Geology and Seismicity Technical Memorandum

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Acronyms and Abbreviations

ASCE	American Society of Civil Engineers
Authority	Sites Project Authority
CBC	California Building Code
CRSBZ	Coast Ranges – Sierran Block Boundary Zone
DWR	California Department of Water Resources, Division of Engineering
DSHA	Deterministic Seismic Hazard Analysis
ft/s	foot per second
GCID	Glenn Colusa Irrigation District
GMPE	ground motion prediction equation
I/O	Inlet/Outlet
MAF	million-acre-feet
m/s	meters per second
M_w	moment magnitude
PSHA	Probabilistic Seismic Hazard Analysis
TCCA	Tehama Colusa Canal Authority
TM	Technical Memorandum
TRR	Terminal Regulating Reservoir
Reclamation, USBR	U.S. Bureau of Reclamation
UHS	Uniform Hazard Spectra
USGS	U.S. Geological Survey
V_S	Shear wave velocity
V_{S30}	Average shear wave velocity in upper 30 meters
WLA	William Lettis and Associates, Inc.

1.0 Introduction

1.1 Project Overview

The Sites Project Authority (Authority) is preparing a feasibility-level evaluation for a 1.5-million-acre-foot (MAF) reservoir as a preferred option for the Sites Reservoir Project. This reservoir would be in the same location as the reservoir studied previously by the California Department of Water Resources, Division of Engineering (DWR), and the U. S. Bureau of Reclamation (Reclamation). Smaller main dams and saddle dams would be constructed to form the smaller reservoir.

The principal storage feature of the project is Sites Reservoir. Figure 1-1 shows the location of Sites Reservoir, and the various dams to be constructed to form the reservoir, and conveyance facilities. Sites Reservoir would have a nominal storage capacity of 1.5 million acre-feet (MAF) for Alternative 1, and 1.3 MAF for Alternative 2.

1.1.1 Reservoir

Water in Sites Reservoir would be impounded by the Golden Gate Dam on Funks Creek; the Sites Dam on Stone Corral Creek; and by a series of saddle dams along the eastern and northern rims of the reservoir. The saddle dams close off topographic saddles in the ridge forming the reservoir. The 1.5-MAF reservoir (maximum Normal Water Surface Elevation 498 feet) requires seven saddle dams and two saddle dikes. Six saddle dams would be required for the 1.3-MAF reservoir (maximum Normal Water Surface Elevation 482 feet), because the maximum reservoir water level would be approximately 16 feet lower in elevation.

The reservoir would be filled through conveyance facilities located to the east that would draw water from the Sacramento River. The proposed Inlet/Outlet (I/O) works are to the south of Golden Gate Dam. The same I/O works would be used to make releases from Sites Reservoir. The I/O works encompass two large-diameter tunnels through the ridge, a vertical inlet tower in the reservoir controlling flows at the upstream tunnel portal, and a system of piping connecting the downstream tunnel portal to the pumping facilities. Releases to or from the reservoir would be made through an array of gated outlet ports around the perimeter of the Sites Reservoir's vertical I/O tower at various elevations to accommodate varying reservoir water levels, and to regulate outlet water temperature. The I/O works concept would be the same for the 1.5-MAF and 1.3-MAF reservoirs; the height of the structure and number of gated ports would be smaller for the smaller reservoir.

Sites Reservoir construction would require relocating county roads (Maxwell Sites Road, Sites Lodoga Road, and Huffmaster Road) and the community of Sites. Other new paved or unpaved roads would also be provided to access project facilities from existing roads, and to improve operation and maintenance access between main dam and saddle dam areas.

1.1.2 Conveyance Facilities

The conveyance facilities include improvements to the Tehama Colusa Canal Authority (TCCA) and Glenn Colusa Irrigation District (GCID) main canal facilities and large diameter (9 to 12-foot diameter) pipelines associated with the Terminal Regulating Reservoir (TRR), Funks Reservoir, and Dunnigan Pipeline alignments to provide water in and out of Sites Reservoir and to convey water to the Colusa Basin Drain and into the Sacramento River.

