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City of Silverton
Dept. of Public Works
306 S. Water Street
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July 21, 1999

Attn: Mr. Richard J. Barstad, P.E.
Public Works Director

Seismic Stability Analysis
Silver Creek Dam
Silverton, Oregon

Dear Mr. Barstad:

In accordance with your authorization, we have completed a seismic stability evaluation for Silver Creek Dam. In addition to seismic stability, the stability of the embankment was analyzed for steady state and rapid drawdown conditions. This report summarizes the results of the analyses.

Background Information

Silver Creek Dam was constructed in 1974 by the City of Silverton for municipal water supply and recreation. The structure is a zoned earth and rockfill embankment with a maximum height above the original ground surface of 65 feet. Embankment slopes are 2H:1V downstream and 3H:1V upstream. Crest width is 20 feet, and crest length 680 feet (including spillway). The spillway, located on the right abutment, consists of a converging concrete chute with an entrance width of 120 feet.

Silver Creek Dam is located on Silver Creek in Section 12, Township 7 South, Range 1 West, Willamette Meridian, approximately 2 miles southeast of Silverton, Oregon. A vicinity map and site plan are shown on Figure 1. During initial reservoir filling, seepage was detected on the downstream face of the dam. The leakage was thought to be occurring through the right abutment foundation materials. Horizontal drains were installed from the downstream toe of the embankment, and a drainage berm was placed on the lower portion of the slope to control leakage. Piezometers were installed in the embankment to monitor groundwater levels—three along Station 3+50 and three along Station 4+50. An as-built plan of the dam, including the drainage blanket and piezometers, is shown on Figure 2.

A Phase I National Dam Safety Inspection was performed for Silver Creek Dam in 1981. The inspection evaluated abutment and foundation conditions, embankment stability, hydraulic and hydrologic conditions, and structural/mechanical features. The inspection found the dam to be in satisfactory condition for continued operation.

Subsurface Conditions

Subsurface foundation conditions at Silver Creek Dam consist of colluvium and ancient landslide debris on the valley slopes, alluvial river deposits in the valley floor and Columbia River basalt bedrock in the stream bed. The left abutment contains colluvial material consisting of basalt rock fragments in a matrix of silt, sand and clay. The material was derived from weathering and erosion of the valley slopes. The thickness of colluvium varies from 10 to 50 feet near the dam site. The right abutment is ancient landslide debris consisting of angular basalt fragments and boulders with occasional silt to clay matrix. The slide debris is 80 feet thick at the right abutment. The alluvial river deposits consist of 5 to 10 feet of silty, sandy gravels and cobbles. The basalt bedrock is hard, slightly weathered and highly fractured. Basalt outcrops in the stream bed and the stilling basin at the base of the spillway is excavated into the basalt. A cross-section of the subsurface materials along the axis of the dam is shown on Figure 3.

Seismicity

Potential seismic hazards which could impact the dam site were based on a review of several recent detailed studies in Oregon including: "Seismic Design Mapping, State of Oregon," prepared in 1995 by Geomatrix for the State of Oregon; and "Seismic Hazard Evaluation, Barney Reservoir Expansion," prepared in 1994 by Cornforth Consultants and Geomatrix for the Barney Joint Commission.

Regional Tectonic Setting. The Pacific Northwest lies within a zone of active tectonic convergence between the Juan de Fuca oceanic plate and the North American continental plate. Within this regional tectonic setting, there are three potential seismic sources which could affect Silver Creek Dam. One source is from relatively shallow earthquakes occurring within the North American plate (crustal sources), and the other two sources are "subduction" events occurring as the Juan de Fuca plate is thrust underneath the North American plate. Subduction earthquakes occurring at the contact between the two plates are referred to as "interface" events. Those occurring entirely within the subducting Juan de Fuca plate are referred to as "intraslab" events. Crustal sources can be subdivided into two types, those occurring on known or suspected faults, and those occurring randomly on unidentified or "blind" faults.

Significant Historical Seismicity. Since 1877, eight earthquakes with magnitudes greater than M 5.0 have occurred within 60 miles of the project site. The largest and closest was the March 25, 1993 M_w 5.6 Scotts Mills earthquake, centered approximately 8 miles northeast of the dam site.

