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Technical Memorandum No. JL-8313-4

Jackson Lake Dam
Minidoka Project, Wyoming

Issue Evaluation Report of Findings — Executive Summary
Seismic Risk Analysis — Non-Sensitive

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                                                 Date

I.   Issue

In March 1999, a Comprehensive Facility Review (CFR) was completed for Jackson Lake Dam. The Report of Findings from the CFR, dated March 23, 1999 [1] included the following new recommendation:

98-SOD-A. Update the ground motions using the new data obtained from recent seismic monitoring, and use those ground motions in reassessing the seismic adequacy of the embankments and the concrete section.

A new seismotectonic report has been completed and a risk analysis was performed during the week of July 15, 2002. Separate reports have been prepared and peer reviewed to document these studies. The Jackson Lake Ground Motion Evaluation was completed in draft in April 2003 [2], although seismic hazard curves and representative ground motions were available prior to the July 2002 risk analysis. A technical memorandum entitled "Jackson Lake Dam - Issue Evaluation - Seismic Risk Analysis" [3], was completed in March 2003 and provides a detailed summary of the analyses that were completed to evaluate the seismic risk of Jackson Lake Dam.

This Report of Findings - Executive Summary provides a non-sensitive summary of the results of the risk analysis that was completed using the updated seismic hazard and ground motions from the new ground motion report cited above. The reader is referred to the documents referenced above for more detail.

II.   Introduction

Jackson Lake Dam is a composite dam consisting of a 4,580-foot-long left (north dike) embankment section, a combined spillway and outlet works concrete gravity section, and a 150-foot-long right (south dike) embankment section for a total combined crest length of 4,952 feet. The dam is located on the South Fork of the Snake River in northwestern Wyoming, 30-miles north of Jackson. The dam was constructed at the mouth of a natural lake by the Bureau of Reclamation in 1911, and enlarged in 1916. Modifications were completed to the dam in 1989 to correct seismic dam safety deficiencies. These modifications included 1) strengthening the north embankment foundation by dynamic consolidation and placement of walls of soil-cement mixed *in situ* to form a honeycomb pattern, 2) replacement of the north embankment section, 3) widening and strengthening the bridge deck on top of the concrete gravity section, 4) widening of the south embankment roadway, 5) placement of an upstream parapet wall and 6) construction of a downstream retaining wall for the south embankment, and replacement of the outlet works gates, stems, and hoists.

The rebuilt left (or sometimes referred to as the north) embankment section, is a zoned embankment with a central impervious core flanked by semi-pervious shells, upstream soil-cement slope protection, and downstream slope protection consisting of seeded topsoil over a soil reinforced system. The crest elevation of the left embankment section is 6780.5 feet. A parapet

wall, which is 3-foot 2-inches high over most of its length, is located on the upstream shoulder of the right end of the left embankment. The crest of the embankment from approximate station dam 14+00 to dam station 10+00 gradually tapers down from elevation 6780.5 to meet the roadway on the crest of the concrete dam at approximate elevation 6777.3 (station 10+00). The upstream and downstream slopes of the left embankment section were designed to be flat for added stability. The composition of the right (or south) embankment section consists of rock, concrete fragments, and some wood timbers for the northern portion, and glacial drift material consisting of gravel, sand, and silt for the southern portion. Slopes of the reconstructed right embankment are protected with riprap on the upstream face and grouted riprap on the downstream face.

Release facilities at the dam include a spillway and outlet works within the concrete gravity section. A concrete highway bridge passes over the spillway.

The outlet works originally consisted of 20 conduit sections, within the concrete gravity section, with flow controlled by manual controls. In 1977, five of the 20 conduits were backfilled with concrete to provide increased seismic stability for the concrete gravity section. The remaining 15 conduits are controlled by slide gates, which were replaced during safety of dams modifications in the mid-1980's. One wheel-mounted bulkhead gate is available to temporarily dewater the conduits.

