LITANI RIVER BASIN MANAGEMENT SUPPORT (LRBMS)

DAM INSTRUMENTATION EVALUATION AND RECOMMENDATIONS

April 2010
This report was made possible by the United States Agency for International Development (USAID). It was prepared by International Resources Group (IRG).

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ACRONYMS

CFRD	Concrete faced rockfill dam
D/S	downstream
FLAC	Fast Lagrangian Analysis of Continua
FERC	Federal Energy Regulatory Commission
LRA	Litani River Authority
LRBMS	Litani River Basin Management Support
PFM	Potential Failure Mode
PFMA	Potential Failure Modes Analysis
PSHA	Probabilistic Seismic Hazard Analysis
U/S	upstream

EXECUTIVE SUMMARY

The objective of Component 4a of the Litani River Basin Management Support program is to assess risks associated with dam failure and develop monitoring tools that can provide advance indications of potential emergency events. The need for monitoring of the Qaraoun Dam is critical as it is for any large dam whose failure would have dramatic consequences.

In order to identify appropriate monitoring instruments for any dam, the first step is to identify and understand the various ways in which potential failure can take place, the triggering mechanism of each mode of failure, and the probability that such failure modes can actually develop. Instruments that have the ability to measure and monitor the trigger mechanisms are then identified and used for safety monitoring.

Such a process, known as potential failure mode analysis (PFMA), has been conducted in order to define instrumentation that is proposed to efficiently monitor the aging Qaraoun dam. During this PMFA, 13 potential failure modes were identified, analyzed and classified. Instrumentation was identified and selected to improve the monitoring of the high risk potential failure modes. The following table presents the list of monitoring instruments proposed as a result of the PFMA exercise.

Item	Description	Purpose	Unit & Qty
1	Vibrating wire piezometers (VWP), complete with cables and accessories	Monitoring water levels in standpipe piezometers / Monitoring pore pressures around inspection gallery / Monitoring water pressures in the dam foundation	10 units
2	Data logger with software	Real time monitoring of VWP	1 unit
2 Alt.	Mini data loggers for each VWP	Reduce the cables lengths	10 units
3	Survey monuments and surveying equipment	Monitoring of displacement of key points on the dam face. Monuments near the downstream edge of the crest, locations TBD in the field	10 mmts. and 1 survey unit
4	Automated leakage measurement	Leakage measurement inside the inspection gallery and at point 11 (Separation of the flow of the spring located inside the dam and the leakage at that same point)	6 units
5	Telemetry system with radio connection	Transmission of the status of the swing valve controlling the penstock inlet at Markabi Power Plant	1 set
6	Reservoir water level sensors and readout	Monitoring the water level in the reservoir	2 units
6	Staff Gage	Fix on Spillway	1 unit
7	Overspeed sensors	Closing of swing valves controlling penstock inlets and Markabi Power tunnel in case of seismic event	4 units
8	Crack Monitors	To be installed across joints or cracks of interest at locations TBD in the field. Not all need to be installed. Some could be held in reserve to be used at locations of future interest.	25 units

Alt. = Alternative

ملخص تنفيذي

يهدف القسم الرابع–أ من برنامج ادارة حوض الليطاني إلى تقييم المخاطر المحتملة وارتباطها باحتمال فشل السد اي احتمال اي نوع من انواع التصدع او الانهيار، وبالتالي تطوير ادوات المراقبة والرصد التي يمكن ان توفر المؤشرات المسبقة عن الاحداث المفاجئة. ان الحاجة إلى مراقبة ورصد اي تغيرات في بنية سد القرعون مهمة جدًا شأنها شأن اي سد كبير وذلك بسبب الاخطار والنتائج الدراماتيكية المحتملة في حال حدوث اي نوع من انواع الفشل.

إن الخطوة الأولى من اجل تحديد ادوات الرصد المناسبة لأي سد هي فهم الطرق المختلفة لاحتمال اي فشل ممكن الحدوث، وبالتالي تحديد الادوات المناسبة لالتقاط الاشارات الاولية مع تحديد آلية واضحة وفعالة قادرة على قياس ورصد معطيات ادوات مراقبة السلامة.

تم اجراء هذه العملية بواسطة الطريقة المعتمدة والمعروفة بإمكانية تحليل وضع الفشل او (PFMA)، من اجل تحديد المعدات المقترحة لبرنامج مراقبة سد القرعون وخصوصًا العمر الكبير نسبيًا للسد. خلال هذا ال PFMA، تم تحديد ١٣ شكل محتمل للفشل كما وتم تحليلها وتصنيفها. وحددت الاجهزة بعد ان تم اختيارها بطريقة يمكنها تحسين المراقبة لمخاطر الفشل المحتمل. فيما يلي جدول يقدم قائمة بالمعدات المقترحة كنتيجة لتجربة الـــ PFMA.

البند	الوصف	الغرض	الوحدة والكمية
١	حساسات لقياس آبار المراقبة (VWP)، مع كافة الملحقات والكابلات	رصد مستويات المياه في آبار المراقبة/ مراقبة ضغط المياه حول نفق المراقبة/ مراقبة ضغط المياه على اساسات السد	١٠ وحدات
2	مسجل للبيانات مع البرنامج الخاص به	مراقبة مباشرة ومتواصلة VWP	1
2تابع	اختصار لطول الكابلات	مسجل صغير الحجم لكل VWP	١٠ وحدات
٣	معدات لمسح آثار التغيرات	مراقبة التغيرات لنقاط المراقبة الرئيسية على وجه السد. مراقبة أثار اي تغيير في حافة السد للجهة الدنيا وللنقطة العليا في جسم السد التي ستحدد مواقعها لاحقاً	10 MMTS ووحدة للمسح عدد ١
٤	معدات لقياس التسرب آلياً	قياس التسرب داخل نفق المراقبة وعند نقطة التسرب رقم ١١(مع وجوب فصل مياه التسرب عن مياه النبع الموجود داخل السد في النقطة نفسها)	٦ وحدات
٥	نقل المعلومات عن حالة سكر مراقبة المياه التي تشغل معمل مركبة لانتاج الطاقة	نظام لنقل المعلومات بواسطة الراديو	مجموعة واحدة
٦	جهاز لقراءات واستشعار مستوى المياه في البحيرة	رصد مستوى المياه في البحيرة	عدد ٢
٦	مسطرة للقياس	التثبيت على منشأة التفريغ	عدد ١
٧	حساسات لقياس التسارع	اغلاق سكر التحكم في المياه التي تزود معامل انتاج الطاقة وذلك في حالات النشاط الزلزالي القوي	٤ وحدات
٨	مراقبة التفسخات (التشققات).	ليتم تركيبها على الفواصل والتشققات في اماكن محددة او اماكن (تشققات) يمكن حدوثها او ملاحظتها لاحقًا.	٢٥ وحدة

I. INTRODUCTION

The Qaraoun Dam is the key asset of the Litani River Authority (LRA). The dam provides income through the production of electricity (a total of 190 MW in three hydroelectric power plants) and supplies irrigation water to agricultural lands. Since Qaraoun Dam is aging and since it is located close to a major fault zone, any signs of deterioration have to be identified at an early stage so that remedial action can be taken in due time.

The LRA intends to improve the Qaraoun Dam instrumentation so that adequate monitoring procedures can be put in place to detect symptoms as soon as they appear. LRA sought the assistance of the USAID/Lebanon to improve the Qaraoun Dam Monitoring System and USAID agreed and included this task as part of the larger Litani River Basin Management Support (LRBMS) project.

In order to properly address the issue, IRG, commissioned by USAID to improve the Qaraoun Dam Monitoring System, has considered the "pull" approach: the instrumentation requirements should emanate from a need. This approach is best achieved by conducting a Potential Failure Modes Analysis exercise that would lead to the definition of the adequate instrumentation and monitoring scheme.

The Quaraoun Dam is a concrete faced rockfill dam (CFRD) with the principal characteristics as summarized below:

Length	1,100m
Height	60m
Volume of employed fill	2 Million m^3
Elevation of the top of the Spillway	858m
Elevation of the highest waters for 600 m^3 spillway flow	860.5m
Elevation of the crest of the dam	861m
Slope of the embankment – downstream	1.35H:1.0V
Slope of the embankment – upstream	ranging 1.2 to 1.0H:1.0V
Thickness of the reinforced concrete facing ranging between 50cm at bottom to 30cm at top	
Dam reservoir capacity (at elevation 858m)	220 Million m^3
Area of the reservoir (at elevation 858m)	1,200 ha
Nominal capacity of the spillway	600m^3/s
Drains capacity below elevation 858m	140m^3/s
Flow through the Markabi water intake	22m^3/s

Figure 1 shows the dam in plan view while Figure 2 presents the maximum cross-section.