The structures associated with the conveyance facilities include multiple sites across the project. The conveyance facility structures include Funks Reservoir Power Generating Plant, Terminal Regulating Reservoir Power Generating Plant, high voltage power transmission towers, GCID main canal structures (Hamilton City Head Works and Willows Railroad Siphon), Dunnigan Pipeline Intake off the Tehama Colusa Canal, Dunnigan Pipeline Colusa Basin Drain Discharge, and Dunnigan Pipeline Sacramento River Discharge.

1.2 Purpose and Scope of Technical Memorandum

The purpose of this technical memorandum (TM) is to provide a general overview of the site geology, including rock units, soils, and geologic structure. In addition, seismic design parameters, including ground motions and potential for fault offset, are provided.

Seismic design parameters are provided for the reservoir structures (dams and I/O tower and tunnels) and bridge (by the HR service provider, AECOM), and for the conveyance facilities (by the HC service provider, Jacobs).

This TM is based on available information referenced herein, and serves as an overview of the site geology and seismicity. Further details, such as geologic conditions at the dam abutments, and other site-specific descriptions can be found in the referenced California Department of Water Resources (DWR) documents.

1.3 Limitations and Assumptions

The scope of work for this TM was restricted to the development of feasibility designs for the Sites Reservoir. It did not include consideration of other Sites facilities beyond those specifically listed.

AECOM represents that our services were conducted in a manner consistent with the standard of care ordinarily applied as the state of practice in the profession within the limits prescribed by our client.

This TM is intended for the sole use of the Sites Project Authority. The scope of services performed may not be appropriate to satisfy the needs of other users, and any use or re-use of this document or of the findings, conclusions, or recommendations presented herein is at the sole risk of said user.

1.3.1 Assumptions and Sources of Data

The geology and seismicity of the area are based on previous data and interpretations by others. The main sources of data for this report were the:

- Geologic Feasibility Report, Sites Reservoir Project, prepared by the California Department of Water Resources (DWR, 2003)
- Phase II Fault and Seismic Hazards Investigation, North of Delta Offstream Storage Integrated Storage Investigations, prepared by Lettis Consultants International, Inc. (formerly William Lettis and Associates, Inc.) (WLA, 2002)
- North-of-the-Delta Offstream Storage Investigation, Appendix B Engineering, prepared by the United States Bureau of Reclamation (USBR, 2020)

We have examined the available project data and have updated it as referenced herein. This TM is meant for use in feasibility-level studies only. As design continues, this TM will need to be updated as new data and site understanding are advanced.

2.0 Project Geology

This section was excerpted from the Geologic Feasibility Report, Sites Reservoir Project (DWR, 2003) and the Phase II Fault and Seismic Hazards Investigation, North of Delta Offstream Storage Integrated Storage Investigations, prepared by Lettis Consultants International, Inc. (formerly William Lettis and Associates, Inc.) (WLA, 2002). Specific geologic information can be found in this reference.

2.1 Geologic Setting and Overview

The project area is in the northwestern part of the Sacramento Valley in the foothills on the eastern side of the Coast Ranges, bordering the Coast Ranges and Great Valley geomorphic provinces (Figure 2-1). The project area is underlain by Upper Cretaceous sedimentary rocks of the Great Valley sequence (Cortina and Boxer Formations) and alluvial deposits of the Sacramento Valley. Surficial geologic units in the project area include Pliocene- to Pleistocene-age deposits of the Tehama Formation, Quaternary older alluvial terrace deposits, and Holocene (Recent) alluvium, colluvium, and landslide deposits. Figure 2-2 shows a regional geology map with the locations of various project features. This figure was generated by combining figures from DWR (2003) and WLA (2002). The figure is intended for feasibility-level analyses only; more detailed geologic maps are provided in DWR (2003).

The project features are located in Great Valley sequence rocks. The two main formations in the project area are the Cortina and Boxer Formations. In the Cortina and Boxer Formations, the two primary rock units are sandstone and mudstone, with some interbedding of these two occurring to varying degrees. The primarily sandstone portions are commonly ridge-formers, and the primarily mudstone portions are generally expressed as topographic lows. The Cortina and Boxer Formation rocks are discussed further in Section 2.1.1.