In 1986, a micro-seismic monitoring network was installed along the Teton fault including instruments on and nearby Jackson Lake Dam. One of the purposes of the micro-seismic network was to provide data to estimate ground motion responses in the vicinity of the dam. The data collected from 1986 to approximately October 2002, indicated that ground response was quite variable along the length of the dam. The ground motions at the concrete dam section, founded on rock, could be significantly different than ground motions along the dam and downstream of the dam which are areas founded on increasing depths of unconsolidated and weak sediments of glacial, alluvial, and fluvial-lacustrine origins. In general, the ground motions tend to become amplified and the duration of shaking is increased, for ground motions in the central and northern end of the left or north embankment section compared to ground motions at the concrete dam section.

As a result of the seismic hazard study developed for the CFR and the new ground motion study developed with data from the seismic monitoring, it became apparent that Jackson Lake Dam could be subjected to stronger ground shaking than the design loadings used in the modification design. The recommendation in Section I. above was generated during the CFR, in recognition of the need to 1) develop updated ground motions incorporating the results from the seismic monitoring, 2) determine the response of the structures to these ground motions, and 3) evaluate the risk to persons downstream, based on the response of the structures. This new study was performed within a risk framework using site response analyses and structural analyses based on the new ground motions developed for this study.

As the first step of the risk analysis, the risk team collectively created a list of all potential failure

modes thought to be possible due to seismic loading at the dam. Initially, no attempt was made to reduce the potential failure modes to only those believed reasonable by the team. All potential failure modes were considered. Once a list of failure modes was completed, the risk team then selected only those failure modes deemed to have a reasonable potential to result in dam failure, for use in quantitative risk analysis and more detailed "event tree" development. Potential failure modes were developed under two discreet categories: failure modes for the embankment section and failure modes for the concrete section.

III.   Seismic Loading

Seismic studies were completed in 1983 [4] for use in modification designs for the concrete dam and embankment structures. Deterministic earthquake loadings from these original studies and studies on other nearby dams, including source, distance, and recurrence interval are summarized in table 1 below:

Table 1. Maximum Credible Earthquakes (from 1983 study)

Source	MCE (M_l)	Epicentral Distance (km)	Focal Depth (km)	Recurrence Interval (years)
Local (Random)	6.5	<5	7	50,000
Teton Fault	7.5	6.5	10	2,000
East Sheridan	7.0	19	15	15,000
Star Valley Fault	7.5	95	15	5,000
Hebgen-Red Canyon	7.5	105	15	450

Based on these seismic sources, ground response analyses that were completed during modification designs, and recommendations from the Consultant Review Board (CRB), ground motions with a peak horizontal ground acceleration of approximately 0.4g were used in design of the remediation. This included the new embankment retaining wall and the concrete dam that were both designed for an earthquake lateral acceleration equivalent to 0.4g. The concrete dam section was also analyzed for sliding along a thin layer within the bedrock foundation for a peak bedrock acceleration of 0.57g and determined to be safe although some permanent "Newmark-type" displacements might remain.

The total seismic hazard at Jackson Lake Dam is generally dominated by ground motions produced by the Teton fault as explained in more detail in the ground motion report. Amplitudes and durations of ground motions along the dam appear to be strongly influenced by the large-scale crustal velocity structure and source radiation at the site. This appears to be true of both observed ground motions obtained from micro-seismic data records at stations along the dam and

in the modeling of the rupture scenarios for the Teton fault. In addition, soil modeling indicates that soil nonlinearity may increase ground response for longer periods. Motions in the longer period ranges are more likely to impact the total deformations of the embankment dam than the concrete section. This is due to the fact that the concrete structure is very stiff, and the natural period of the embankment is more likely to be in the longer period ranges, which could increase response. The increase in soil response occurs for reasons such as:

      1. Jackson Lake Dam is located <10 km from the large Teton fault.

      2. Jackson Lake Dam and reservoir are located within a large primary, low-velocity basin.

      3. The embankment is located within a secondary, very low-velocity basin.

      4. The dam is located on the hanging wall and subject to a degree of rupture directivity.

Jackson Lake Dam happens to be located within a near large-amplitude critically reflected distance range from western portions of the large basin. This has the effect of introducing a secondary source of strong ground motions along the western margins of the basin. In effect, earthquakes on the northern Teton fault segment produce ground motions at the dam that are the superposition of two "earthquakes"; seismic radiation from the entire northern Teton fault segment, and re-radiation of seismic energy from the top several kilometers of the western portion of the low-velocity basin due to rupture directivity. Since the primary fault rupture produces the strongest ground motions near the western margin of the low-velocity basin due to the rupture directivity, the "secondary source" along the western margin of the basin produces ground motion amplitudes comparable to primary fault rupture and prolongs the duration of the strongest ground shaking. Certain mitigating factors may reduce some of the potential for ground motion amplification. The dam is approximately 4-6 km east of the area which appears to have the strongest directivity from the fault source and soil nonlinearity would likely decrease peak high frequency motions.