The original design included instrumentation to monitor performance of the dam and included the following:

- An array of foundation piezometers to monitor groundwater conditions installed both upstream and downstream of the dam body.
- A grid of survey points embedded in the upstream concrete face slab of the dam to monitor vertical and horizontal displacement.
- Flow measurement weirs to monitor seepage through the dam body.
- Flow measurement of leakage through discrete points in the upstream inspection gallery walls using manual collection and measurement methods.

Figure 1 – Qaraoun Dam, Plan View

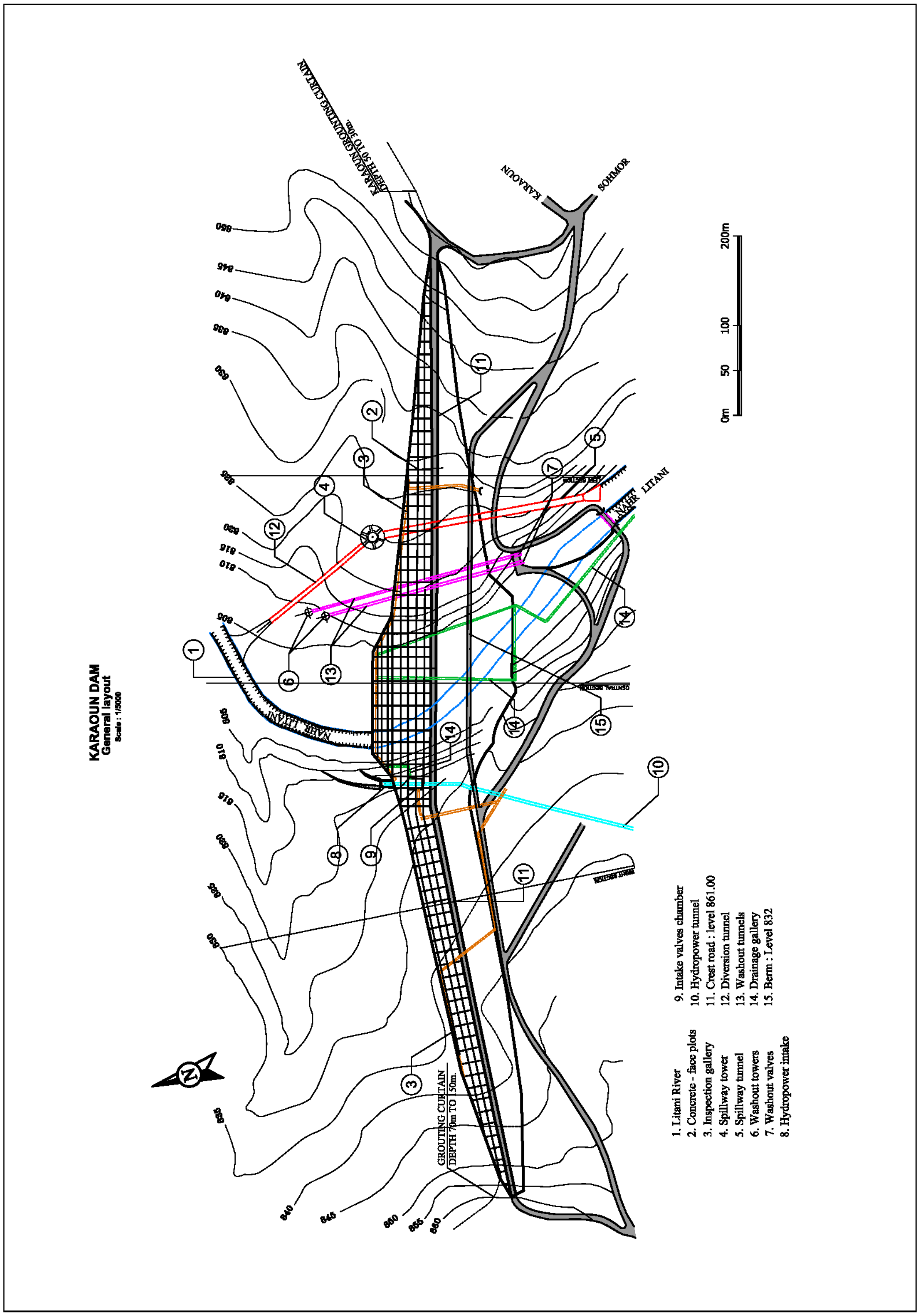
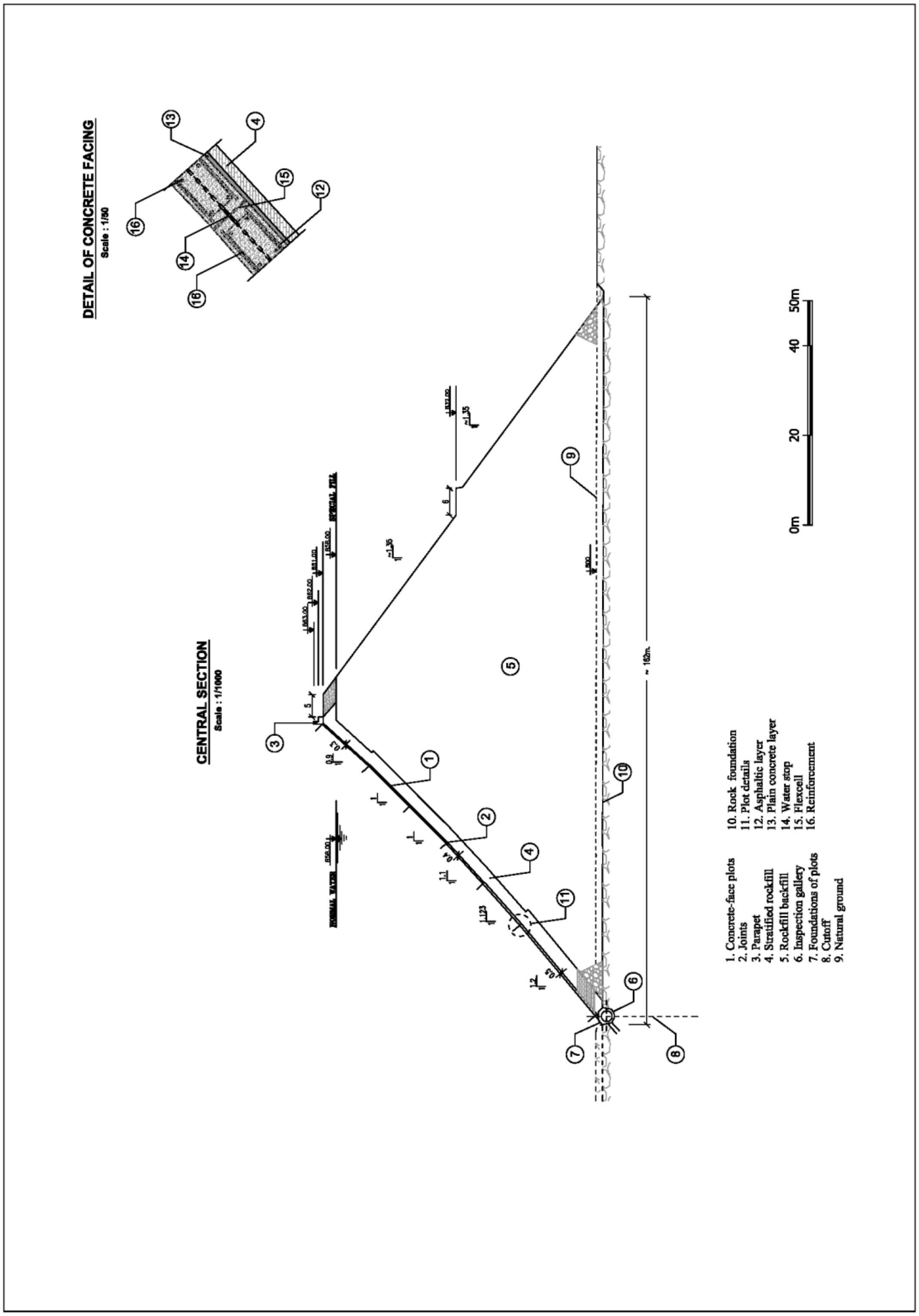


Figure 2 – Qaraoun Dam, Maximum Cross-Section



2. GENERAL METHODOLOGY

To accomplish this task, the LRBMS team employed the commonly accepted "pull" approach, i.e. the instrumentation should be need-driven. This first step in this process is to perform a Potential Failure Modes Analysis (PFMA) study to identify potential failure modes and risks associated with each to understand potential triggers of failure. The next step is to identify data that can be collected to monitor factors that can contribute to potential failures. Once these issues are understood, the instrumentation required to monitor trends that could lead to detrimental behavior of the dam can be identified.

2.1. DEFINITION OF A POTENTIAL FAILURE MODE ANALYSIS

A Potential Failure Mode Analysis is an exercise to identify all potential failure modes under static loading, normal operating water level, flood water level, and earthquake conditions, including all external loading conditions for water-retaining structures and to assess those potential failure that warrant continued awareness and attention to visual observation, monitoring and remediation as appropriate.