The proposed Golden Gate Dam site is in a stream-cut water gap on Funks Creek in the Venado sandstone member of the Cortina Formation. The intake channel near Golden Gate Dam would be founded on the Yolo member of the Cortina Formation. The proposed Sites Dam site is in a stream-cut water gap on Stone Corral Creek, in the Boxer and Cortina Formations. The saddle dam sites would be located entirely in the Boxer Formation. Additional discussion of the geologic conditions of these sites is provided in DWR (2003).

As shown in Figure 2-2, the project lies in the Coast Range foothills, bounded to the west by the Coast Ranges, and to the east by the Sacramento Valley. Passing beneath the proposed site are westerly dipping fault planes of the Funks and Bear Valley segments of the Great Valley thrust fault. The Fruto Syncline, Sites Anticline, S-3 fault, and Salt Lake fault pass through the project site in a generally north-south trend, with the Salt Lake Fault passing through the proposed site for Saddle Dam No. 2. The GG-1, GG-2, GG-3, and S-2 faults pass through the project site in a generally northeasterly trend, with several of the faults passing near the Golden Gate and Sites dam sites. Further details on structure and faulting are provided in Section 2.3.

2.1.1 Great Valley Sequence Rocks

The Boxer Formation consists of thin-bedded mudstones with scattered thin- to medium-bedded sandstones representing basin-plain deposits of distal turbidites (Ingersoll, 1978). The basal member includes the Salt Creek Conglomerate. The Boxer Formation rock units consist mainly of mudstone (Kbm), interbedded sandstone and mudstone (Kbsm), and minor sandstone (Kbs), and conglomerate (Kbcgl). The formation is less resistant to weathering and erosion, and seldom is exposed in outcrop; therefore, except for minor outcrops of discontinuous sandstone interbeds and the bold conglomerate outcrops, the main units, Kbm and Kbsm, are mostly not exposed.

The Cortina Formation consists of a greater proportion of sandstone, with moderate-to-thick mudstone interbeds. The basal member of the Cortina Formation is the Venado sandstone. Near the base, the sandstone is primarily fine- to medium-grained and hard, occurring chiefly in 1- to 10-foot-thick interbeds. Petrographic studies indicate that the rock is cemented by carbonates with a silica-clay matrix. The Venado includes a lesser amount of well-indurated, crudely fissile mudstones that occur as 1/8- to 6-inch-thick beds. Mudstone constitutes about 5 percent of the basal Venado. Above the basal unit, mudstone beds increase to nearly 50 percent of the section. Further up the section, the Venado consists of repetitive intervals of medium- to thick-bedded sandstone and thinner-bedded sandstone with about an equal amount of mudstone.

The mudstones of the Yolo Shale Member are laminated to thin-bedded. The Yolo Shale ranges from 800 to 1,000 feet thick, and occupies the strike valleys between the Venado and Sites sandstone members.

In the project area, outcrops of sandstone beds are mostly brown, moderately strong, and range from thinly laminated to massive. In the drill core, fresh sandstones are mostly light green to gray, and hard. Commonly, they are interbedded with conglomerates, siltstones, and mudstones. Massive sandstones are well-indurated and hard, with widely spaced joints, and form the backbone of most of the ridges.

In the project area, mudstones typically underlie the valleys and some west-facing ridges, and are not found in outcrop due to their closely spaced fracturing and minimal resistance to weathering and erosion. Exposed mudstone units tend to readily slake. In the drill core, fresh mudstones are mostly dark gray to black, thinly laminated, moderately hard, and closely fractured due to pervasive jointing.

Discontinuous conglomerates are found in the northern end of the valley. The interbedded conglomerates consist of lenticular and discontinuous beds that vary in thickness from several feet to more than 100 feet. These conglomerates, commonly cemented, are similar to the sandstone in hardness and jointing. Clasts in the conglomerate range in size from pebbles to boulders, but are mostly gravel-sized. The clasts are composed primarily of volcanic rocks, granitic rocks, and sandstones set in a matrix of cemented sand and clay.