There are no historic records of subduction earthquakes in Oregon. Two significant intraslab events have occurred in the Puget Sound region of Washington in 1949 (M 7.1) and 1965 (M 6.5). However, there currently is a large amount of indirect paleoseismic evidence that has been collected along the Oregon coast which suggests that great subduction interface events have occurred in the past. Radiocarbon dating indicates that the last event occurred approximately 300 years ago. Estimates of recurrence intervals range form 350 to 700 years.

Crustal Sources. The closest active fault to the dam site is the Mount Angel fault. The 1993 Scotts Mills earthquake is thought to have occurred on an extension of the Mount Angel fault. The Mount Angel fault is considered capable of producing maximum credible earthquakes (MCE) of 6.6. No other significant crustal faults are known to lie within 20 miles of the site; however, it is possible that an earthquake could occur on a blind fault within this 20-mile radius (similar to the Scotts Mills earthquake). In Oregon, current engineering practice to account for a random crustal earthquake on a blind fault is to assume that an earthquake ranging in magnitude from MCE 6 to 6.6 could occur within a 10-mile radius of the subject site. This practice would not result in ground motions larger than a MCE 6.6 on the Mount Angel fault. Therefore, the seismic stability of Silver Creek Dam will be evaluated for crustal faults using the Mount Angel fault source.

Subduction Sources. As mentioned, no subduction earthquakes have occurred in Oregon dating back to 1827. However, substantial indirect evidence of past subduction has been collected. There is currently much debate in the seismologic community as to the MCE and eastern edge of the subduction interface zone. Based on previous seismic hazard studies, we have assigned a MCE = 8.5 for the interface event, and a MCE = 7.3 for the intraslab event. Both subduction sources would occur 55 to 70 miles west of the dam site near the Oregon coast. Even though the MCEs for these sources are larger than the Mount Angel fault, the great distance of the subduction sources to the dam site would result in lower ground motions at the site than ground motions produced by the Mount Angel fault. For this reason, the Mount Angel fault is the controlling ground motion at the dam site.

Recent research indicates that the eastern edge of the "locked" interface zone could extend further inland from what was previously thought, perhaps as far east as Corvallis. This same research also suggests that the wider interface zone could produce a Magnitude 9 earthquake. However, this research is still very preliminary and additional studies and data are needed to corroborate these early findings. As such, the engineering community has not incorporated this evidence into practice. For example, the Portland District Corps of Engineers still evaluates the seismic safety of their Willamette Valley dams using a Magnitude 8.3 subduction earthquake located off the Oregon coast.

Embankment Section

Several cross-sections of the dam embankment are shown on Figure 4. The embankment consists of five material types: the impervious core, the downstream filter, Zones I and II rockfill shells, and the downstream drainage berm. Material properties for the stability analyses were obtained from a review of previous laboratory testing, or where sufficient information was not available, on a comparison with typical values for similar material types.

Impervious Core. Construction documents and as-built correspondence indicates that the impervious core consists of compacted, sandy, clayey silt. Material properties for the stability analyses were assigned based on a review of laboratory testing by CH2M Hill during the original design of the dam. From triaxial test data, the core material was assigned effective stress parameters of $\phi' = 34$ degrees and $c' = 0$, and total stress parameters of $\phi = 1$ degrees and $c = 360$ pounds per square foot (psf). Field density tests indicated wet densities ranging from 105 to 119 pounds per cubic foot (pcf). Stability analyses from the National Dam Safety Inspection in 1981 used a conservative moist unit weight of 104 pcf. The current analyses also used a moist unit weight of 104 pcf.

Filter. Construction documents describe the filter material as a well-graded, 3-inch minus crushed rock with not more than 4 percent passing the No. 200 sieve. We have assigned the filter material a friction angle of $\phi' = 40$ degrees and a moist unit weight of 120 pcf.

Zones I and II Shell. Zone I shell material consists of a mixture of silty, sandy gravel. Zone II consists of silty rock fragments. CH2M Hill performed direct shear tests on the ¼-inch minus fraction of this material. Test results indicated a friction angle of $\phi' = 3.5$ degrees. This value was used in the current stability analyses, although it is probably conservative due to the large percentage of rock and gravel which has been excluded from the shear test. A moist unit weight of 120 pcf was assigned to both zones.

Drainage Berm. Limited gradation information is available for the drainage berm. Therefore, for the stability analyses we have assumed a 3-inch minus aggregate, with a friction angle of $\phi' = 40$ degrees and a moist unit weight of 120 pcf.