A PFMA is an informal examination of "potential" failure modes for a dam or other project works by a team of persons who are qualified either by experience or education to evaluate a particular structure. It is based on a review of existing data and information, first-hand input from field and operational personnel, a site inspection, completed engineering analyses, identification of potential failure modes, failure causes and failure development, and an understanding of the consequences of failure. The PFMA is intended to provide enhanced understanding and insight of the risk exposure associated with the dam. A PFMA includes and uses all of the available data and information from standard engineering analyses of an existing dam.

A PFMA utilizes an intensive team inquiry process beginning from a basis of no preconceived notions. The potential failure mode examination process has the ability to:

- Enhance the dam safety inspection process by helping to focus on the most critical areas of concern unique to the dam under consideration
- Identify operational related potential failure modes
- Identify structural related potential failure modes (e.g. piping) not covered by the commonly used analytical methods (e.g. slope stability, seismic analysis)
- Enhance and focus the visual surveillance and/or instrumented monitoring program
- Identify shortcomings or oversights in data, information or analyses necessary to evaluate dam safety and each potential failure mode
- Help identify the most effective dam safety risk reduction measures
- Document the results of the study for guidance on future dam safety inspections. By updating the documentation (as a living document), the benefit of increased understanding and insight lives on.

A PFMA does not include new analyses, it relies on existing information, data, analyses, and the judgment of the staff participating in the exercise.

2.2. CATEGORIZATION OF FAILURE MODES

Each potential failure mode is categorized by the team in order to provide an indication of the importance of each mode to assist in designing the surveillance and monitoring plan and to provide focus for inspection teams in the future. The categories used in this assessment followed the Federal Energy Regulatory Commission (FERC) categories are described as follows:

> *Category I: Highlighted Potential Failure Modes – Those potential failure modes of greatest significance considering need for awareness, potential for occurrence, magnitude of consequence and likelihood of adverse response (physical possibility is evident, fundamental flaw or weakness is identified and conditions and events leading to failure seemed reasonable and credible) are highlighted.*
>
> *Category II: Potential Failure Modes Considered but not Highlighted – These are judged to be of lesser significance and likelihood. Note that even though these potential failure modes are considered less significant than Category I, they are all also described and included with reasons for and against the occurrence of the potential failure mode. The reason for the lesser significance is noted and summarized in the documentation report or notes.*
>
> *Category III: More Information or Analyses are Needed in order to Classify– These potential failure modes to some degree lacked information to allow a confident judgment of significance and thus a dam safety investigative action or analyses can be recommended. Because action is required before resolution the need for this action may also be highlighted.*
>
> *Category IV: Potential Failure Mode Ruled Out – Potential failure modes may be ruled out because the physical possibility does not exist, information came to light which eliminated the concern that had generated the development of the potential failure mode, or the potential failure mode is clearly so remote a possibility as to be non-credible or not reasonable to postulate.*

The step-by-step procedure described above was used for the Qaraoun Dam PFMA. The process faced the constraint of limited data. An extensive effort was made to collect the needed information; however, some key information such as as-built drawings, geotechnical data from the original design and construction, flood hydrographs, etc. were not available to the staff. This was overcome by obtaining anecdotal information from individuals involved during the original design and construction, reviewing photos, and other data/records in personal possession of various individuals.

A list of staff involved in the PFMA is presented in Annex 1 while the data collected and distributed to the staff prior to the PFMA exercise is identified in Annex 2.

3. POTENTIAL FAILURE MODE ANALYSIS (PFMA)

3.1. STEP BY STEP PROCESS

Step 1	Designation of the Potential Failure Mode Analysis participants (Core Team: Dam Designer, Geotechnical Engineer, Hydraulics Engineer, and Civil Engineer). Facilitator / Team Leader
Step 2	Collection of background data on the dam for review by the Core Team
Step 3	Site review including interviews with key owner personnel at the Project (Core Team)
Step 4	Comprehensive review of all of the background data on the dam by the Core Team
Step 5	Conduct of the PFMA Session
Step 6	Consideration of Surveillance and Monitoring opportunities and/or risk reduction measures for identified potential failure modes
Step 7	Documentation of the PFMA and Surveillance and Monitoring and/or risk reduction opportunities

The main activities of the team during the meeting sessions were to:

- Brainstorm potential failure modes and failure scenarios with the group of persons most familiar with design, analysis, performance, and operation of the dam. Record the identified potential failure modes, the reasons why each potential failure mode is favorable/less likely and adverse/more likely to occur and identify any possible actions related to each that could help reduce risk (i.e. monitoring enhancement, investigation, analysis, and/or remediation).
- Specifically identify possible surveillance and monitoring enhancements and/or risk reduction measures for each potential failure mode for consideration by the owner.
- Document the analysis, including immediately recording the major findings and understandings from the brainstorming session.

3.2. FAILURE MODES IDENTIFIED/ EVALUATED DURING PFMA

The PFMA session resulted in shedding light on some major events that might threaten the Qaraoun Dam. These are listed here below:

3.2.1. STATIC LOADING CONDITION

1. Dam failure resulting from deformation caused by collapse of the bearing stratum
2. Dam failure resulting from pore pressures causing foundation deformations
3. Dam failure resulting from excessive long term settlement
4. Dam failure resulting from concrete dam face and/or joint deterioration causing excessive flow and sediment through the dam body

3.2.2. FLOOD LOADING CONDITION

5. Spillway tower failure resulting from cavitation during flood event
6. Dam failure resulting from collapse of drainage gallery caused by extreme flood event
7. Dam failure resulting from slope instability under extreme flood loading
8. Dam failure resulting from overtopping of the crest under extreme flood

3.2.3. SEISMIC LOADING CONDITION

9. Dam failure resulting from deformations caused by seismic loading
10. Spillway tower failure caused by seismic loading
11. Power waterway failure caused by seismic loading
12. Outlet works failure caused by seismic loading
13. Dam failure resulting from drainage Gallery collapse caused by seismic loading

A detailed description of each of these potential failure modes is provided in Annex 3.

3.3. SUMMARY OF RESULTS

The lack of design, construction, and long-term monitoring data that usually forms the basis of a PFMA required certain assumptions in the PFMA process and reliance on anecdotal information and interpretation of construction photographs. However, sufficient information was obtained and the PFMA exercise that was undertaken has been very helpful in understanding the credible failure modes for the project features and the areas of highest potential risk where monitoring is most important.

The PFMA results indicate the following:

- The Qaraoun Dam and appurtenant structures have functioned satisfactorily to date. Leakage through the dam face joints has occurred to varying degrees over the years but that is to be expected for a concrete facing placed on dumped rockfill. Joint repairs have been made on several occasions and the amount of leakage has never reached alarming levels. Settlement of the dam was high during and shortly after construction but survey measurements show that settlement has been stable for the last 19 years.
- The potential for large seismic events to take place in the region, the dam's proximity to the Yammouneh and Rachaiya faults, the steep slopes of the dam, and the fact that the project was reportedly designed for a pseudo-static load of 0.1g makes seismic loading the greatest risk to the dam and its appurtenant structures.
- Extensive damage to the dam and appurtenant structures is possible under severe seismic shaking. However, there is no known method of measuring and collecting data that would alert operations staff to the danger. Earthquakes are not predictable and therefore do not lend themselves to a monitoring program.
- Under static loading, the most indicative dam performance parameter is the leakage through the concrete face slab joints as indicated by seepage measurements.
- Foundation seepage is also considered an area requiring monitoring due to its potential detrimental effects on the karstic limestone foundation underlying a portion of the dam.

- Seepage measurements will typically include a combination of face leakage and foundation seepage but the trend in the total seepage will give warning of deteriorating conditions.
- The most effective monitoring instrument is considered human observation/inspection. No instrumentation can predict earthquakes and the potential adverse effects on the dam and distress under static loading will most probably develop over time (if at all); therefore, regular monitoring by the site staff is considered to be the most effective means of detecting unacceptable performance under normal loading conditions.
- Real time data collection is not considered a critical need; however, to ensure timely access to accurate data, consideration will be given to automating data collection/reporting related to monitoring dam leakage and reservoir level.

A detailed review of the potential failure modes was considered when identifying monitoring instrumentation needs. The evaluation of existing instrumentation and need for additional monitoring instruments focused on the following: leakage through the dam face, foundation pore pressures, reservoir level, dam body deformation, and protection of the power waterways.