In order to construct the event trees, it is necessary to include the recurrence of a given seismic load (expressed in terms of peak horizontal acceleration (PHA)) expressed as the annual probability of loading. Event trees were constructed for each failure mode using various load ranges selected by the risk team. The load ranges are developed by the team based on threshold loadings at which the team believes the structural responses might vary. For the concrete dam structure and embankment, load ranges were selected in terms of PHA and the response of the structure estimated through each branch of the event tree. For the various load ranges selected by the risk team, recurrence probabilities were taken directly from data developed in the new ground motion evaluation and provided to the risk team in the form of tables 2A, 2B, and 2C below.

Table 2A: Concrete Section

PHA Interval	Annual Probability
< 0.5g	-0.9997
0.5 - 0.8g	1/5000 (0.0002)
> 0.8g	1/9500 (-0.0001)

Table 2B: Alternate Concrete Section

PHA Interval	Annual Probability
< 0.65g	-0.9997
0.65 - 0.8g	(1/3500 - 1/9500) (-0.0002)
> 0.8g	1/9500 (-0.0001)

Table 2C: Soil/Embankment Sections

PHA Interval	Annual Probability
< 0.3g	0.9926
0.3 - 0.4g	1/223 (0.0045)
> 0.4g	1/436 (0.0029)

IV.   Reservoir Operation and Freeboard Considerations

Under normal reservoir operations, Jackson Lake maintains a significant amount of freeboard with respect to the total height of the dam. In general, the reservoir annually fills and then fluctuates by a significant amount as water is released for downstream uses. A review of reservoir operational data for the last 33 years of operation (excluding the mandatory restriction between 1984 and 1989) indicates that the reservoir is well below the crest of the dam for a large percentage of time during any given year.

Emergency reservoir evacuation capability of Jackson Lake Dam was evaluated and summarized in a technical memorandum during modification designs in 1986 [5]. Reservoir evacuation capability was shown to meet Reclamation guidelines.

V.   Seismic Failure Modes

A. Concrete dam and retaining walls:

      1. Sliding of the concrete dam section along a thin layer in the foundation leading to erosional failure at the embankment interface.

      2. Cracking/failure of the outlet works walls and subsequent sliding of the concrete section.

      3. Spillway gate/pier failure.

      4. Failure of the north embankment retaining wall leading to slumping and erosion failure the embankment.

         a. Embankment slope failure below reservoir surface resulting in overtopping of the embankment.

         b. Significant disruption of the retaining wall/embankment interface leading to an erosional failure of the embankment.

      5. Differential response of concrete section/embankment interface leading to cracking and erosion without failure of the wall.

      6. Disruption of the retaining wall/south embankment interface leading to an erosional and/or overtopping failure.

B. Embankment dam:

      1. Liquefaction of foundation material resulting in enough deformation in the embankment that the crest of the dam drops below the reservoir water surface elevation, leading to overtopping. Foundation liquefaction was evaluated for two separate cases of embankment failure: sliding beneath the soil-mix-wall (SMW) treatment zone, and sliding through the cracked, and disturbed, SMW material.

      2. Liquefaction and subsequent deformation, leads to disruption of the upstream SMW cutoff wall and foundation piping.

      3. Disruption of the embankment due to deformation, without liquefaction, leads to piping of the embankment material.

      4. An earthquake on the Teton Fault generates a seiche wave which overtops the dam causing erosion and eventual failure.

C. Failure modes selected for event tree analysis:

Five of the twelve potential failure modes were ranked by the team as the most likely to lead to embankment or catastrophic failure. These failure modes were evaluated with the use of event trees.