Stability Analyses

Slope stability analyses were performed for the maximum embankment section of 65 feet, located at Station 3+50 (see upper right corner of Fig. 4). The stability analyses were performed using the computer program UTEXAS2 (Edris and Wright, 1987). The program calculates the factor of safety (FS) for a given failure surface using Spencer's method of analysis. By definition, the factor of safety compares the forces tending to cause movement (driving forces) with the forces resisting movement. Mathematically, the resisting forces are in the numerator and the driving forces are in the denominator. If the forces are equal, then the FS = 1.0. For a stable condition, the resisting forces exceed the driving forces and the FS is greater than 1. For unstable conditions, the reverse is true and the FS is less than 1.

Trial circular and wedge failure surfaces were evaluated using both search routines and manually specified surfaces. Critical trial failure surfaces for dam safety are shown on Figure 5, along with a table summarizing the calculated factors of safety (FS). Several checks were performed using the computer program GSLOPE (MITRE Software Corporation).

Steady-State Conditions. The results of the analyses indicate that there is an adequate FS for steady-state seepage conditions. Piezometric levels within the embankment were based on levels measured in piezometers P-4 and P-6 during the storm events of February 1996. The readings were obtained two days after the flood crest of February 6, 1996 on Silver Creek. Piezometer levels measured in P-10 (core area) were not used due to the proximity of the piezometer tip close to the filter zone, i.e. the piezometer is essentially dry. Steady-state stability analyses were performed using effective stress parameters.

The minimum stability for both sides of the embankment is FS = 1.5 for surficial failure surfaces on the outer portion of the rockfill shell. These failure surfaces are not shown on Figure 5, as shallow slope raveling would not impact dam safety. The lowest calculated factor of safety for deeper-seated failure surfaces under static conditions is FS = 2.1. This surface is a potential wedge failure along the upstream side of the core, angling through Zone I rockfill towards the upstream toe. On the downstream side of the dam, a minimum FS = 2.14 was determined for a potential deep-seated circular failure from crest to toe.

Rapid Drawdown. The critical static failure surfaces on the upstream slope were evaluated for rapid drawdown conditions. Under this scenario the reservoir level is lowered faster than the pore-water pressures in the impervious core can dissipate. This analysis requires a two-step procedure to determine the undrained shear strength of the core material. The first step is to determine the effective confining pressures on the core under steady-state conditions. These pressures are then used with the total stress parameters to obtain the undrained shear strength. This procedure resulted in undrained core strengths of S_u = 650 to 750 psf. The rockfill shell is assumed to be free-draining. The results of the rapid drawdown analysis for a fully lowered reservoir indicate adequate factors of safety ranging from FS = 1.4 to 2.2.

Pseudo-Static Seismic Stability. A review of regional seismicity indicates that the controlling seismic ground motions would be generated by a M 6.6 crustal earthquake on the Mount Angel fault. Due to the close proximity of the M 6.6 crustal earthquake to the site as compared with the subduction earthquakes (M 7.3 and M 8.5), the crustal earthquake would produce the highest ground accelerations. Therefore, the pseudo-static analysis was performed using a seismic coefficient of $k = 0.1$. This value has been recommended by Seed (1979) for M 6.5 earthquakes for dams constructed of materials which would not lose more than 15 percent of their initial strength or buildup large pore-water pressures during earthquake shaking, as is the case for the materials at Silver Creek Dam.

It is important to note that the seismic coefficient (k) is often erroneously confused with the peak horizontal ground acceleration (a_{max}). The seismic coefficient is an empirically derived value used in a static slope stability analysis to model the dynamic forces caused by the earthquake. Seed (1979) recommends seismic coefficients ranging from $k = 0.1$ to 0.15 for earthquakes ranging from M 6.5 to 8.25. These recommended coefficients are significantly lower than the corresponding peak ground accelerations, which could range from $a_{max} = 0.3$ to 1.0 g. These coefficients more closely represent the average acceleration occurring within a potential failure mass at any given time during the earthquake.

The results of the pseudo-static analyses indicate adequate factors of safety for earthquake shaking. The lowest FS is 1.29 for a potential deep-seated, circular failure surface in the upstream side of the embankment. The analyses were performed using undrained shear strengths.

We have also evaluated the maximum seismic coefficient the embankment could withstand on the analyzed failure surfaces. The results indicate that the most critical failure surface would require a seismic coefficient of $k = 0.19$ to reduce the FS to 1.0 (Failure Surface ③, Fig. 5). This indicates that the dam would be stable even during a theoretical MCE 8.25 earthquake occurring close to the dam site.