The following table presents the main findings of PFMA:

PFMA mode	**FERC Category**	**Proposed Instrumentation/Monitoring**
Dam failure resulting from deformations caused by seismic loading	I	Visual observation following the seismic event
Dam failure from deformation caused by collapse of the bearing stratum and/or sliding	IV	Pursuing the ongoing survey monitoring activity
Foundation pore pressure build-up that "would cause it to break"	II	Installation of vibrating wire piezometers and follow up of pore water pressures & Automated leakage measurement
Dam failure resulting from excessive long-term settlement	IV	Pursuing the ongoing survey monitoring activity
Dam failure resulting from concrete dam face and/or joint deterioration causing excessive flow carrying fine soil particles through the dam body	IV	Installation of crackmeters on selected joints and monitoring their evolution & visual and quantitative observation of sediments accumulation inside the drainage gallery & automated leakage measurement
Spillway Tower Failure Due to Cavitation	IV	Periodic visual inspection of the Tower structure
Dam failure from collapse of drainage gallery at upstream (U/S) toe of dam due to flood loading	II, gallery IV, dam	Visual inspection following the flood event & installing a staff gage on the spillway tower as well as reservoir water level sensors to monitor the water level evolution in the dam reservoir to take preventive measures in due time

Stability failure of the dam under flood loading	IV	Visual inspection following the flood event & survey & installing a staff gage on the spillway tower as well as reservoir water level sensors to monitor the water level evolution in the dam reservoir to take preventive measures in due time
Overtopping dam failure due to extreme flood	I	Perform design flood routing to assess the potential for overtopping. Visual inspection following overtopping & installing a staff gage on the spillway tower as well as reservoir water level sensors to monitor the water level evolution in the dam reservoir to take preventive measures in due time
Spillway Tower Failure due to Seismic Loading	II, spillway IV, dam	Visual inspection following the seismic event
Power waterway failure resulting from seismic loading	I, waterway IV, dam	Visual inspection following the seismic event & Installation of over-speed sensors
Dam failure resulting from outlet works failure caused by seismic loading	II, outlet woks IV, dam	Visual inspection following the seismic event
Dam fails from collapse of drainage gallery at upstream (U/S) toe of dam due to seismic loading	II	Visual inspection following the seismic event

4. INSTRUMENTATION AND MONITORING RECOMMENDATIONS

4.1. EXISTING INTSRUMENTATION AND MONITORING

As noted above, visual monitoring of the dam and appurtenant structures is considered very important and critical to detecting trends that could lead to problems with the project structures under static loading.

At present, the monitoring scheme of the LRA for the Qaraoun Dam consists of the following tasks:

- Records of groundwater elevations in an array of piezometers installed upstream and downstream of the dam (reported frequency = once a week).
- Measurements of the movement of the dam in settlement and in translation through three "layers" of monitoring studs by traditional surveying equipment (frequency = twice a year)
- Measurement of the flows at leakage points (Frequency = twice a week, except from 15/01 to 30/04: daily):
    a. Inside the gallery at the toe of the dam, by filling a known volume bucket and recording the elapsed time
    b. Outside the gallery (or the dam) through weirs.
- Recording of the quantity of mud cleared from the gallery at the toe of the dam (frequency= twice a year)

Regarding the available data, all data are available starting from 1968, however, these were not recorded on a regular basis. For instance, there is a written trace of the levels and displacements readings in 1968, 1991 and 2001. As far as piezometer data are concerned, the "regular" records are available as of 1997.

However, in order to serve its purpose, the ongoing monitoring program needs to be strengthened and institutionalized.

The LRBMS team will undertake the following to assist LRA to develop an effective inspection and visual monitoring cadre:

- Prepare guidelines for strengthening the dam safety unit within LRA
- Prepare guidelines for strengthening dam monitoring data collection, archiving and analysis
- Provide dam safety training to staff identified by LRA to be assigned the dam safety function
- Provide assistance to LRA with implementation of guidelines

4.2. INSTRUMENTATION RECOMMENDATIONS

In preparing the list of recommended instrumentation to be upgraded/added at the Qaraoun dam, the results of the PFMA were given primary consideration to identify areas where instruments would provide data related to high risk potential failure mechanisms. A secondary, although important, consideration was reliability of data and obtaining data on a frequency that is required and practical.

Accelerometers (strong motion seismographs) were considered, however, as stated in the FERC Dam Safety Performance Monitoring Program guide (Section 14.4.2), "Seismographs provide a valuable research tool …. However, they are not useful for monitoring performance of dams but can confirm the response of the dam to an earthquake, e.g. crest amplification of shaking." These instruments provide data after the fact and such data is useful for re-evaluating a dam's ability to withstand seismic shaking and to provide input for establishing seismic design code values. However, they add nothing to monitoring performance trends for taking action to avoid failures. Additionally, LRA does not have the qualified staff at present to operate and maintain such instruments nor should they add staff to perform these functions at the expense of adding staff to perform their legally mandated functions. Accelerometers are therefore not recommended.

During construction of the dam a network of deformation monitoring points was installed on the upstream face of the dam; they have been monitored using manual survey techniques since initial operation. The data available is of good quality and demonstrates that the deformation of the dam was quite high immediately after construction but has been stable for the past 19 years. A few dam owners have chosen to install sophisticated three-dimensional deformation monitoring instruments (GPS or laser-based systems) to collect "real time" data on deformations. Such systems can be justified for new dams where deformation will take place due to a combination of: initial reservoir filling, long-term consolidation of the foundation and the embankment, and seismic shaking. The Qaraoun dam is founded on a competent rock formation, has experienced initial reservoir filling, annual reservoir fluctuations and minor seismic shaking, and has experienced most of its consolidation as demonstrated by the stable vertical deformation over 19 years. Therefore, it is recommended that the existing network of monitoring points be retained and measured semi-annually and that a limited number of new movement monuments be considered for addition to the crest of the dam and integration into the deformation monitoring program. In addition, it is recommended that crack gages be installed across the upstream concrete face joints and parapet wall joints to monitor movement of the concrete face which is an indicator of dam deformation.

Leakage through defects in the concrete face joints, through cracks in the concrete face, and through the foundation is being monitored at present but accuracy of the leakage volume requires improvement, particularly at monitoring point #11. In addition, real time data collection during periods of high reservoir level is desirable and recommended.

A limited upgrade of the piezometer system in the area downstream of the embankment in the right abutment foundation is recommended to improve monitoring of the foundation seepage. Piezometric levels are less direct than measurements of leakage and good visual observations of any surface expression of seepage, however the addition of piezometers is considered prudent.

Sediment deposition in the drainage gallery is a minor concern and provision of monitoring methods should be carefully investigated and implemented if considered beneficial.

Monitoring of sediment deposition in the reservoir is recommended. This should be accomplished annually by hydrographic surveying techniques.

The following table presents a list of monitoring instruments proposed as a result of the PFMA exercise.

Item	Description	Purpose	Unit & Qty
1	Vibrating wire piezometers (VWP), complete with cables and accessories	Monitoring water levels in standpipe piezometers / Monitoring pore pressures around inspection gallery / Monitoring water pressures in the dam foundation	10 units
2	Data logger with software	Real time monitoring of VWP	1 unit
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5	Automated leakage measurement	Leakage measurement inside the inspection gallery and at point 11 (Separation of the flow of the spring located inside the dam and the leakage at that same point)	6 units
6	Staff Gage	Fix on Spillway	1 unit
7	Telemetry system with radio connection	Transmission of the status of the swing valve controlling the penstock inlet at Markabi Power Plant	1 set
8	Reservoir water level sensors and readout	Monitoring the water level in the reservoir	2 units
9	Crack Monitors	To be installed across joints or cracks of interest at locations TBD in the field. Not all need to be installed. Some could be held in reserve to be used at locations of future interest.	25 units

Alt. = Alternative

4.3. RECOMMENDED DAM SAFETY REVIEWS

4.3.1. PERIODIC EXAMINATIONS OF THE DAM

Currently the practice is to examine the dam on an annual basis. The scope and the requirements for recording the outcomes of these examinations are not formally defined.

It is recommended that formal annual examinations continue and that the requirements for the examinations be documented. The scope should include the status and accomplishment of maintenance, the trends from monitoring, and conclusions from visual examination of the project features. A formal record of the results of the examination should be prepared.

4.3.2. PERIODIC DAM SAFETY REVIEWS

There is currently no process in place for a periodic comprehensive review of the safety of Qaraoun Dam. That does not mean that dam safety is being ignored. Issues such as seismic safety are being raised in addition to the ongoing attention to seepage and leakage under normal loading.

It is recommended that requirements for a formal periodic comprehensive engineering review of the safety of Qaraoun Dam be documented and implemented. In preparation for the first review, it is recommended that the site seismicity be defined in probabilistic terms and that the dynamic deformations of the dam be analyzed for ground motions that are consistent with the seismic hazard. Also in preparation for the first review, it is recommended that the top-of-dam flood frequency be determined using current flood prediction practices. It is recommended that the comprehensive dam safety reviews be conducted approximately every 5 years.

