

ATTACHMENT 3

# **Description of Potential Geologic and Geotechnical Hazards**

---

# Description of Potential Geologic and Geotechnical Hazards

---

## Introduction

This attachment includes descriptions of potential geologic and geotechnical hazards that may affect proposed Project facilities. Locations where these hazards may be present and potential impacts of these hazards on proposed Project facilities are discussed in the main text of this technical memorandum. Recommended measures to mitigate potential impacts associated with these hazards are also presented in the main text.

## Landsliding and Slope Instability

Landslides, earthflows, and debris flows are relatively common features along ridges and hillsides within the Project area. A landslide is a mass of rock, soil, and/or debris that has been displaced downslope by sliding, flowing, or falling. Landslides include cohesive block slides and disrupted slumps that have formed by the translation or rotation of slope materials along one or more planar or curvilinear surfaces. Earthflows, sometimes referred to as creeping slopes, are relatively shallow deposits of soil or other colluvial material that have oozed downslope under the force of gravity, commonly at a rate too slow to observe except over long duration. Debris flows are generally short-lived phenomena resulting from rapid failure of surficial slope materials. Typically, debris flows leave a train of mud and debris in a scoured channel following runout of the flow.

Landslides, earthflows, and debris flows occur when shear stresses within a soil or rock mass exceed the available shear strength of the mass. Failure conditions may occur when stresses acting on a slope increase, the internal strength of the slope decreases, or a combination of both occurs. Stresses can increase through an increase in the weight of overlying slope materials (by saturation), the addition of material (surcharge) to the slope, application of foundation loads, or seismic loading. Slope shear strength can be reduced through erosion or removal of supporting material at the slope toe, increased pore water pressure within the slope, and weathering/decomposition of supporting soils. Zones of low shear strength within slopes are generally associated with the presence of certain clays, bedding, or fracture surfaces.

Landslide potential is influenced by a number of factors; some of the most significant being degree of slope, the presence and movement of water, and zones of weakness. In general, degree of slope is the most important factor contributing to landslide hazard, with steep slopes being more susceptible to failure than shallow slopes. The presence of water within a slope, often the most variable factor contributing to landslide potential, has a doubly detrimental effect on stability by both increasing slope stresses and reducing slope strength. Although landslide activity is generally greatest during wet winter seasons, landslides can occur at any time, with no apparent triggering mechanism. Bedding planes, joints,

discontinuities, weathered seams, and pre-existing failure surfaces may also create zones of weakness within a slope that increase the potential for failure.

## Fault Surface Rupture

A fault is a fracture or zone of fractures in rock along which displacement has occurred on one side relative to the other. Fault displacement, or rupture, occurs in response to stresses in the earth's crust. Fault rupture may occur suddenly and rapidly, releasing strain energy in the form of earthquake-producing seismic waves. Fault rupture may also occur slowly over time, without producing seismic waves, through a phenomenon known as fault creep.

The potential for fault surface rupture exists where an active or potentially active fault is exposed at or near the surface of the earth. Movement along exposed fault traces during an earthquake or as a result of fault creep may cause displacement of the ground surface. Surface displacement may be horizontal, vertical, or a combination of the two, depending on the orientation and direction of movement along the fault. During a major earthquake, surface displacements on the order of 10 feet or more may occur along main fault traces. Along creeping faults, surface displacements may occur at rates of tenths or hundredths of an inch per year.

Although the greatest amount of displacement typically occurs along the main fault trace, surface rupture may also occur on secondary fault traces or other planes of weakness in surrounding soil and rock materials. As observed during historical earthquakes on major faults, surface rupture and significant distortion of the ground surface may occur within a zone extending several tens or hundreds of feet on either side of the main fault trace. The difficulties involved in accurately identifying, locating, and assessing the potential activity of individual fault traces create significant uncertainty in predicting precisely where ground displacements are most likely to occur during an earthquake on a given fault.

The Alquist-Priolo Special Studies Zones Act, passed in 1972, requires the establishment of "earthquake fault zones" (formerly known as "special studies zones") along known active faults in California (CGS, 1992). The California Geological Survey (CGS) is the state agency responsible for establishing earthquake fault zones. Strict regulations on development within these zones are enforced to reduce the potential for damage due to fault displacement. See Attachment 2 for further discussion of Alquist-Priolo requirements for establishing and regulating development within earthquake fault zones.

