 l/s[10].

For Aguamilpa Dam[16] with a height of 187 m both rockfill and alluvium material were used. The main fill material was sand gravel fill, hence, Aguamilpa Dam is considered to be the highest CFSGD for the present time. The leakage reached a value of maximum 200 l/s[3]. Several other high dams were constructed by using sand-gravel fill materials exploited from alluvial deposits such as the Salvajina Dam with H = 148 m and the Golillas Dam with H = 125 m[3].

Most cracks occur during the first impoundment. The maximum slab deformation provides an indication of the overall deformation behavior. Case studies showed extreme values of over 1.0 % of the dam height, as for the Salt Spring CFRD with H = 100 m. This extreme value was obtained due to the application of dumped rockfill material. Referring to selected case studies this value reaches usually a smaller range of 0.05-0.5 % of the dam height[18]. For example, Shuibuya CFRD (H = 233 m) showed a value of 0.5 % of its height[5].

Also during the first impoundment of Aguamilpa Dam (H = 220 m) persistent cracks of the concrete surface slab occurred which showed a maximum width of 15 mm and were located within the upper slab area[10]. Aguamilpa CFSGD has an upstream dam body of sand-gravel fill material and a downstream shell of rockfill showing less elasticity moduli than the upstream zone. This led to a deflection of the concrete slab at the upper region. The cracks within the cushion zone (2B) at Tianshengqiao CFRD (H = 178 m) in China reached a width of 50 mm, a length of 96 m and a depths of 1.5 m. Later on the vertical joints suffered damage due to compression. The vertical cracks were 24 m in length and 1 mm wide on average. In order to avoid damage/cracks the Tianshengqiao CFRD was impounded in several stages. Several other dams showed cracks close to the plinth where usually the critical deformations occur during first impoundment, as it was the case for Ita and Itapebi Dams in Brazil[17]. For Shuibuya dam a huge number of small cracks were encountered during the first filling. The maximum deformation of the concrete slab was 1.18 m which was twice as much as predicted during the design phase when a maximum deformation of 0.50 m was determined[5]. This maximum deformation of the concrete slab occurred approximately at one third of the dam height.

Up-to-now only one dam using sand-gravel fill is reported to have failed. The Gouhou Dam in China with H = 140 m also showed some design “miracles”. Hence, the failure was not only related to the choice of unsuitable materials and an unfavourable design but also to missing an effective draining zone[3].

Although the height of the CFRD structures has steadily increased and extra-high dams were constructed, the valuable experience and knowledge gained in the 1980s and 1990s contributed to the fact that settlement and cracking could be limited. Such was the case for Chinese projects Hongjiadu CFRD (H = 179.5 m), Sanbanxi CFRD (H = 186 m) and Shuibuya CFRD (H = 233 m) applying sophisticated rockfill materials and specifications guaranteeing an elasticity modulus not less than 80-100 MPa[10].

3.3 Reasons for Slab Cracking

Harmful cracks are usually caused by unfavorable deformation of the dam body itself, the foundation or the abutments which affects the concrete slabs. Cracks can be classified as shrinking cracks (Type A), bulging cracks (Type B), and settlement cracks (Type C)[18]. Shrinking cracks show usually a width of less than 1.0 mm and, therefore, are of minor interest in regard to seepage aspects. Bulging cracks occur usually during construction. These deformations can be caused by static or dynamic loads. A critical load case in regard to cracking reflects the first impoundment. Referring to several well monitored load cases the settlement in the course of the first impoundment frequently reached 50 % of the total long-term settlement and more[18]. Particularly, if no pre-settlement was allowed and low elasticity moduli of the applied rockfill materials (< 25 MPa) are achieved. Compression cracking is sometimes the result of creeping tendencies of the banks. Of course, locating the dam body and the plinth on compressible soils, mainly alluvial deposits, increases the potential deformations in comparison to foundations on suitable bedrock.

As stated for the Shuibuya CFRD in China[5] the cracks occurred because the actual in-situ rock material parameters did not conform to the parameters assumed for the design. Therefore, the design of the slab could not fully meet the actual loading and deformation.

Earthquakes can lead to a direct displacement of the concrete slab blocks and the failure of the joint sealing components such as copper inlays. Applied fill materials can be loosened or sheared which also leads to instabilities or settlements.

After the Wenchuan earthquake 2008 in China ICOLD members gathered data in order to describe the occurred damages and their reasons[19]. Some CFRD dams in China showed damage to the slab's jointing system for both horizontal and vertical joints. Refurbishment measures were carried out, e. g., at the Zipingpu CFRD[20]. At Zipingpu CFRD the horizontal acceleration reached 0.5 g and the settlement at the crest was 0.74 m. The earthquake caused a prompt increase of the seepage flow from 10 l/s to 19 l/s[13].

Further, earthquakes can lead to a compaction or loosening of the fill material underneath the slab. Usually, the discussed types of dams are not subject to liquefaction thanks to the choice of the dam fill materials. Also, waves can cause an impulse on the blocks which may lead to displacements. An indirect threat is reflected in landslides which may cause a direct impulse onto the concrete face or cause shock waves. Shock waves may cause overtopping which can show critical consequences for embankment and rockfill dams due to their sensitivity against surface erosion processes.

Complete failure of modern CFRD or CFSGD has only singularly occurred up to now due to their usually prevailing favorable seepage and stability behavior. Only when unexpected loading/deformation conditions and a suboptimal design/zoning occurred in combination with inappropriate construction quality, e. g., as it was the case for Gouhou Dam (China) in 1993[21].

Mostly, during first impoundment with its corresponding unsymmetrical deformation patterns caused by the water loading, large cracks occur. Rarely, large cracks occur during construction until the end of construction. Experience with earthquake loads onto concrete face sealants were collected mainly during the last huge earthquake in China 2008[19,20]. Dam failures caused by face slab cracking during first impoundment or operation are not recorded or documented in the considered literature.