4.4. SEISMIC VULNERABILITY

4.4.1. DAM SAFETY EVALUATION

The dam is located in an earthquake-prone zone where high intensity earthquakes are considered probable. The Qaraoun Dam is considered to be susceptible to damage and potential catastrophic failure under high earthquake loading and therefore a safety evaluation is strongly recommended. Such an evaluation consists of the following:

1. Site specific Probabilistic Seismic Hazard Analysis (PSHA) including development of ground motion time histories for the site

2. Dynamic deformation analysis using an accepted modern approach such as Fast Lagrangian Analysis of Continua (FLAC) analysis

The PSHA is required to determine the input characteristics necessary for the dynamic deformation analysis. Since the most probable dam failure modes identified are all associated with seismic loading and there are no known methods of monitoring factors that would provide advance warning of failure due to earthquake loading, undertaking these studies in the near future is critical. In addition to evaluating the safety of the dam under seismic loading, it is recommended that the power waterways be structurally re-evaluated using seismic ground accelerations recommended in the PSHA. If these studies indicate that the dam and/or power waterways would undergo unacceptable damage under seismic loading, the next step would be to identify the required remedial measures.

The studies recommended above are needed to protect critical infrastructure and human life but are not included in the scope of the LRBMS contract. The cost of performing these two analyses is estimated to be on the order of $175-200,000. Provision of these services in the very near term should be given serious consideration by LRA and USAID.

4.4.2. EMERGENCY MANAGEMENT

Due to the potential for failure of the dam and/or the surface segments of the power waterways, it is recommended that LRA develop a formal emergency management plan. Based on discussions with operations staff, an informal plan does exist. However, it is important that a formal plan be developed to ensure that all personnel know and understand the communications protocols and actions that are assigned to various staff under emergency conditions. The LRBMS team will prepare guidelines for LRA to utilize in developing a formal emergency management plan.

ANNEX 1. PFMA PARTICIPANTS

The PFMA was accomplished by a core team with information obtained from resource participants and technical review by two dam specialists. The core team as composed of: (a) Dr. John Smart, Consultant on Dam Safety (retired Reclamation Dam Safety Officer), to guide the PFMA exercise, (b) Mr. Andy Tczap, Civil Engineer and water sector expert familiar with CFRDs , (c) Mr. Elias Haddad, Civil/Structural Engineer, also covering the hydraulic issues, and (d) Mr. Wael Sabra, Geotechnical Engineer, to assess the soil and embankment issues and also serve as the PFMA team leader.

The resource group was composed of key personnel at the LRA and other people with valuable experience in domains related to the dam. From the LRA, Mr. Ali Abboud, who has extensive experience in LRA facilities, Mr. Ghassan Gebran, who is in charge of the dam and its related operations, Dr. Nabil Amacha, who is in charge of the present dam monitoring program, as well as other LRA staff and affiliates. Other contributors were mainly ex-LRA staff, who kept valuable records of the dam, and Prof. Dr. Alexandre Sursock, Director of the Lebanese Center for Geophysics (seismicity), Mr. André Attallah, Dam Designer, who has an extensive and valuable experience in dams in general and who is knowledgeable on the design and construction of the Qaraoun Dam.

The PFMA was conducted in two stages; first meetings were held in Beirut with the resource group led by the PFMA Team Leader and Mr. Haddad. The output of the meetings consisted of a preliminary assessment of potential failure modes. The second stage consisted of the Core Team reviewing the results of Stage I outputs, discussion via teleconferences and finalization through consensus of the core team on the results presented in this report.

ANNEX 2. QARAOUN DAM AVAILABLE DATA

The following data were provided to the Team to carry out the above PFMA:

- Pictures showing the dam under construction, property of Mr. Afif Soubra and Mr. Ahmad Issa, 1960
- EDF joints repair guide books, 1979
- Concrete face joints inspection campaign report, 1992
- Piezometers layout drawing, LRA
- Front view of the concrete face joints, LRA
- Concrete face panels settlement and displacement records, LRA, 1964, 1968, 1991&2010
- Piezometers readings and leakage records, LRA, 1997 to 2009
- General geological map of the Qaraoun area, Dubertret, 1952
- The Jubilee (50 years) book, LRA
- Mohamed H. Harajli et al., 1994, seismic hazard assessment of Lebanon: Zonation maps, and structural design seismic regulations, Ministry of Public Works – Lebanon, 198 pp.
- 1964 International Committee on Large Dams (ICOLD) paper
- General cross-section (schematic) of the dam, LRA
- Gamma ray diffraction of sediments taken from the lake, CNRSL
- Laboratory testing of the rock samples taken from the quarry and the mud sample collected from the inspection gallery, SANA Engineers, 2010.
- Summary of some findings related to some geotechnical and seepage aspects beneath the dam foundation
- Professor Sursock, 2009, Recent seismic study of Lebanon
- LRA Operation Department, 1965, Barrage de Karaoun (Réserve utilizable en m3 d'eau), Office National du Litani
- Geotechnical campaign carried out by USBR, 1954
- General layout drawings and schematics

The following data usually utilized in a PFMA analysis was not available:

- Dam embankment stability analysis
- Qaraoun Dam design
- Official records of the construction of the dam including photographs
- Records of repair or re-asphalting of the dam crest.
- Records of piezometers readings prior to 1997
- Hydrological study for the basin and the spillway
- Details of construction of the dam
- Details of the dam foundation exposed at the time of construction

ANNEX 3. POTENTIAL FAILURE MODE (PFM) DESCRIPTIONS

1) PFM dam failure resulting from deformations caused by seismic loading

Loading: Earthquake Causing Significant Shaking of the Dam Structure

Description: The dam structure would be expected to deform under the cyclic loading from earthquake ground motions that would be added to the normal loads from the reservoir and gravity. The deformation would be the result of volumetric strain and shear strain in the rockfill embankment. The effects of the deformations could include the following:

- Joint offsets or openings and damage to the waterstops in the concrete facing resulting in leakage through the rockfill embankment
- Dislocation of concrete facing elements exposing the rockfill directly to the reservoir resulting in flow through the rockfill embankment
- Mass settlement and slope failure of the embankment resulting in loss of freeboard

A breach of the dam could form if the flow through the rockfill is sufficient to erode the rockfill to such an extent that the support for the concrete face is lost and the face collapses to a point below the reservoir level. The reservoir would then flow over the area of collapsed face and erode the rockfill embankment to enlarge the breach into a catastrophic loss of the reservoir.

In the case of deformations that result in freeboard loss to such a degree that crest is lower than the reservoir, a breach could occur by overtopping erosion of the rockfill structure. Such a breach would enlarge through progressive erosion and collapse of the crest of the dam as described above resulting in a catastrophic loss of the reservoir. This breach could form whether or not there is flow through the rockfill as the result of damage to the concrete facing.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• High level of seismic activity in the area of the dam • Dumped rockfill embankment that has proven to be deformable as evidenced by settlements and downstream movement during early years of operations • Steep embankment slopes that would tend to increase deformation	• Rockfill has the ability to pass large flows without eroding • Rockfill is not saturated so strength loss from pore pressure buildup during the earthquake is not expected to be significant • Freeboard (3.0 meters plus the parapet height above the spillway crest) would make overtopping unlikely • Low-level outlets that provide considerable drawdown capability

Potential for Rapid Breach: For the scenarios that require internal erosion of the rockfill, the breach could be delayed by hours or possibly days following the earthquake shaking. For the overtopping as a result of freeboard loss, the breach formation would be expected to be rapid delayed only by the erosion rate of the rockfill as it is subjected to the overtopping flow.

FERC Category: I, Highlighted Failure Modes of Greatest Significance

2) PFM: Dam failure from deformation caused by collapse of the bearing stratum and/or sliding

Description: From the soil investigation campaign results (missing records, however the information was written in a technical paper provided by Mr. André Atallah), carried out at the design stage, the stratum on which the dam embankment was founded was found to be of karstic nature and containing clay pockets. Furthermore, the same paper indicates high seepage levels, estimated at 300l/s, feed the Ain az Zarka spring located downstream. Although grouting was performed following construction and in the early 1980 and the seepage levels were reduced, the fundamental potential failure mode remains.

The continuous flow at Ain Az Zarqa source attests to the possibility of open joints in the foundation capable of carrying adequate flow to result in erosion of the clay material filling the cavities, and possibly the enlargement of solution cavities or even underground sinkholes.

The specific potential failure mode path would be a collapse of some existing cavities after the fine material filling the voids has been washed out (block caving subsidence is a product of a complex rock mass response to caving. This response comprises massive failure of rock mass in tension and compression, along both existing discontinuities and through intact rock bridges, and involving complex kinematic mechanisms). This would, in turn, lead to the settlement of the dam embankment. Although the foundation characterization is "clay pockets," one has to consider the presence of clay seams that could lead to sliding along continuous clay seams.

The effects of the settlement could be joint offsets or openings and damage to the waterstops in the concrete facing resulting in leakage through the rockfill embankment. Sliding along foundation clay seams could result in similar failure modes.