Liquefaction Potential. Liquefaction-induced settlement and/or lateral spreading can occur in loose, saturated cohesionless deposits. These materials would include loose silts, sands or gravels. As previously mentioned, the embankment materials consist of the impervious core (compacted silty clay), the downstream filter (compacted 4-inch minus crushed rock), Zones I and II shells (compacted rockfill), and the downstream drainage berm (non-saturated, crushed rock). Based on a review of these material types and placement procedures, it is our opinion that there is a very low potential for liquefaction.

The foundation materials consist of a thin layer of alluvium in the valley floor and colluvium and rocky slide debris on the abutments (Fig. 3). The alluvium is described as "dense to very dense", and the left abutment colluvium is described as "basalt rock fragments in a matrix of silt and clay". These materials also have a very low potential for liquefaction. The right abutment is described as "loose, angular rock fragments 4-inch average size with variable amounts of silt and clay matrix". There is a remote possibility that pockets of the right abutment could consist of loose, gravelly silt, which could be potentially liquefiable; although due to the heterogeneous nature of the right abutment (slide debris), we would not expect the potentially liquefiable pockets to be laterally continuous. Therefore, it is our opinion that lateral spreading would be minimal. Potential liquefaction-induced settlements could possibly crack the concrete spillway. However, it is our opinion that localized settlement of the spillway would not result in an uncontrolled release of water.

Appurtenant Structures

The main features of the dam for seismic safety consist of the embankment and the foundation materials. The appurtenant structures at the dam consist of a rectangular, reinforced concrete spillway, an adjacent concrete fishladder, and a 42-inch diameter, concrete outlet pipe. These appurtenant structures are not considered critical to dam seismic safety and, in our opinion, potential damage to these structures from earthquake shaking would not result in dam failure.

Conclusions

The stability of Silver Creek Dam crest was evaluated for three loading conditions: steady-state, rapid drawdown and seismic. The results of the analyses indicate that the embankment has adequate factors of safety against sliding for each loading condition.

This opportunity to be of service is appreciated. If you have any questions regarding this report, please call.

Very truly yours,

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Our professional services were performed, our findings obtained, and our recommendations prepared in accordance with generally accepted engineering principles and practices. This warranty is in lieu of all other warranties, either expressed or implied.

The geotechnical report was prepared for the use of the Owner in the design of the subject facility and should be made available to potential contractors and/or the Contractor for information on factual data only. This report should not be used for contractual purposes as a warranty of interpreted subsurface conditions such as those indicated by the interpretive boring and test pit logs, cross-sections, or discussion of subsurface conditions contained herein.

The analyses, conclusions and recommendations contained in the report are based on site conditions as they presently exist and assume that the exploratory borings, test pits, and/or probes are representative of the subsurface conditions of the site. If, during construction, subsurface conditions are found which are significantly different from those observed in the exploratory borings and test pits, or assumed to exist in the excavations, we should be advised at once so that we can review these conditions and reconsider our recommendations where necessary. If there is a substantial lapse of time between the submission of this report and the start of work at the site, or if conditions have changed due to natural causes or construction operations at or adjacent to the site, this report should be reviewed to determine the applicability of the conclusions and recommendations considering the changed conditions and time lapse.

The Summary Boring Logs are our opinion of the subsurface conditions revealed by periodic sampling of the ground as the borings progressed. The soil descriptions and interfaces between strata are interpretive and actual changes may be gradual.

The boring logs and related information depict subsurface conditions only at these specific locations and at the particular time designated on the logs. Soil conditions at other locations may differ from conditions occurring at these boring locations. Also, the passage of time may result in a change in the soil conditions at these boring locations.

Groundwater levels often vary seasonally. Groundwater levels reported on the boring logs or in the body of the report are factual data only for the dates shown.

Unanticipated soil conditions are commonly encountered on construction sites and cannot be fully anticipated by merely taking soil samples, borings or test pits. Such unexpected conditions frequently require that additional expenditures be made to attain a properly constructed project. It is recommended that the Owner consider providing a contingency fund to accommodate such potential extra costs.

This firm cannot be responsible for any deviation from the intent of this report including, but not restricted to, any changes to the scheduled time of construction, the nature of the project or the specific construction methods or means indicated in this report; nor can our firm be responsible for any construction activity on sites other than the specific site referred to in this report.