The occurrence of cracks has to be evaluated in regard to the applied materials and the measured engineering parameters such as the elasticity modulus. In this context, it has to be stated that sand-gravel fill zones show a more favorable deformation behavior since the achievable deformation moduli are considerable higher than for common rockfill materials. Furthermore, the design of the joints is decisive for the allowable deformations. Particularly, for extra high CFRD the vertical joints were frequently subject of cracking processes, e. g., as it was the case for Barra Grande (H = 185 m) and Campos Novos (H = 202 m) in Brazil as mentioned in the passages above.

3.4 Consequences & Risks of Slab Cracking

When the face slab cracks, seepage may infiltrate into the dam body causing partial saturation of affected zones and corresponding pore water pressures within the dam body. The effective stresses are reduced by the pore water pressure within the affected zones. In case of inadequate design, particle transport may occur leading to internal erosion or at least, a change of the actual material properties of the affected zones.

If the draining capacity of the dam body is insufficient to control the seepage conditions the slope stability of the dam may be endangered. A global sliding failure usually leads to the formation of a breach and flooding downstream. During the Gouhou CFRD catastrophe almost 300 fatalities were reported[3,21]. Corresponding flood scenarios and risk assessment approaches/methods are described extensively in literature[3,22]. A process based assessment of the potential failure mechanism is helpful to identify the risks and to prepare emergency measures and action plans. Again, the authors would like to reiterate that CFRDs and CFSGD are safe and reliable structures which may compete with concrete gravity dams with regard to safety and long-term behavior if designed, maintained and constructed corresponding to prudent engineering practice and principles.

In most cases, a rapid drawdown is taken into consideration in order to reduce the seepage flow, but may cause sliding of reservoir slopes within the reservoir area. Also, the stability of the upstream dam slope maybe endangered by rapid drawdown if the water table within the dam body does not sink simultaneously with the upstream reservoir level. A sliding of the upstream slope in case of drawdown may also cause a complete failure but due to the lowered reservoir level the consequences would be less than for a full reservoir regarding the downstream flood resulting from a breach. But, the consequences can be fatal and need to be assessed in detail within an overall risk assessment of dams and reservoirs. A sliding of the upstream slope does not necessarily initiate breaching, particularly for low reservoir levels. If the crack occurs within the area of zone 1A the crack is expected to be closed by self-healing. If the crack occurs in the upper regions self-healing can be supported by adding fines or other materials and sealing substances.

Rockfill material may be subject to saturation settlements if saturated whereas sand-gravel fills are not likely to react as sensitively to saturation as artificial rockfill material, particularly if alluvial deposits are used for the sand-gravel fill.

3.5 Measures against Cracking and Uncontrolled Seepage Flow

If the dam design is prepared according to the principles and figures in this paper and in the cited references, both CFRD and CFSGD structures of a limited height of $H < 150$ m should not be subject to considerable cracking and/or seepage flow. Particularly helpful are literature published after 2000[3,6,10,13].

Of course, the design itself and the applied technical specifications for the compaction of the applied material are critical. Sparing investments by reducing the compaction work and the material processing may result in considerable damage requiring refurbishment works and/or a reservoir drawdown so that the investment “saved” may be used for later refurbishment measures. Heading for higher CFRD and CFSGD the materials and deformation behavior has to be analyzed accurately and extensively having also in mind the inherent risk of extremely high dams ($H > 300$ m).

Usually, simple measures are taken such as adding silty sand or flyash if the specific leakage flow per a reference area of, e. g., 10,000 m^2 of the slab surface is considerably high. As mentioned above, a considerable reduction of the seepage flow was gained for the Shiroro Dam in Nigeria.

The joint design and their deformability is especially decisive in avoiding cracks within the face slab. Compression cracks along vertical joints are frequently avoided by the application of compressible wood fillets. To avoid cracks at the toe of the slab the deformation resulting from the dam body has to be limited by guaranteeing appropriate elasticity moduli. In order to avoid cracks in the upper area of the face slab the upstream and downstream dam body should show similar deformation parameters. This could be learnt from the Aguamilpa Dam cracking as explained above.

Also, the thickness of the concrete slab and its reinforcement pattern are an important tool for avoiding cracks. Nowadays, the thickness of centre slabs is sometimes increased since compression cracks are frequently observed in this area.

Uncontrolled seepage flow is best controlled by adding drainage layers and increasing the permeability of the applied zones downstream by at least a factor of 10-100 at each interface.

The application of a self-healing zone 1A is state of the art. If cracking is expected at higher elevations this zone can be increased corresponding to the project specific requirements. At Messorochora CFRDs with H = 150 m in Greece zone 1A was formed up to 50 m above the foundation level reaching 33 % of its height.

Direct refurbishment measures require usually a reservoir drawdown and direct access to the slab. Then, new (partial) concrete linings[15] are applicable as well as geomembranes[23]. The latter can also be placed partly underwater. The application of exposed geomembrane waterstops to seal vertical cracks was used successfully for the rehabilitation of Strawberry CFRD (USA) in 2002[24].

4 SEEPAGE CONDITIONS OF DAMS WITH CRACKED SURFACE SLAB

4.1 Recommendations and Performed Analyses

For concrete faced dams the following design criteria are highlighted and recommended by the authors in order to obtain a reliable and an economic design. These recommendations certainly correspond to prudent dam engineering practice as described in the corresponding engineering codes, books and papers[3,6,10,13,14,20]:

- Increasing material permeability towards downstream shell
- High shear strength parameters at the slopes and toes
- Low deformable materials close to sensitive structures such as plinth and concrete face
- Complete sealing of the high permeable subsoil / foundation rock by cut-off walls and grouting
- Avoid seepage flow through unspecified (random) materials, also for dirty rockfill or sand-gravel fill material
- Check of consistence of design and actual construction parameters (iteratively)
- Adequate joint design in order to cover the predicted deformation
- Allowance of pre-settlement and late construction of the slab if necessary
- Staged impoundment process if necessary
- Adequate monitoring concept, particularly providing seepage and deformation measurements

If the availability of favorable, high strength, and low compressible materials is limited and/or economic reasons argue for violating some of these principles the design has to be accurately investigated, adjusted and “optimized” in order to meet the safety requirements. In this case, the slope inclination can be designed flatter to increase the dam body which contradicts to economic aspects.