In order to qualify for status as an earthquake fault zone, faults must be "sufficiently active" and "well defined." As a result, only faults or portions of faults with a relatively high potential for ground rupture are zoned, while other faults, which may meet only one of the "sufficiently active" and "well defined" criteria, are not zoned. Active faults, as defined by the CGS, are faults on which displacement has occurred during the Holocene period (within about the last 11,000 years). Faults on which displacement last occurred during the pre-Holocene Quaternary period (between about 1.6 million and 11,000 years ago) are classified by the CGS as "potentially active" faults.

Because of the relatively long design life and critical nature of most dams and other impoundment structures, the California Division of Safety of Dams (DSOD) has established stricter standards for characterizing fault activity than those set by the CGS (Fraser, 2001).

Faults that have ruptured within the last 35,000 years are considered “active” by the DSOD and must be accounted for in dam analysis and design. In accordance with DSOD guidelines, fault inactivity is demonstrated by a confidently located fault trace that is consistently overlain by unbroken geologic materials older than 35,000 years. Faults known to be Quaternary active, and for which displacement history is not known well enough to determine activity or inactivity, are classified by the DSOD as “conditionally active.”

## Strong Seismic Ground Shaking

Based on the activity of major regional seismic sources, it is likely that all of the potential storage sites will be exposed to strong seismic ground shaking as a result of one or more large earthquakes during the lifetime of the Project. The most significant sources of potential strong seismic ground shaking within the Project area are the Rodgers Creek – Healdsburg, San Andreas, and Maacama faults. As discussed in Attachment 2, each of these faults is active and capable of generating earthquakes on the order of magnitude 7.0 or larger.

Strong seismic ground shaking takes the form of complex vibratory motion in both the horizontal and vertical directions. The amplitude, duration, and frequency content of ground shaking experienced at a particular site during an individual earthquake are highly dependent on several factors, including the magnitude of the earthquake, characteristics of the fault rupture, the distance of the fault rupture from the site, topographic features, and the types and distributions of soils beneath the site. Large-magnitude earthquakes typically produce stronger ground shaking than small-magnitude events and sites located close to the zone of fault rupture typically experience stronger motions than similar sites located farther away. Topographic features, including basins and ridgelines, may locally amplify ground motions. Locally, site soils have the capability to amplify or dampen ground motions within particular frequency ranges. Soft soils tend to produce larger responses for long-period structures than firm soils.

## Liquefaction and Lateral Spreading

Liquefaction can occur when relatively loose, saturated, cohesionless soil is subjected to undrained, cyclic loading, such as that generated by earthquakes. Excess pore pressures developed during cyclic loading cause a decrease in the effective stresses between individual soil particles and a corresponding decrease in the internal shear strength of the soil. As effective stresses approach zero, the soil-water mixture begins to behave as a fluid.

A soil’s susceptibility to liquefaction decreases as its relative density and fines content increase. Soils particularly susceptible to liquefaction generally include very loose to medium-dense sand, silty sand, and clayey sand. Gravels and low-plasticity silt materials may also be susceptible to liquefaction. Potential consequences of liquefaction include loss of soil strength and bearing capacity, post-liquefaction settlement, sand boils, and lateral spreading. In general, the occurrence and severity of these phenomena depend on the lateral and vertical extent of liquefied material, the type and condition of overlying materials, and existing slope and loading conditions.

As porewater pressures dissipate, liquefied soil tends to consolidate to a denser state than that prior to liquefaction. Post-liquefaction consolidation may result in settlement of the

ground surface. Settlement may also occur as a result of sand boils, which form when excess porewater pressures at depth cause groundwater to flow upward to the ground surface through fractures and other discontinuities in the soil. As groundwater flows upward, it collects and transports soil material to the ground surface. At the ground surface, the ejected soil and water typically forms a cone-shaped vent. Loss of soil material from subsurface deposits as a result of sand boils may result in settlement of the ground surface and/or development of voids below the ground surface.

Lateral spreading may occur where a relatively continuous deposit of liquefied soil underlies sloping ground or is located adjacent to a free face, such as a riverbank or shoreline slope. Under such conditions, liquefied materials tend to flow downslope (or toward the free face), carrying overlying soil and structures with them. As a result of the extremely low internal shear strength of liquefied soil, lateral spreading may occur on very shallow slopes of a few percent or less. Depending on the geometry of the slope and the continuity and extent of liquefied deposits, lateral spreading may result in large horizontal and vertical deformations at the ground surface.