A breach of the dam could form if the flow through the rockfill is sufficient to erode the rockfill to such extent that the support for the concrete face is lost and the face collapses to a point below the reservoir level. The reservoir would then flow over the area of collapsed face and erode the rockfill embankment to enlarge the breach into a catastrophic loss of the reservoir.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	**Conditions Making Failure Mode Unlikely (Favorable Factors)**
• High levels of karstification beneath the dam embankment foundation • Dumped rockfill embankment that has proven to be deformable as evidenced by settlements and downstream movement during early years of operations • Steep embankment slopes that would tend to increase deformation	• The presence of continuous foundation clay seams is considered remote for the type of foundation materials present at the site • Rockfill has the ability to pass large flows without eroding • The karst formation area is located only under the right side of the embankment, while the other part is founded on a different type of formation where solution cavities do not form • Freeboard (3.0 meters plus the parapet height above the spillway crest) would make overtopping due to settlement unlikely

Potential for Rapid Breach: Settlement resulting from collapse of clay pockets, if any, would occur very slowly. Continuous foundation clay seams are not considered realistic. Thus the potential for rapid breach is practically non-existent under this scenario.

FERC Category: IV, this potential failure mode was ruled out for causing a dam breach

3) PFM: Foundation pore pressure build-up that "would cause it to break"

Description: A technical paper on the Qaraoun Dam (summary provided by Mr. André Atallah) indicates high seepage levels through the foundation strata below the dam embankment. This seepage, estimated at 300l/s, feeds the Ain az Zarka spring located several kilometers downstream. This phenomenon is concentrated on the right side of the embankment where the limestone formation is present. It is believed that this formation is jointed and fractured.

Furthermore, filling the dam reservoir and maintaining the water level inside it at a high level could cause the pore pressure to increase. An increase in pore water pressure that migrates as "pulse" away from the reservoir after filling may be sufficient to reduce the strength of the rock to the point where rupture could occur, resulting in unstable ground. In fact, it is hard to predict the complex rock mass response that would result from this phenomenon. This response may comprise massive failure of rock mass in tension and compression, along both existing discontinuities and through intact rock bridges, involving complex kinematic mechanisms.

The specific potential failure mode path would be a ground subsidence beneath the dam foundation that would, in turn, lead to the settlement of the dam embankment or even localized sliding of the embankment if the subsidence is large enough.

The effects of the settlement could be joint offsets or openings and damage to the waterstops in the concrete facing resulting in leakage through the rockfill embankment

A breach of the dam could form if the flow through the rockfill is sufficient to erode the rockfill to such extent that the support for the concrete face is lost and the face collapses to a point below the reservoir level. The reservoir would then flow over the area of collapsed face and erode the rockfill embankment to enlarge the breach into a catastrophic loss of the reservoir.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	**Conditions Making Failure Mode Unlikely (Favorable Factors)**
• High levels of jointing and fracturing of the Limestone stratum beneath the dam embankment foundation • Dumped rockfill embankment that has proven to be deformable as evidenced by settlements and downstream movement during early years of operations • Steep embankment slopes that would tend to increase deformation	• Rockfill has the ability to pass large flows without eroding • The continuous flow at Ain Az Zarka which acts as a relief and prevents pressure build up. • Freeboard (3.0 meters plus the parapet height above the spillway crest) would make overtopping unlikely

Potential for Rapid Breach: The subsidence that is expected, if any, shall be of minimal extent. Thus the potential for rapid breach is practically non-existent under this scenario.

FERC Category: II, Potential failure mode considered but not highlighted

4) PFM: Dam failure resulting from excessive long-term settlement

Description: From the available records of settlement of the dam made available to us by LRA, it was found that the dam embankment has undergone considerable settlement under its own weight so far.

Should this settlement go on, the effects of the settlement could be joint offsets or openings and damage to the waterstops in the concrete facing resulting in leakage through the rockfill embankment.

A breach of the dam could form if the flow through the rockfill is sufficient to erode the rockfill to such extent that the support for the concrete face is lost and the face collapses to a point below the reservoir level. The reservoir would then flow over the area of collapsed face and erode the rockfill embankment to enlarge the breach into a catastrophic loss of the reservoir.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• Dumped rockfill embankment that has proven to be deformable as evidenced by settlements and downstream movement during early years of operations • Poor quality of rockfill material • Steep embankment slopes that would tend to increase deformation	• Rockfill has the ability to pass large flows without eroding • Rockfill tests results that have shown that the rockfill used is of very high quality. • Freeboard (3.0 meters plus the parapet height above the spillway crest) would make overtopping unlikely • Settlement experienced to date took place during and shortly after construction. Settlement has not been significant during the last 19 years.

Potential for Rapid Breach: The settlement that is expected, if any, shall occur very slowly. Thus the potential for rapid breach is practically non-existent under this scenario.

FERC Category: IV, potential failure mode ruled out for causing dam breach

5) PFM: Dam failure resulting from concrete dam face and/or joint deterioration causing excessive flow carrying fine soil particles through the dam body

Description: From the reports of the previous concrete face joints inspection and repair campaigns, it appears that the joints between the slabs forming the concrete face are subject to tearing and puncturing.

Furthermore, it was observed that sediments are flowing inside the inspection and drainage galleries. Such sediments could be resulting from the fines being washed out from the rockfill material. Should this be the case, some settlement should be expected to occur and to increase over the years.

The effects of the settlement could be joint offsets or openings and damage to the waterstops in the concrete facing resulting in leakage through the rockfill embankment.

A breach of the dam could form if the flow through the rockfill is sufficient to erode the rockfill to such extent that the support for the concrete face is lost and the face collapses to a point below the reservoir level. The reservoir would then flow over the area of collapsed face and erode the rockfill embankment to enlarge the breach into a catastrophic loss of the reservoir.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• High fines content in the rockfill embankment • Dumped rockfill embankment that has proven to be deformable as evidenced by settlements and downstream movement during early years of operations • Steep embankment slopes that would tend to increase deformation	• Rockfill has the ability to pass large flows without eroding • The sediments found in the galleries find their origin in the lake (testing underway) • Freeboard (3.0 meters plus the parapet height above the spillway crest) would make overtopping unlikely • Periodic inspection and repair of the concrete face joints (planned in the coming months)

Potential for Rapid Breach: The settlement that is expected, if any, shall occur very slowly. Thus the potential for rapid breach is practically non-existent under this scenario.

FERC Category: IV, potential failure mode ruled out

6) PFM: Spillway Tower Failure Due to Cavitation

Loading: Reservoir at flood level, discharge causing erosion of the elbow concrete due to cavitation under high flows to the extent that the tower becomes unstable

Description: The spillway consists of a 12m diameter morning glory type tower spillway. The total height is 58.4m with 24.4m being in a vertical shaft excavated in rock and a 34m free standing tower above ground. Figure 3 shows the spillway configuration.

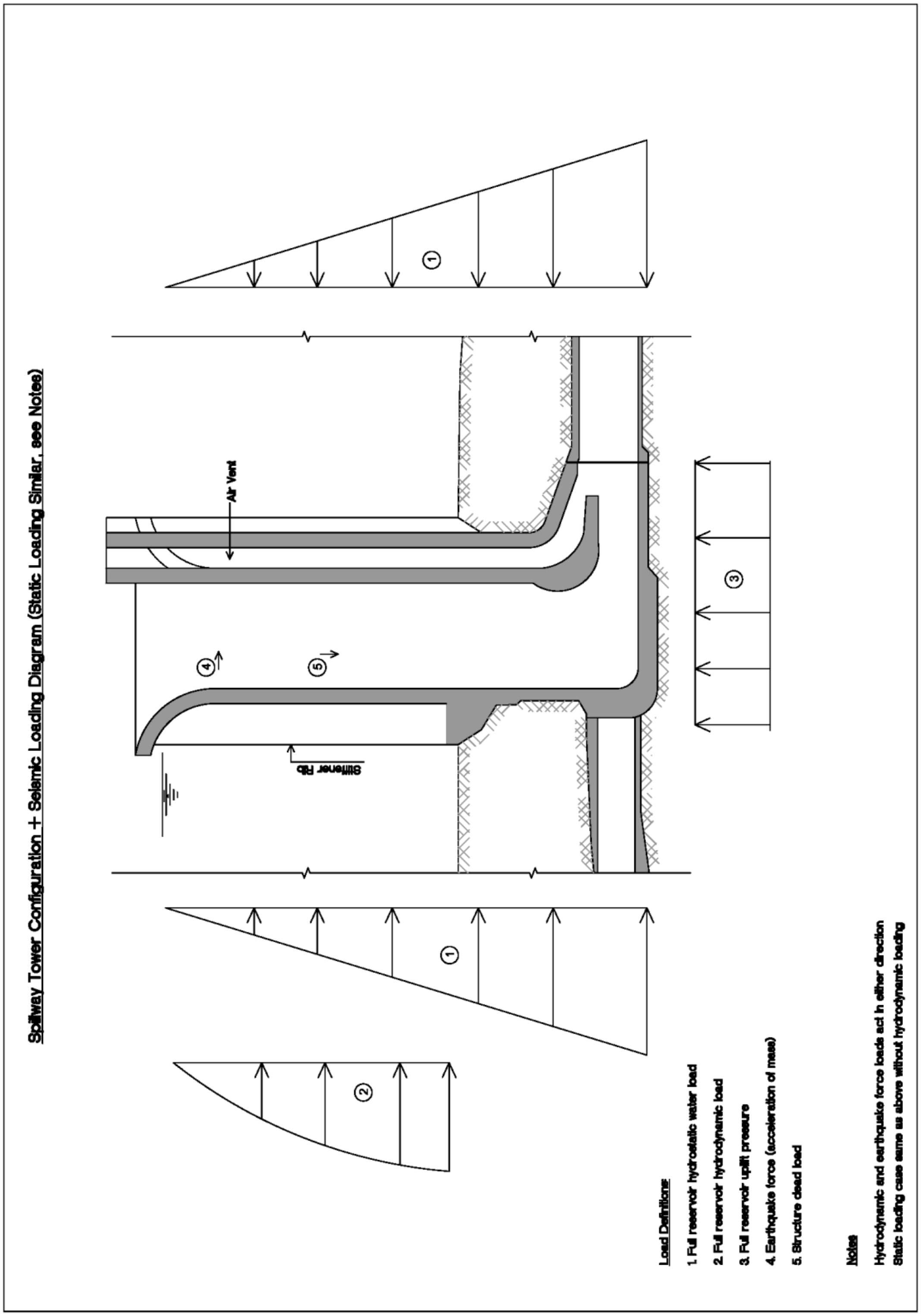
The likelihood of severe cavitation causing failure is considered low due to the following:

- The geometry of the tower is such that flow is constricted at the entrance of the discharge tunnel downstream of the tower. The critical point for cavitation is located at the constriction which is also the point where the 3m diameter air vent is located. The generous air vent capacity will be effective in minimizing the risk of cavitation.
- Severe cavitation erosion requires high velocity flow for a prolonged period of time. Since the spillway operates for relatively short durations, erosion will be limited if it develops at all.
- If cavitation or other distress were to occur, it would occur in the underground portion and the surrounding rock would mitigate the failure until inspection and correction could take place.
- Visual inspections can be made after every flood event and repairs made if needed. This will preclude the possibility of severe cavitation

Potential for Rapid Breach: This failure mode does not threaten the dam due to its location upstream of the dam.

FERC Category: IV, This potential failure mode was ruled

Figure 3 – Qaraoun Spillway Configuration and Seismic Load Diagram



7) PFM: Dam failure from collapse of drainage gallery at upstream (U/S) toe of dam due to flood loading

Loading: Hydrostatic reservoir loading under flood conditions coupled with face slab dead load reservoir sediment loading and saturated rock load

Description: The drainage gallery is a reinforced concrete structure located at the upstream toe of the dam. The face slab of the concrete faced rockfill dam abuts the gallery for some unknown length while in some areas the dam face slab extends to the foundation on the U/S side of the gallery. The exterior of the gallery where the dam face slab abuts the gallery is subjected to a point load from the dam face slab, full reservoir pressure, and the pressure of any sediment deposition that takes place at the U/S toe of the dam (directly against the gallery). These loads are applied on a portion of the upstream half of the structure. The exterior of the gallery within the dam body is subjected to loads from the rockfill and hydrostatic loading from water that leaks through the dam face or though the foundation and ponds against the gallery.

Figure 4 depicts the gallery cross-section and the loading condition.

Under flood loading conditions, the effects on the gallery could include the following:

- Localized collapse of the concrete walls of the gallery resulting in a constant loss of reservoir water through the access adits that connect to the gallery
- Localized, sudden movement of rockfill into the gallery that could propagate upwards within the dam embankment to cause progressive settlement of the U/S section of the dam body
- Opening of dam face slab joints or dislocation of the dam face slab resulting in direct connection of the reservoir to the dam rockfill with resulting flow through the rockfill

The probability of a breach in the dam resulting from a failure of the gallery is considered to be low.

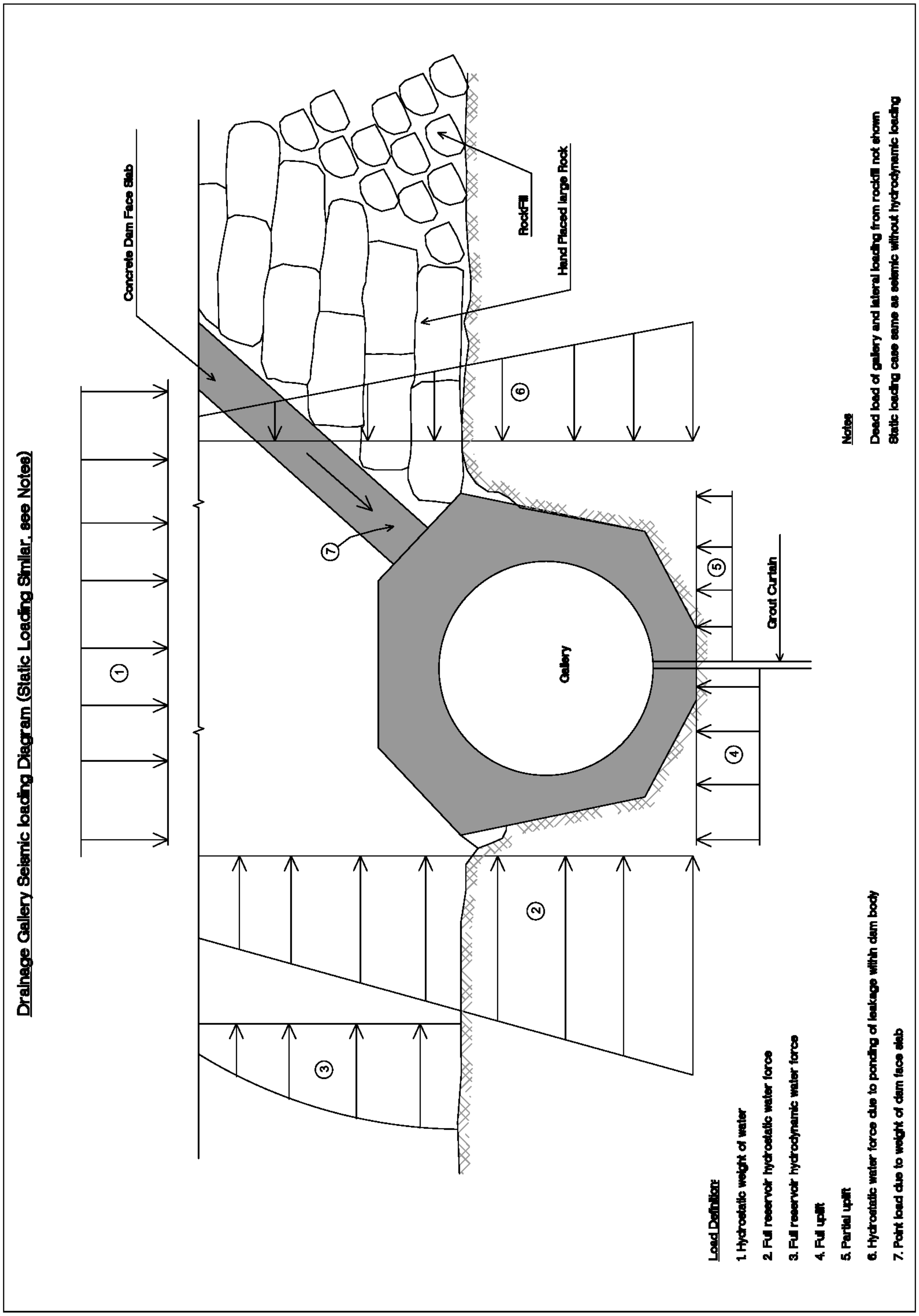
Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlkely (Favorable Factors)
• Steep U/S dam slope that would make sliding of the concrete face possible • Possibility of some loss of strength of the gallery walls due to age	• Safe functioning of the gallery for 45 years under various reservoir levels including low to moderate intensity earthquake loads • Presence of low level outlet provides ability to draw the reservoir down • Frequent visual inspections performed

Potential for Rapid Breach: The potential for a rapid breach of the dam resulting from slumping of the U/S toe of the dam from a gallery failure is considered very low.

FERC Category: IV, Potential failure mode ruled out for dam breach and category II for failure of the gallery

Figure 4 – Qaraoun Dam Drainage Gallery and Seismic Loading Diagram



8) PFM: Stability failure of the dam under flood loading

Loading: Hydrostatic loading with reservoir at flood level

Description: High reservoir levels under flood condition will increase driving loads on potential failure planes through the dam such that resisting forces will be exceeded resulting in wedge or circular surface movements within the downstream shell of the dam.