However, a prudent monitoring concept enables the engineers responsible to react to the behavior of the structure. A long-term seepage control should be guaranteed in any case. The combination of sealing elements and drainage bodies should be able to control the seepage conditions also in case of extreme load cases. Often, the tailwater level submerges parts of the dam. For this case, a project specific design for the seepage monitoring is required which may be combined with a separate downstream (coffer)dam.

For concrete faced dams the situation is usually favorable compared to embankment dams. The decision of applying CFRD or CFSGD dam types is usually based on the fact that sufficient granular fill material is available and no compressible (clay) layers are located within the foundation area. Therefore, processed, selected materials are applied corresponding to the aforementioned criteria. Of course, the processing works (sieving, crushing, washing…) have to be limited in regard to costs and time. But, the authors agree that the use of random fill does not necessarily lead to a better design in consideration of both safety and economics. This does not mean that the local, natural material cannot be used for fills but it needs to be investigated and considered to be fit for purpose, and it has to be appropriately specified.

For the following case studies 2D analysis were carried out comprising both seepage and slope stability. The applied software programs are SLOPE/W and SEEP/W of the package GEOSLOPE. For the stability analysis circular sliding surfaces were investigated using the Morgenstern-Price method. For the seepage analysis steady state conditions were investigated applying Darcy-flow patterns and considering only saturated flow conditions. For the crack modeling the applied software package offers a tool which allows the engineer to model a crack along a line of the applied mesh defining the permeability and thickness of the crack. Post-Darcy flow patterns showing turbulences were not considered. Therefore, the amount of seepage flow is generally overestimated regarding the flow through the crack and underestimated regarding the hydraulic capacity of drain bodies. The authors are aware of this simplified approach but did not put emphasis on the modeling of the precise actual seepage flows and conditions, but on the general hydraulic behavior of concrete faced dams suffering cracks in the face slab.

4.2 Seepage of a CFRD with cracks

In Figure 3 a section of a case study CFRD dam located in East Turkey is shown. The height is 113 m. The foundation showed strong rocks approximately 5-10 m beneath the the river bed and the abutments. Therefore, the dam body could be placed directly on low compressibility bedrock. For the dam body up to three different rockfill materials were taken into consideration. The low strength material should be placed in the middle of the dam body, the stronger material at the shells. Within upstream zones the low compressible material should be placed with corresponding high compaction. A rough check of the slope sliding stability of the downstream face considering also the pseudo-static earthquake loads revealed that approximately a mean friction angle of $\varphi = 45°$ is required to fulfill the safety requirements (Figure 4). The pseudo-static approach was chosen to obtain an idea of the static equilibrium considering also Operation Basis Earthquake (OBE), Maximum Design Earthquake (MDE), Maximum Credible Earthquake (MCE) within the preliminary stability analysis. The authors' opinion is that the pseudo-static approach does not reflect the actual loading conditions during earthquake and, therefore, can lead to a conservative design. However, the required input parameters for dynamic modeling frequently show a wide range which also makes it difficult to evaluate the results. Hence, a sensitivity analysis is inevitable to cover the natural range of the material properties, and may contribute to decision-making in terms of design and stability assessment.

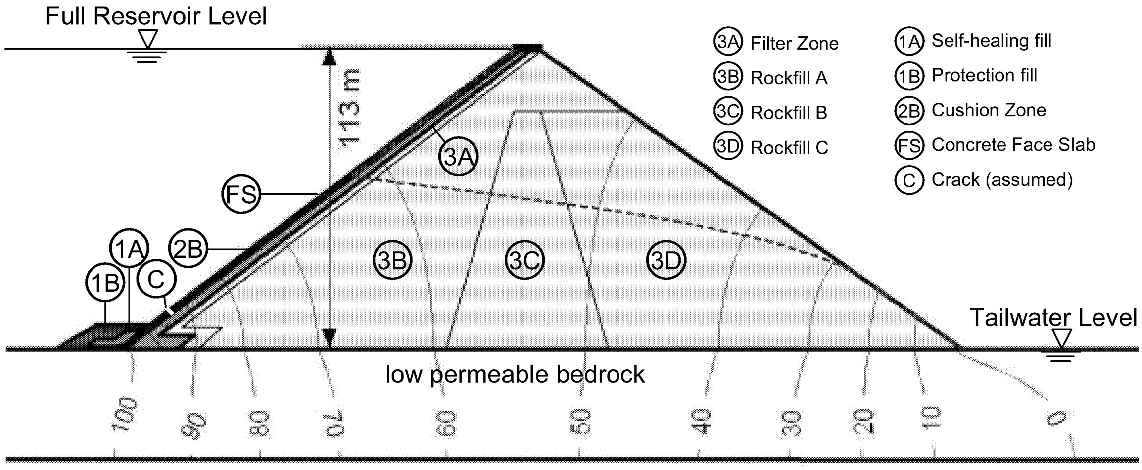

Figure 3: Typical cross-section of the concerned case study dam (showing seepage conditions with crack in the concrete face slab for $k_{2B} = k_{3A} = k_{3B} = k_{3C} = k_{3D}$)

At the downstream zone of the dam body coarse rockfill material with high permeability shall be placed. The assumption for the shown potential lines and phreatic line of seepage is $k_{2B} = k_{3A} = k_{3B} = k_{3C} = k_{3D}$ which reflects an unrealistic and conservative approach. The actual rockfill properties and dam zoning will be more favorable in terms of seepage control.