1. Liquefaction of foundation material leads to embankment sliding beneath the SMW treatment zone.

2. Liquefaction of foundation material leads to embankment sliding through the cracked and disturbed SMW treatment zone.

3. Cracking/failure of outlet works walls and subsequent sliding of the concrete section.

4. Sliding of the concrete dam section along a thin layer in the foundation leading to erosional failure at the embankment interface.

5. Disruption of the north or south retaining wall/embankment interface leading to embankment slumping and erosional failure of the embankment.

D. Failure modes eliminated from further consideration:

1. Liquefaction and subsequent deformation leading to disruption of upstream SMW cutoff wall and foundation piping.- This failure mode was felt to contribute very little to the overall risk of dam failure for the following reasons:

a. From approximate station 29+00 to the left end of the embankment, the maximum differential hydraulic head under normal reservoir conditions is approximately 6 feet. Due to the very small seepage gradient, erosion of foundation materials would be very unlikely.

b. To the right of station 29+00 the SMW structure designed to prevent liquefaction of soils beneath both the upstream and downstream outer shells of the embankment, is in place. If the upstream SMW cutoff wall was cracked, seepage flows would likely be limited through the crack. The soil-cement wall would be resistant to erosion enlargement of the cracks. If the structure was not severely broken, seepage would be forced quite deep and the seepage gradient would be greatly reduced. If the structure were to become badly cracked and broken, it is more likely that seepage could find an open path to the downstream toe. However, a seepage path through the broken structure would likely be discontinuous and tortuous, also leading to a small average gradient. In addition, the soil-cement SMW structure would have some resistance to erosion and further enlargement of cracks.

c. The risk team also felt that it would be unlikely that the structure could support large open cracks. This is due primarily to the soft material surrounding the SMW and the large overburden stresses that would tend to close cracks.

2. Disruption of the embankment due to deformation, without liquefaction, leading to piping and/or internal erosion through the dam.- This failure mode was considered very unlikely simply because the dam was designed for such a failure condition. The embankment contains both upstream and downstream cohesionless filter zones, zone 2, and a filter blanket along the foundation, zone 2A. These zones were also designed with permeability in mind, to transmit seepage entering through cracks. It is also possible that the upstream zone could act as a crack stopper in the event of cracks within the core zone 1 material.

3. Failure of the embankment due to a seiche wave generated by movement of the Teton Fault which overtops and fails the dam.- The following reasons were cited by the risk team leading to the conclusion that this failure mode was unlikely:

a. The embankment was designed to resist seiche wave overtopping with the use of geogrid reinforcement in the downstream slope material of the left embankment, grouted riprap on the downstream slope of the right embankment, soil-cement on the upstream face, and a paved crest road.

b. In a Teton faulting event, the reservoir would drop down more than the embankment actually increasing the freeboard.

c. There are a series of large, protective islands that would effectively break up a seiche wave traveling across the reservoir toward the embankment and likely dampen the wave action.

4. Spillway pier/gate failure.- A failure of one or more of the spillway piers or gates could result in uncontrolled, but limited flow from the damaged section of the spillway. However, since the total spillway capacity is less than the safe channel capacity just downstream of the dam, no structures would be threatened. It is extremely unlikely that all 19 gates would fail. Therefore, this failure mode was not given further consideration.

5. Differential seismic response of the concrete section/north embankment interface leading to cracking and internal erosion failure of the dam.- This failure mode was not considered by the risk team to contribute significantly to the overall risk of failure for the following reasons:

a. The embankment contains filters/drainage elements which would help to minimize the potential for internal erosion to enlarge the cracks and lead to a breach.

b. The upstream wall is counterforted while the downstream wall is counterforted with some structural box-shaped elements. If separation occurred, any potential open seepage paths would be tortuous and likely have small seepage gradients.

c. Pervious and non-cohesive materials both upstream and downstream

adjacent to the walls (similar to the typical embankment cross-section) would be less likely to sustain open cracks and could serve as crack stoppers when saturated.

6. Differential seismic response of the concrete section/south embankment interface leading to cracking and internal erosion failure of the dam.- This failure mode was considered to be a low risk to create dam failure due to the fact that the south embankment contains an existing core wall within the embankment founded on bedrock, and both upstream and downstream retaining walls. These walls would have to be cracked and any seepage water would have a torturous seepage path to a downstream exit point. In addition, the hydraulic height of the south embankment section is small for normal water surface conditions. This small hydraulic height would produce a correspondingly small hydraulic gradient across the south embankment section in the event of cracking.