## **Seismically Induced Slope Instability and Ground Cracking**

Strong earthquakes often cause landslides, particularly in areas already susceptible to landslides due to the presence of steep slopes and/or existing landslide deposits. Although landslides may be triggered by relatively low levels of ground shaking, the potential for seismic instability of natural and constructed slopes becomes increasingly significant during earthquakes of magnitudes of 5.0 and greater, especially at times and locations where earth materials are water-saturated. Failure of steep slopes, collapse of natural-stream banks, and reactivation of existing landslides may occur widely during a major earthquake.

Ground cracking is a secondary effect of seismic ground shaking. It appears as fissures or cracks in the ground that open in response to strong shaking. Ground cracking typically occurs along the crests of relatively steep ridges. The exact mechanism that causes earthquake-induced ground cracks is not clear; however, these fissures could severely damage overlying structures during an earthquake.

## **Soft, Loose, and/or Compressible Soils**

Soft, loose, and/or compressible soils are typically found in active or recently (in geologic terms) active depositional environments and areas that have been disturbed by human activity. Because of their physical and/or engineering characteristics, these soils present unique challenges for design and construction of Project facilities. Soft, loose and/or compressible soils interfere with the development of adequate foundation support for overlying structures. Soft, loose, and/or compressible soils typically present adverse conditions for earthwork operations and other construction activities. The presence of such materials may also affect the potential for other geologic hazards such as landsliding, slope instability, and liquefaction.

## Expansive Soils

Shrink-swell or expansive soil behavior is a condition in which clayey soil reacts to changes in moisture content by expanding or contracting. Swelling occurs when water infiltrates between and within clay particles, causing them to separate. The amount of separation is dependent on the chemical properties and crystalline structure of the clay, which influence the strength of electro-chemical bonds between individual clay particles. Shrinkage occurs as water leaves the soil, allowing the clay particles to come more closely together.

Soil that has a high expansion potential exhibits relatively large volume changes, while soil that has a low expansion potential exhibits relatively small volume changes in response to variations in moisture content. For expansive soils, the extent of shrink-swell behavior is limited by the extent of variation in moisture content, which may occur as a result of seasonal wetting and drying cycles, irrigation patterns, changes in groundwater levels, or vegetative evapotranspiration. As a result of the lower confining pressures and greater potential for moisture variation, expansive soils near the ground surface generally tend to exhibit larger volumetric changes than those at depth.

## Shallow Groundwater and Seepage

Shallow groundwater is found relatively near the ground surface and has the potential to affect design and construction of the proposed Project facilities. The presence and depth of shallow groundwater may be influenced by: seasonal fluctuations in temperature and precipitation; water levels in nearby streams, ponds, and other bodies of water; subsurface soil conditions; local irrigation practices; pumping from nearby wells; and a variety of other factors. Shallow groundwater may be locally perched, a condition in which infiltrating groundwater collects above a low-permeability soil layer that restricts the amount of flow into underlying, unsaturated layers.

Groundwater travels both horizontally and vertically through pore spaces in saturated and unsaturated soils and through fractures in bedrock formations. The rate of groundwater movement through a soil or bedrock formation is governed by the pressure differential, or gradient, under which the flow is driven and the permeability of soil or rock materials within the formation. In terms of leakage from storage facilities such as the proposed ponds, seepage gradients increase as the difference in elevation between the surface of the pond and the underlying groundwater table increases.

The permeability of a soil or rock formation is dependent on the size and continuity of its pore spaces and fractures. In general, sandy and gravelly soils and highly fractured bedrock formations are far more permeable than silty and clayey soils and unfractured bedrock formations. Typical permeabilities of natural soils, ranging from coarse gravel to high plasticity clay, may vary by seven or more orders of magnitude. As a result, localized seepage through a relatively small seam of sand or gravel may far exceed the amount of seepage through a large deposit of clay. Similarly, in bedrock materials, seepage through fractures and discontinuities may greatly exceed seepage through surrounding materials.

## References

California Geological Survey (CGS). 1992. Fault Rupture Hazard Zones in California, Alquist-Priolo Special Studies Zone Act of 1972 with Index to Special Studies Zones Maps. California Geological Survey (formerly California Division of Mines and Geology, CDMG) Special Publication 42, Revised 1992. State of California Department of Conservation.

Fraser, W.A. 2001. California Division of Safety of Dams Fault Activity Guidelines. California Department of Water Resources, Division of Safety of Dams.