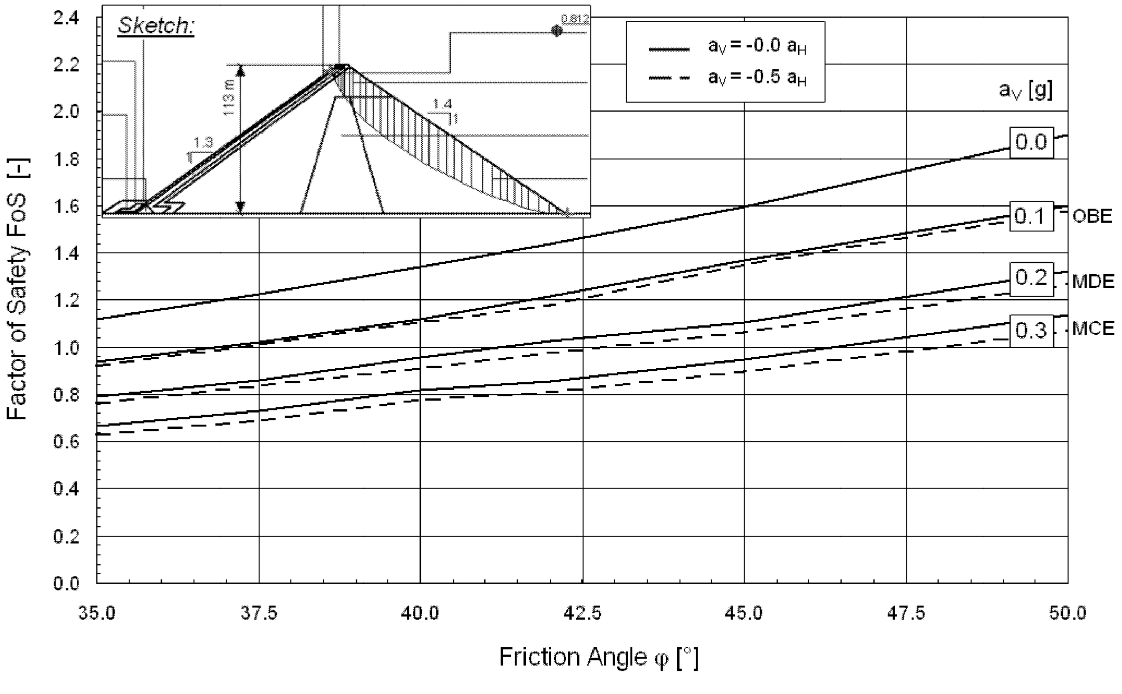

Figure 4: Factors of safety vs. friction angle regarding the slope sliding stability of the downstream slope of the case study CFRD considering pseudo-static loads of OBE, MDE and MCE

The same CFRD structure was investigated in terms of its seepage behavior in case of cracking of the concrete face slab. The results are given in Figure 5. For a crack close to the plinth a range of crack widths of T = 0.0002-1.0 m was analyzed assuming a hydraulic homogenous dam body ($k_{2A} = k_{3A} = k_{3B} = k_{3C} = k_{3D}$). For "low" permeable rockfill materials showing a permeability of $k = 10^{-5}$ m/s or less the seepage is controlled by the dam body and not by the cracks. Whereas, for high permeable rockfill materials of k = 10^{2} m/s and more the crack is likely to be the limiting factor for the seepage flow. For very large cracks with a width of T = 0.1 m and larger the dam body permeability is still the constraint which is limiting the seepage flow through the dam body if the permeability of the dam body is k = 10^{-1} m/s or more.

In practice the width, length and the depth of potential cracks is important. If superficial cracks "only" affects the face slab cushion (2B) and transition (3A) layers may control the seepage intrusion.

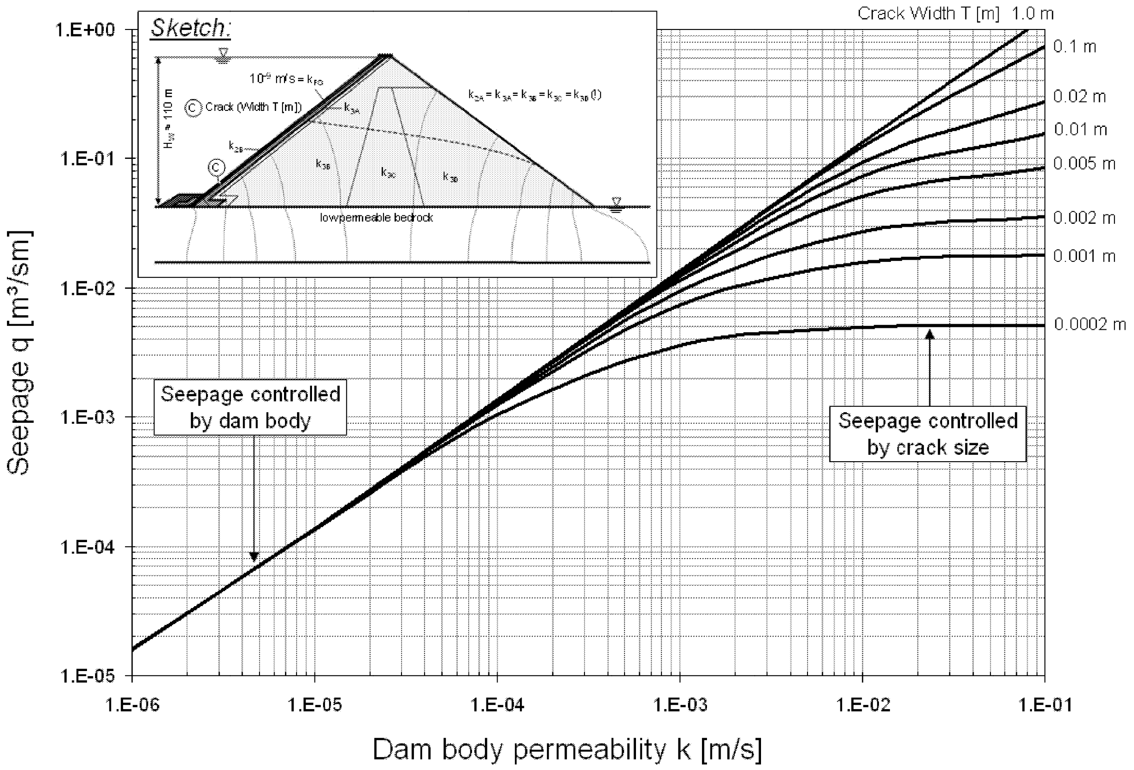

Figure 5: Seepage flow for different dam body permeabilities and various crack widths for the concerned CFRD case study

Corresponding results were already obtained by the main author for small embankments with center sealing showing cracks[9], and for large dams with leakage zones by other researchers[25,26,27]. Hence, the general behavior could also be confirmed for high CFRD dams, and in general for dams with sealings showing locally limited leakages such as cracks. Although, the crack width cannot be predicted accurately and they are controlled not only by theoretical, computable aspects such as stresses and deformations, but also by the construction works itself and its quality. However, the presented approach and similar analyses may be helpful for the responsible engineers for the process of determining the final design and the required parameters/technical specifications. Finally, the presented approach allows a cross-check of the measured values after impoundment and during operation and enables a back-analysis of the occurred cracks and their hydraulic capacity.