7. Failure of the embankment retaining walls leading to embankment slumping and direct overtopping.- The team determined that this failure mode was very unlikely due to the fact that the embankment slopes are relatively flat, the concrete retaining walls are strong, counterforted walls, liquefiable soils are not present in this area of the foundation, and high freeboard often exists.

VI.   Potential Loss of Life Estimates

Two loss-of-life evaluations were utilized by the risk team to estimate the loss of life for calculation of annualized loss of life probability values for each failure mode. One evaluation was taken from the March 1999 Comprehensive Facility Review (CFR) Report of Findings. The second reference is a review of potential loss of life completed by Wayne Graham (USBR), dated July 18, 2002, at the request of the team leader for this risk analysis [7]. Both loss of life studies were based on a review of flood inundation boundaries completed by Reclamation's Boise office in August 1980 and previous studies of flooding impacts by both Reclamation (1999 CFR) and the U.S. Geological Survey. Persons at Risk (PAR) from a failure of Jackson Lake Dam are typically located at significant distances from the dam. For most of the PAR, warning times for flooding due to failure of the dam, are measured in hours.

The conclusion from Graham's report is that an earthquake-induced failure of Jackson Lake Dam would result in little to no loss of life. Primarily this is based on the significant amount of warning time to most of the PAR, number of eyes on the dam, and low severity flows for most of the PAR. In Graham's report, it is noted that the floodplain downstream from the dam is more than a mile wide in some areas between the dam and the Teton National Park Headquarters at Moose. Most loss of life from historic dam failures has occurred in narrow canyons or valleys where the water levels rise very rapidly. The wide floodplain downstream of Jackson Lake Dam would retard the downstream movement of flooding and it would temper the rate at which the flood level rises at all locations. At the two closest locations of permanent PAR to the dam (i.e. Buffalo Fork entrance and Bar BC ranch), the permanent residential structures are on the edge of the potential flood plain where flooding would not likely be severe.

The conclusions from both of these reports were considered by the team. Actual values used to compute annualized loss-of-life were individually selected by the team for each specific failure mode. In addition, a probability distribution function (PDF) was typically applied by the team to each range of loss-of-life. This probability distribution function essentially represented the team's thinking as to the likelihood of the loss of life in a given failure event being near the low end, near the mode (best estimate), or the high end of the loss of life range.

It should also be noted that the risk team's estimates of loss of life are slightly higher than those estimated by Graham. However, the risk team's best estimates are within the general range of the numbers suggested by Graham. The risk team estimates are higher because of judgements that the historic case studies of dam failures do not reflect potential loss of life after a severe earthquake results in downstream flooding. In such a scenario, it may be that some persons are trapped and unable to move to safety, communication lines may be down (resulting in slower communication and response times), escape routes may be damaged or blocked, and the movement of persons out of the floodplain may be slowed by the general chaos that follows a major earthquake event.

VII.   Failure Event Trees

Detailed failure event trees were constructed for each of the five failure modes listed in section V.C. Each failure mode was divided into discreet events, or branches, which were individually assigned a probability of occurrence. When estimating the probability to be assigned at each node in the event tree, the range of estimates from the team is represented by a probability distribution function, similar to the loss of life estimates. This probability distribution function is a quantitative way of representing the distribution of the risk team's degree of belief for a given event. In most cases, the mode of the probability distribution function is referred to as the "best estimate".

Each failure mode event tree was developed with data from structural analyses and deformation analyses using the seismic loadings and ground motions developed from the ground motion report. Each event tree is summarized in detail in the issue evaluation report.

VIII.   Conclusions

The risk team collectively developed a list of all failure modes believed to be possible under seismic loading at the dam. Once a list of failure modes was completed, the risk team used a qualitative approach to select only those failure modes deemed to have a reasonable potential to result in dam failure for quantitative risk analysis. For these failure modes, previous analyses were reviewed and new stability, deformation, and stress analyses were completed for the risk analysis meetings; these results were incorporated into detailed "event tree" development. A total of five potential failure modes were developed in two discreet categories: failure modes for the embankment section and failure modes for the concrete section. Seismic loadings and recurrence rates were obtained from the updated seismic hazard study and ground-motion analysis for

Jackson Lake Dam.