Concrete faced rockfill dams have inherently high factors of safety due to: (1) high frictional resistance of the rockfill if the material is durable and does not contain an excessive amount of fine particles; (2) the concrete face slab spreads the driving forces within the dam in a manner to bridge any weak layers so that loads will not be concentrated on the weak areas; (3) the body of the dam does not experience any pore pressures due to its relatively high permeability; and (4) the concrete face adds resistance to sliding failures.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• Rockfill was placed without compaction • Opening of dam face slab joints or dislocation of the dam face slab resulting in direct connection of the reservoir to the dam rockfill with resulting flow through the rockfill • Dam body slopes are steep	• Consolidation of the rockfill has taken place resulting in improved in-place density of fill • Rockfill material is durable • Reservoir has spilled infrequently therefore this loading condition is considered unusual • Staff is on site daily and can monitor the embankment during flood conditions and will have time to take action • Low level outlet provides significant drawdown capability

Potential for Rapid Breach: The potential for a breach developing rapidly is considered low.

FERC Category: IV, Potential failure mode ruled out

9) PFM: Overtopping dam failure due to extreme flood

Loading: Extreme flood occurrence causes the dam to be overtopped

Description: Flow over an embankment dam (earth or rockfill) is a very serious condition and usually leads to erosion of material on the downstream slope and failure of the dam. Overtopping of Qaraoun Dam could result in movement of the material on the downstream (D/S) slope of the dam with progressively more material dislodged causing collapse of the concrete face panels resulting in higher flows over the dam until total collapse occurs.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• Steep slope of the D/S face of the dam • Rockfill was placed without compaction	• Freeboard of 3m plus the parapet height above the spillway crest makes overtopping unlikely • On-site staff available to monitor reservoir level during flood events and take action • Low level outlet provides ability to evacuate the reservoir

Potential for Rapid Breach: This potential failure mode has significant potential to cause a rapid breach of the dam if overtopping is significant.

FERC Category: I, Highlighted Failure Modes of Greatest Significance

10) PFM: Spillway Tower Failure due to Seismic Loading

Loading: Earthquake resulting in shaking of the tower structure, hydrodynamic reservoir loading, hydrostatic loading and dead loads

Description: Under severe seismic loading the tower would be subjected to hydrodynamic reservoir loading in addition to hydrostatic loading, gravity loading and seismic loading due to the structures mass. Figure 3 (see page 19) presents the loading condition of concern.

The worst case scenario for this failure mode is failure by overturning of the spillway tower or crushing of the tower walls causing collapse. This would lead to loss of reservoir storage to the level that failure of the tower took place. If the collapse did not result in blocking and reducing the spillway discharge capacity, the result could be loss of life downstream due to rapid increase in stream flow.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• High level of seismic activity in the area of the dam • Design consisted of pseudo-static analysis using 0.1g acceleration	• Structural and hydraulic design appears conservative • Anecdotal information is that construction was of high quality

Potential for Rapid Breach: The spillway tower is located some 20m U/S of the toe of the dam and it has a total height of 58.4m consisting of a 34m free standing tower above ground and a 24.4m vertical shaft excavated in rock with its discharge tunnel approximately 15m underground. A complete failure of the above ground tower is not considered a risk to the dam and therefore a rapid dam breach due to this failure mode is considered highly unlikely.

FERC Category: IV, Potential failure mode ruled out for resulting dam breach and Category II, Potential failure mode considered but not highlighted, for the spillway structure

11) PFM: Power waterway failure resulting from seismic loading

Loading: Earthquake causing significant shaking and/or displacement along the power tunnel alignment

Description: The Qaraoun reservoir provides water to a cascade of three hydroelectric power plants. Each plant waterway consists of a combination power tunnel/penstock with diameters ranging from 3.1m to 3.4m. The power tunnels are lined with reinforced concrete while the penstock tunnels are steel lined concrete and the surface penstocks are reinforced concrete conduits. The effects of seismic shaking and/or fault displacement could include the following:

- Total collapse at the power tunnel intake area could cause slumping of the upstream toe of the dam with significant local damage to the dam face slab.
- Offsets in the tunnel lining causing high pressure tunnel flows to exit through fissures in the foundation
- Failure of the above ground penstocks causing release of high velocity flows onto the hillside with potential loss of life at the power plant or on roads in the vicinity of the power plant and landslides
- Collapse of the concrete tunnel lining could cause rubble to flow to the power plant and cause significant damage to the shut off valves, turbine, scroll case, and/or scroll case vanes.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• High level of seismic activity in the project area • Surface Penstock and other Segments Designed for 0.1g	• Power tunnel lining is undergoing repair and rehabilitation at present • Massive concrete encasement of the intake • The waterway downstream of the intake is in a tunnel below the dam foundation

Potential for Rapid Breach: A rapid dam breach due to collapse of the intake structure inlet is considered unlikely.

The consequences of a power tunnel failure will be severe economic loss due to the inability to generate power until repairs can be made and possibly loss of life if a rupture of the tunnel/penstock results in a sudden release of water to the surface that could cause landslides, sudden increase in stream flows and/or flooding of the power plant area or nearby roads.

FERC Category: IV, Dam failure due to this mode is ruled out and Category I, Potential failure mode considered and highlighted for the waterways downstream of the dam body

12) PFM: Dam failure resulting from outlet works failure caused by seismic loading

Loading: Earthquake causing significant shaking of the outlet works structure

Description: The outlet works consists of 2-14m high, free-standing, uncontrolled inlet towers located in the reservoir more than 70m upstream of the dam toe. Each inlet connects to a 2.5m diameter, steel lined tunnel conduit passing under the dam which terminates in a D/S control house with two regulating valves. Seismic loading could result in the following failure mechanisms:

Collapse of the intake tower resulting in blockage of the inlet with loss of full discharge capacity

Failure of the discharge conduit resulting from offset of the conduit allowing water under full reservoir pressure to communicate with the foundation and through foundation fissures to the dam body rockfill.

Damage to the regulating valves rendering them inoperable resulting in loss of ability to draw the reservoir down.

Failure of the natural slope above the discharge control house resulting in collapse of the control house and damage to the operating valves.

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• High level of seismicity in the area of the dam • Project structures are design using pseudo static loading of 0.1g	• Inlet structure is located away from the dam minimizing potential dam breach in case of inlet failure • Outlet conduit is in a tunnel with concrete and steel lining • Rupture of the outlet conduit occurs only if offset of the conduit occurs and there are no known fault lines that would produce offsets in the conduit

Potential for Rapid Breach: A rapid dam breach resulting from failure of the outlet works is considered highly unlikely.

FERC Category: IV, potential failure mode ruled out for dam breach and Category II, Potential failure mode considered but not highlighted for the outlet works structures

13) PFM: Dam fails from collapse of drainage gallery at upstream (U/S) toe of dam due to seismic loading

Loading: Earthquake shaking causing hydrodynamic and hydrostatic reservoir loading coupled with face slab movement, reservoir sediment loading and saturated rockfill loading

Description: The drainage gallery is a reinforced concrete structure located at the U/S toe of the dam. The face concrete face slab of the rockfill dam abuts the gallery with a water stopped joint for some unknown length while in some areas the dam face slab extends to the foundation on the U/S side of the gallery. The gallery where the dam face slab abuts the gallery is the critical area of concern. The upstream portion of the gallery is potentially subject to a point load from the dam face slab, full reservoir static and hydrodynamic pressures, and the pressure of any sediment deposition that takes place at the U/S toe of the dam (directly against the gallery). These loads are applied on the upstream portion of the structure. The exterior of the gallery within the dam body is subjected to loads from the rockfill and hydrostatic loading from water that leaks through the dam face or though the foundation and ponds against the gallery. These loads are applied to the D/S portion of the gallery. The seismic loading condition considered is shown in Figure 4 (see page 21).

Under severe seismic loading, the effects on the gallery could include the following:

- Localized collapse of the concrete walls of the gallery resulting in a constant but relatively low rate loss of reservoir water through the access adits that connect to the gallery
- Localized, sudden movement of rockfill into the collapsed gallery that could propagate upwards within the dam embankment to cause progressive settlement of the U/S section of the dam body and downward movement of the dam face slab
- Opening of dam face slab joints or dislocation of the dam face slab resulting in direct connection of the reservoir to the dam rockfill with resulting flow through the rockfill

Factors Making this Failure Mode Likely or Unlikely:

Conditions Making Failure Mode Likely (Unfavorable Factors)	Conditions Making Failure Mode Unlikely (Favorable Factors)
• High level of seismic activity in the area • Steep U/S dam slope that would make sliding of the concrete face possible • Potential loss of strength of the gallery walls due to age	• Rockfill has ability to pass large flows without serious erosion • Low level outlet works provides ability to draw down the reservoir

Potential for Rapid Breach: For the assumption that the gallery fails without having the seismic loading result in other failure mechanisms within the dam body, the risk of a rapid breach of the dam is considered low. Slumping of the U/S toe of the dam resulting from a gallery failure would not result in massive slumping of the dam crest nor is it reasonable to assume the flow through the base of the dam would dislodge the rockfill resulting in a dam breach.

FERC Category: II, Potential failure mode considered but not highlighted

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