4.3 Seepage of a CFSGD with cracks and general aspects of sand-gravel materials

Sand-gravel fill material is usually obtained from alluvial deposits of the main river or of lateral valleys. In case of the alluvium shows considerable depth the dam body and, particularly, the plinth cannot be founded on suitable, low compressible bedrock and higher deformations have to be expected compared to a dam founded directly on bedrock. Experience worldwide shows that the depth of alluvium does generally not exceed 70 m. Only Puclero Dam rests on an alluvial deposit of over 100 m depth[5]. The alluvium is then usually sealed by a cutoff wall in order to control the seepage and avoid particle transport in the foundation[28]. If compressible fine grained (clay) soil layers are present, deep excavations may be required in order to limit the settlement. A typical CFSGD section showing a deep excavation is given in Figure 6 assuming the availability of two different sand-gravel fill materials and one quarried rockfill material.

Special attention has to be paid to the deformation behavior of the plinth structure where the highest water loads occur and deformations are expected to be largest. In order to reduce the plinth's deformation the elasticity moduli of affected subsoil zones should be appropriate. Using well compacted sand-gravel fill material the achievable elasticity moduli should be 100 MPa and more referring to studies performed in 2002[29].

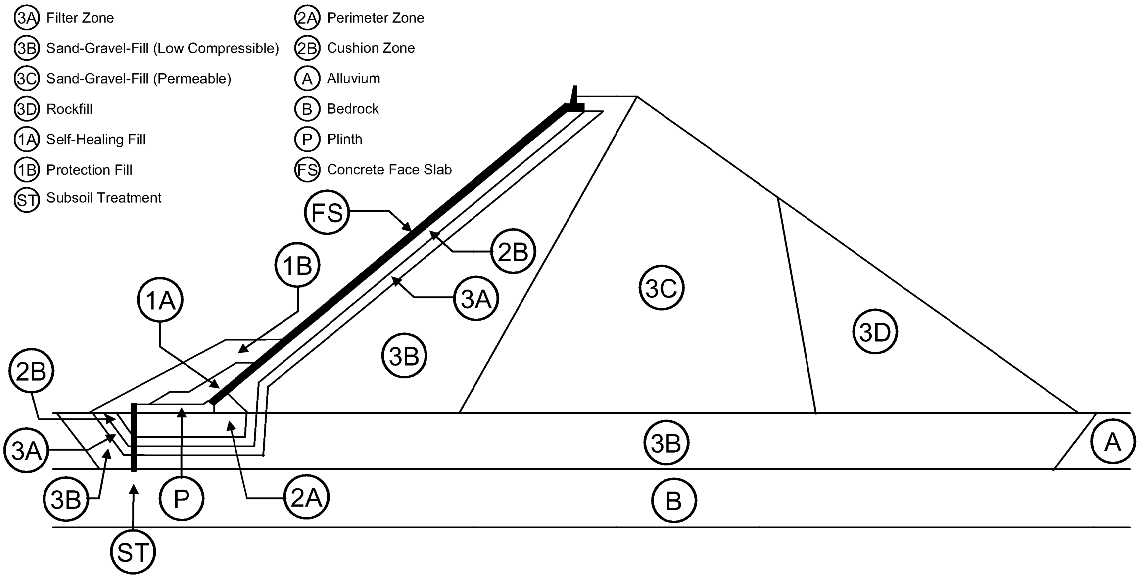

Figure 6: Typical CFSGD section/zoning applying two sand-gravel fills and one rockfill material

Figure 7 shows the elasticity moduli for construction and for first impoundment taken from several case studies. Sand-gravel fills show considerable larger values than the considered rockfill materials. This thesis also conforms to statements given in other literature sources3. For Oroville Dam (H = 244 m) elasticity moduli of 365 MPa were achieved. The sand-gravel fill of Aguamilpa Dam showed an elasticity modulus of 250 MPa11. Rockfills with a strength more than 70-240 MPa are classified as very high strength rockfill material[18]. In general, "gravel rockfills" are considered to show smaller post construction settlements by a factor of up to 10 in comparison to medium strength rockfill[18].

The application of sand-gravel fill materials frequently requires an intensive soil investigation program since the material may consist of several rock types and show different properties within the complete borrow areas. In regard to the erosion/transportation process, the transportation distance and the composition of the material alluvium fills show also a wide property range as well as rockfill materials, which are controlled by the base rock strength and the degree of weathering and/or the existing discontinuities. Alluvial deposits may show interbedded fine grained soil lenses/layers which may affect the suitability of the selected materials if mixed during the excavation process. Lateral valleys/tributaries usually have coarser, less strong material due to the shorter transportation distance compared to the alluvial material in the main river. But, the main river alluvial material may show a more favorable stress-dependent behavior (shear strength, deformation). Contrary, alluvial deposits having a long transportation distance are likely to show a favorable stress-dependent behavior, lower particle breakage due to the natural selection process and may react less sensitive to saturation.