Based on Reclamation's Public Protection Guidelines, the total mean value for annualized loss of life values is in the range of diminishing justification for further risk reduction actions. The total annual probability of failure value is borderline for justification for further risk reduction actions.

Based on the discussions and analyses performed for this risk analysis, the following important points should be noted:

     A. One of the most significant areas of uncertainty is the estimate of the magnitude of embankment deformations in a large earthquake. The primary uncertainties lie in the determination of the effect of long-duration shaking produced by the site-specific basin effects on the ground motions felt by the embankment and the response of the SMW structure in the foundation. In order to reduce the uncertainty of these judgements, limited FLAC (Fast Lagrangian Analyses of Continua) dynamic deformation analyses were completed, historical case histories of liquefaction-caused embankment failures were reviewed, and the SMW structure was conservatively modeled in the analyses to be a liquefied zone of soil only. The risk team is satisfied with the mean estimates used in the event trees based on results of FLAC analyses, historical dam performance during earthquakes, and mitigating factors that the risk team feels to be supportive of its judgements concerning deformations. The supporting factors used to judge the level of dynamic embankment deformations, and their impact on the failure scenarios are described below:

     1. For a large period of any given year, Jackson Lake Dam maintains a significant amount of freeboard on the embankment. Under normal water surface conditions, the dam has a proportionately large amount of freeboard in relationship to its maximum height at the maximum section. This ratio improves the farther north one moves along the embankment from the concrete dam section.

Limited data from historical embankment failures under strong seismic loading suggest that deformations exceeding 25 - 30 percent of total embankment height have not occurred unless the entire foundation, and possibly the embankment itself, were liquefiable. This is not the case with Jackson Lake Dam where potentially liquefiable soils are not present in the embankment and are generally deeper in the foundation. The available freeboard at Jackson Lake Dam, based on a percentage of embankment height, normally equals or exceeds the historic maximum magnitude of deformations observed in embankment dams which have deformed as a result of strong ground shaking. At many locations along the embankment, the available freeboard is much greater than the historic maximum deformations observed in other dams. In addition, limited FLAC deformation analyses at embankment station 18+50, using a severe, long duration earthquake produced from the basin modeling, support the judgement by the risk team that deformations would not exceed freeboard and several feet of embankment crest would remain after shaking stopped.

2. The embankment dam is a well-constructed and well-compacted dam. Both the concrete dam and the embankment dam were structurally modified in the 1980s to withstand strong ground motions based on the current understanding of the tectonic activity at the time of the modifications. The embankment dam contains many seismic defensive design features which would help to mitigate damage in an earthquake. These include upstream crack stoppers, filters, drains, etc. that would help to prevent, or slow, a complete failure of the dam due to seismically induced deformations leading to cracking and subsequent piping or internal erosion. The structural components of the concrete dam were rebuilt in some cases and strengthened in others, to perform safely in the event of a large earthquake. Defensive design features such as soil-cement upstream slope protection, grouted riprap, and reinforced soil on the downstream slope of the embankment, were also added to help prevent damages to the embankment in the event of overtopping from seiche waves. In addition, geogrid reinforcement was placed across the foundation of the dam to help restrain differential movements or strains within the foundation resulting from settlements and/or deformation.

3. Immediately downstream of Jackson Lake Dam the population at risk is small. It is primarily limited to recreationists and sightseers at the Buffalo Fork entrance area of Grand Teton National Park, including a small number of permanent residences for National Park Service employees near the entrance. In addition, these areas would be almost devoid of people in the very late fall, winter and early spring and the limited permanent residences are on the outer edge of the inundation boundary. Warning times for areas downstream which contain higher populations are significant and are likely to result in sufficient warning of a failure.

B. For the case of Jackson Lake Dam, the annualized loss of life is in the range of diminishing justification for further risk reduction actions. However, the annual probability of failure is borderline for justification of further actions based only on the seismic loading conditions. This is driven largely by the high probability of the site experiencing very large ground motions. Additional analyses could be performed to reduce the uncertainties, and there is a reasonable chance that the increased understanding would reduce the annual failure probabilities.

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