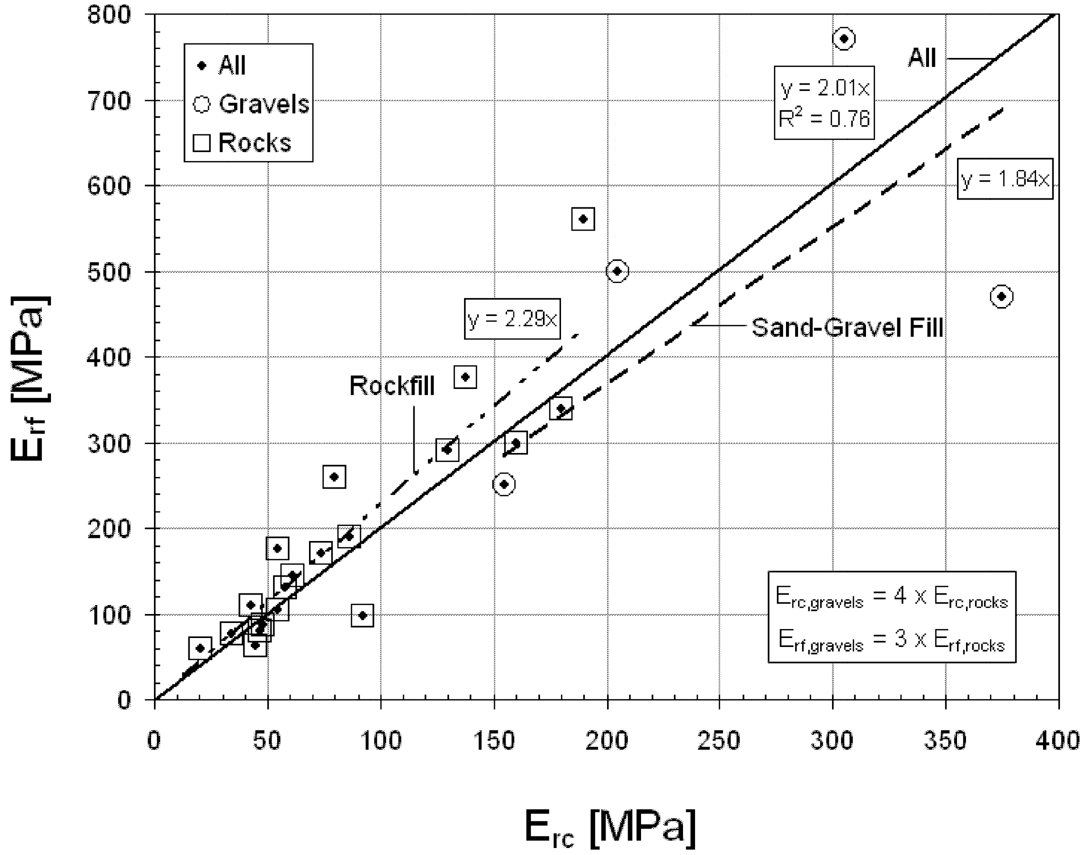

Figure 7: Construction elasticity modulus vs. pseudo modulus for first impoundment for rocks and gravels (according to Hunter & Fell, 2002[29])

For CFSGD types which are founded on alluvium deposits and require deep excavations due to the occurrence of compressible soil layers, the seepage control during the construction phase is likely to be guaranteed by applying additional sealing in combination with the upstream and downstream cofferdams in order to provide a dry construction pit. A combination of the upstream cofferdam including subsoil sealing and the concrete surface sealing is desirable but often not feasible due to the foundation/deformation requirements of the plinth and the corresponding construction process. In order to limit the deformation of the plinth loose, low density alluvial materials should be replaced by well compacted fill material. If the elasticity modulus of the natural alluvium is considered to be appropriate, replacement is not necessary if incompressible layers are present.

In Figure 8 the principal cross-section/zoning of another case study dam in Turkey is shown. The height is approximately 115 m and due to the occurrence of clay layers, deep excavation and refilling has to be carried out. Lateral valleys offer different sand-gravel fill materials with varying properties. Rockfill material is also available and shall be placed at the downstream toe as drain and to cut the potential slope sliding surface of the downstream slope. The dam design is still under preparation and intensive material investigation works were carried out which confirmed that the available alluvial sand-gravel fill materials show considerably different parameters. The zoning will be adapted correspondingly. The application of several different zones and materials also requires a sophisticated and elaborate site supervision concept and efficient logistics.

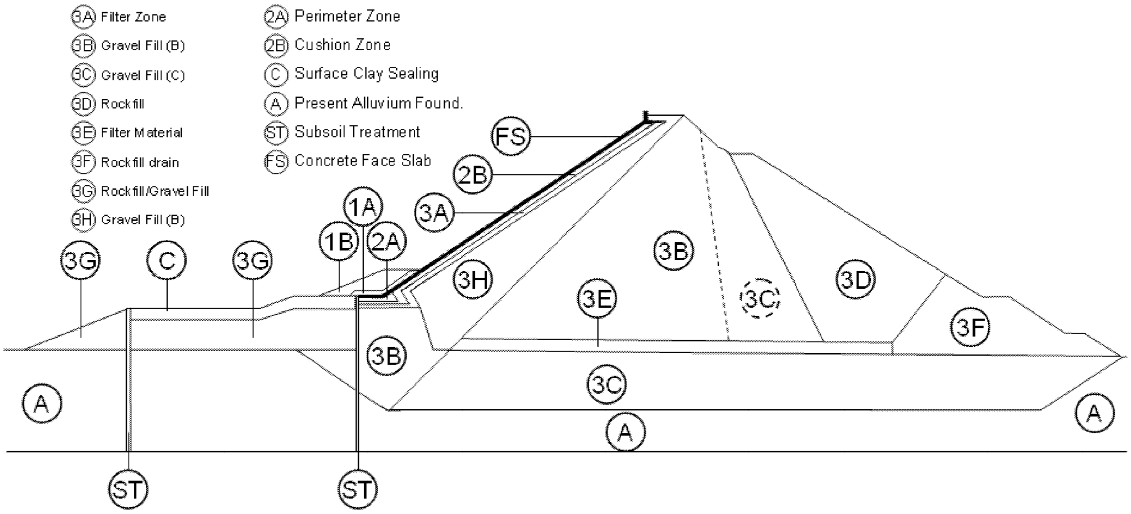

Figure 8: Principal cross-section of a case study CFSGD in Turkey

In order to avoid any unfavorable seepage and pore water pressure affecting the stability of the upstream and downstream slopes the effect of cracking was investigated. Assuming a crack close to the plinth, crack widths of T = 0.001-1.0 m were investigated. The pore water pressures (PWP) beneath the concrete face slab and the seepage flow were determined by a 2D seepage analysis (Figure 9). In this context it has to be noted that for wide valleys the effect of locally limited leakages is usually overestimated by a 2D analysis[9]. Whereas for small valleys and/or an unfavorable (high) valley shape values (H/W) 3D effects maybe dominating, and a 2D seepage analysis may lead to an underestimation of the seepage[21].

Simultaneously, the required design properties of a horizontal filter layer (thickness, permeability) (Figure 8, 3E) were also investigated in order to withstand critical cracking conditions and avoid high PWP beneath the face slab. It was assumed that the slab, the cushion zone (2B) and the transition zone (3A) are completely crossed by the crack. For large cracks and the considered constraints the PWP at point P1 is reaching almost the upstream reservoir level.

For a very coarse and highly permeable filter layer 3E with $k = 10^{-1}$m/s a persistent crack with a width of $T_{Crack} = 0.01$ m does not cause a considerable increase of the PWP underneath the face slab at point P1. The conclusion can be drawn that the dam design is able to withstand this persistent surface crack without endangering the upstream and the downstream slope stability. For larger cracks the PWP increases to almost the upstream reservoir level as mentioned. In case, a “Rapid Drawdown” of the reservoir level will be performed in order to initiate refurbishment measures, the stability of the upstream slope depends on the reservoir water level (retaining force) and the PWP beneath the slab. In case the stability is endangered the drawdown process has to be slowed down so that the PWP is decreasing simultaneously with the decreasing reservoir water level. Since the crack width is unknown, neglecting the backflow through the cracks maybe a conservative but reliable assumption. Then, the draining process is controlled “only” by the dam body zoning and the applied materials within the dam body and the subsurface. For a detailed investigation an unsteady seepage analysis has to be carried out. In consideration of the measured PWP conditions the drawdown process can be controlled reliably on the basis of the results of mentioned analysis.

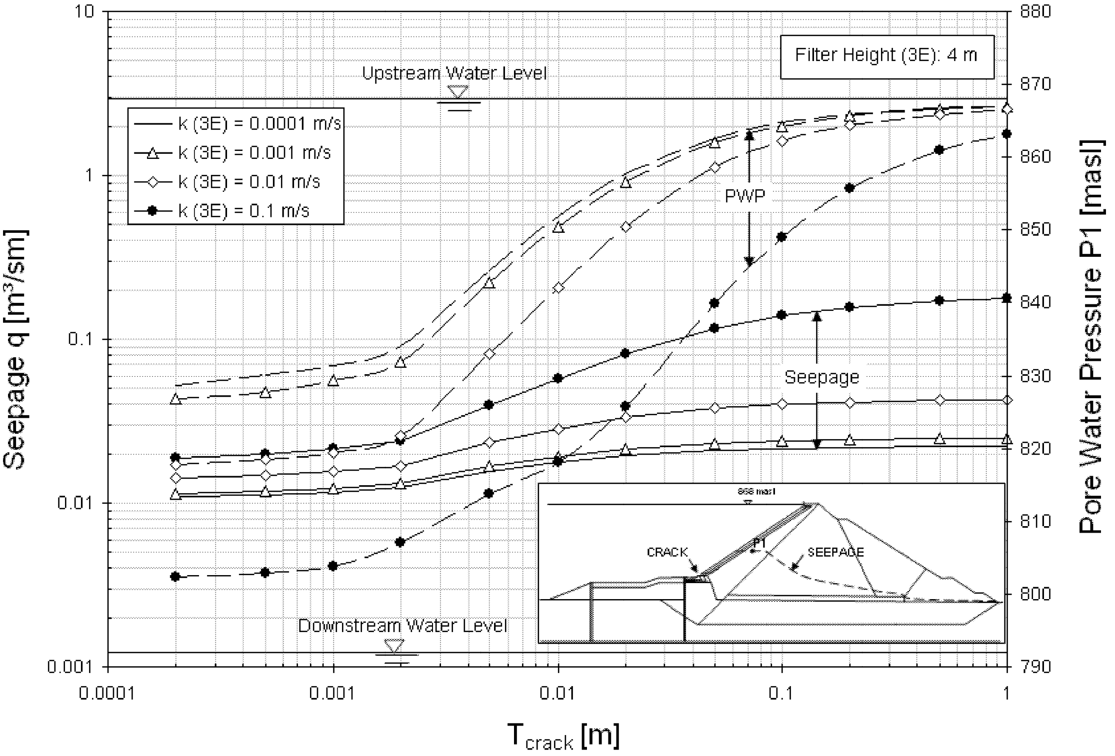

Figure 9: Seepage flow and pore water pressure beneath the face slab for the case study CFRD

5 CONCLUSIONS

The design of the zoning and the selection of appropriate materials are key aspects for controlling the seepage in case of cracking of concrete face slabs, which is most likely to occur during first impoundment or earthquakes. Small cracks with widths of $T < 0.01$ m cause considerable seepage intrusion in high dams given that the crack shows also a corresponding length and depth. The stability of the downstream slope is usually not endangered by cracking if the dam is designed and constructed according to prudent engineering practice and principles. For the upstream slope a limitation of the PWP beneath the face slab may be required for the “Rapid Drawdown” load case.

Experience gathered over recent decades which led to a general improvement of design criteria and construction techniques so that enormous deformations and cracks which were observed in the middle of the last century are very unlikely to occur in modern projects. Generally, the experiences and knowledge of rockfill materials seems to be more developed and definite than for sand-gavel materials which is to be explained simply by the number of completed CFRDs and CFSGD. However, the occurrence of different types of cracks in the face slab of concrete face dams cannot be excluded in the future since each single phase, process and step of the project may be subject to mistakes, undefined uncertainties, force majeure and/or incorrect assumptions. In particular, the accurate investigation of the foundation and the applied materials are a key aspect on the way to avoiding unfavorable conditions endangering the stability of the slopes or initiating internal erosion.

The presented approach for the seepage analysis considering different crack widths and dam body permeability/zonings for concrete face dams can be applied for the verification of the design and for the back-analysis of crack conditions. An unsteady seepage analysis may be required for the determination of the stability of the upstream slopes after cracks occurred and the reservoir level is drawn down to initiate refurbishment works. By this, the maximum allowable drawdown rate can be predicted and controlled by measurement.

REFERENCES

[1] M. Foster, *The probability of failure of embankment dams by internal erosion and piping*, PhD thesis, School of Civil and Environmental Engineering, The University of New South Wales (1999)

[2] USSD, *Strength of Materials for Embankment Dams*, White Paper, Committee on Materials for Embankment Dams, United States Society of Dams (USSD), Denver (USA) (2007)

[3] R. Fell, P. MacGregor, D. Stapledon, G. Bell, *Geotechnical Engineering of Dams*, A. A. Balkema Publishers, Leiden London New York Philadelphia Singapore (2005)

[4] ANCOLD, *Ancold Guidelines on Concrete-Faced Rockfill Dams*, Australian National Committee on Large Dams (ANCOLD), Tasmania (1991)

[5] A. Szostak-Chrzanowski, N. Deng, M. Massiera, *Monitoring and Deformation Aspects of Large Concrete Face Rockfill Dams*, 13th FIG Symposium on Deformation Measurement and Analysis, 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering, “Measuring the Changes”, 12.-15. May, Lisbon (2008)

[6] ICOLD, *Concrete Face Rockfill Dams – Concepts for Design and Construction*, International Committee on Large Dams, Committee on Materials for Fill Dams (Draft) (2005)

[7] J. Brauns, *Erosionsverhalten geschichteten Bodens bei horizontaler Durchströmung*, Wasserwirtschaft 75, Heft 10, S. 448 – 453 (1985)

[8] H. R. Cedergren, *Seepage control in earth dams*, in Embankment Dam Engineering, Casagrande Volume, Hirschfeld, R. C. and Poulos, S. J. (eds), Wiley (1972)

[9] R. Haselsteiner, *Hochwasserschutzdeiche an Fließgewässern und ihre Durchsickerung*, Dissertation. Lehrstuhl und Versuchsanstalt für Wasserbau und Wasserwirtschaft, Mitteilungsheft Nr. 111, Technische Universität München (2007)

[10] H. Ma, K. M. Cao, *Key technical problems of extra-high concrete faced rock-fill dam,* Science in China, Series E, Technical Series, Oct. 2007, Vol. 50, Supp. I, pp. 20-33 (2007)

[11] B. Materon, *Higher and higher*, International Water Power & Dam Construction, February Issue, pp. 30-31 (2008)

[12] F. Mendez, A. Perez, The beaviour of a very high CFRD under first reservoir filling, Hydropower & Dams, Issue 2, pp. 44-49 (2007)

[13] N. L. de S. Pinto, *The design and construction of extra high CFRDs*, Hydropower & Dams, Issue 3, pp. 41-44 (2009)

[14] C. Kutzner, *Erd- und Steinschüttdämme für Stauanlagen*, Ferdinand Enke Verlag, Stuttgart (1996)

[15] J. A. Sobrinho, L. V. Xavier, S. C. Alnertoni, C. Correa, R. F. Pereira, *Performance and concrete face repair at Campos Novos*, Hydropower & Dams, Issue 2, pp. 39 – 42 (2007)

[16] L. E. Montanez-Cartaxo, *The Perimetric Joint Design for Aquamilpa Dam*, International Water Power & Dam Construction, April Issue, 22-28 (1992)

[17] P. Dakoulas, Y. Thanopoulos, K. Anastassopoulos, *Non-linear 3D simulation of the construction and impounding of a CFRD*, Hydropower & Dams, Issue 2, pp. 95-101 (2008)

[18] G. Hunter, J. Glastonbury, D. Ang, R. Fell, *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)

[19] M. Wieland, C. Houqun, *Lessons learnt from the Wenchuan earthquake*, International Water Power & Dam Construction, September Issue, pp. 36-40 (2009)

[20] M. Wieland, *CFRDs in highly seismic regions,*. International Water Power & Dam Construction, March Issue, pp. 28-31 (2010)

[21] Q. Chen, L. M. Zhang, *Three-dimensional analysis of water infiltration into the Gouhou rockfill dam using saturated-unsaturated seepage theory*, Canadian Geotechnical Journal, Volume 43, pp. 449-461 (2006)

[22] N. P. Huber, *Probabilistische Modellierung von Versagensprozessen bei Staudämmen*, Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen (RWTH), Aachen (2008)

[23] A. M. Scuero, G. L. Vaschetti, J. Wilkes, *Repair of CFRD with Synthetic Geomembranes*, Proceedings of Symposium on 20 Years for Chinese CFRD Construciton, English Part, 19-26 September, Yichang, China, pp. 121-127 (2005)

[24] A. M. Scuero, G. L. Vaschetti, J. Wilkes, *Construction of New Exposed Waterstops and Their Application to Repair of CFRD*, Proceedings of Symposium on 20 Years for Chinese CFRD Construciton, English Part, 19-26 September, Yichang, China, pp. 100-107 (2005)

[25] J. Brauns, *Wasserverluste und Durchsickerung von Leckagen in schmalen Dammdichtungen*, Wasserwirtschaft 68, Heft 12, S. 351 – 356 (1978)

[26] J. Brauns, U. Saucke, *Der Lastfall „Leck in der Dichtung“ bei Staudämmen mit synthetischen Dichtungen,* Wasserwirtschaft 95, Heft 11, S. 20 – 26 (2005)

[27] J. Brauns, U. Saucke, *Bedeutung begrenzter Dichtungslecks in Staudämmen mit synthetischen Dichtungen*, Wasserwirtschaft 96, Heft 11, S. 28 – 32 (2006)

[28] S. Malla, M. Wieland, *Design Aspects of Cut-off Wall for Concrete Face Rockfill Dam Located on Thick Alluvial Soil Layer*, Proceedings of Symposium on 20 Years for Chinese CFRD Construciton, English Part, 19-26 September, Yichang, China, pp. 69-78 (2005)

[29] G. Hunter, R. Fell, *The deformation behaviour of rockfill*, UNICIV Report No. R-405, ISBN: 85841 372 8, The University of New South Wales, Sydney, Australia (2002)