At the Golden Gate and Sites dam sites, the bedding is most prominent in the resistant sandstone beds that are exposed on the northerly trending ridges that compose the abutments. The bedding strikes mostly north-south, and dips to the east (downstream) about 50 degrees. Jointing is pervasive, and the most dominant set strikes mostly east-west (nearly normal to the bedding) and dips steeply to the north or south. There are two secondary sets that roughly strike north-south, with one dipping in a broad range to the northeast, and the other dipping to the southwest. Bedding at the saddle dam sites strikes mostly north-south, and dips variably (10 to 70 degrees) to the west, depending on the proximity to the axis of the Fruto Syncline.

2.1.2 Tertiary Sedimentary Deposits

Tertiary and Quaternary fluvial sedimentary deposits unconformably overlie the Great Valley Sequence. In the study area, these belong to the Plio-Pleistocene Tehama Formation. Thin, discontinuous, and deeply weathered alluvial fan deposits were derived from the erosion of the Coast Ranges and Klamath Mountains. Eastward, the deposits thicken and coalesce, forming a broad, thick, fluvial outwash plain that contains pale-green to tan semi-consolidated sand, tuffaceous sand, and silt with lenses of gravel. The Nomlaki Tuff Member occurs near the base of the Tehama Formation, and has been age-dated at about 3.3 million years. It consists of white, tan, or pink dacite pumice tuff and lapilli tuff that is about 30 feet thick along the western side of the valley. Most of the tuff appears to have been deposited as an ash fall from a major volcanic eruption.

In places east of the project area, the distinctively red clayey gravel of the Red Bluff Formation caps the Tehama Formation. The Red Bluff Formation remnants represent an extensive Pleistocene peneplain that once covered much of the northern Sacramento Valley.

2.1.3 Quaternary Deposits

Erosion of the Great Valley Sequence rocks has deposited sediments from Holocene to mid-Pleistocene in age. These deposits include stream terraces, floodplain sediments of clay and silt, colluvium, landslides, and active stream channel deposits of sand and gravel.

Stream terraces (Older Alluvium, Qoal) form flat benches adjacent to and above the active stream channel (Recent Alluvium, Qal). Up to nine different stream-terrace levels have been identified in the project area (WLA, 2002). Terrace deposits consist of several to 10 feet or more of clay, silt, and sand overlying a basal layer of coarser alluvium containing sand, gravel, cobbles, and boulders. These formations range in age from 10,000 to several hundred thousand years old.

Alluvium consists of clay, silt, sand, gravel, cobbles, and boulders found in recent stream channels and clay, silt, and sand found on floodplains. Quaternary alluvium is generally loose clay, silt, sand, gravel, and boulders that may occasionally be cemented.

Colluvium is an accumulation of soil and weathered rock that occurs on the ground surface of a hill and at its base. It consists mostly of soil, but contains a sizable angular fraction of underlying rock fragments and some organic material.

Landslide deposits are similar to colluvium, but move along a basal slip surface, have more defined margins, and generally are thicker. Landslides occur along the reservoir rim or steep west-facing ridges, but are generally small, shallow debris or earth flows. These could activate or enlarge in the event of a rapid drawdown of the reservoir. Rock fall deposits are present in the reservoir, especially on the backside of dip-slope sandstone ridges and in some of the water gaps.

2.2 Reservoir Geology

Sites Reservoir would inundate Antelope Valley. Except for a small area upstream of the Golden Gate Dam site, the reservoir would lie entirely over the Boxer Formation. The reservoir area in Antelope Valley is characterized by a gently sloping valley with some subtle rounded knolls, mainly in the vicinity of the saddle dams. It is drained primarily by easterly flowing Funks and Stone Corral Creeks, with some minor northeasterly flowing drainages in the northwestern part of the reservoir. The topography is mostly subdued, with the steeper slopes located in the vicinity of the Golden Gate and Sites dam sites. The geologic mapping performed during

DWR's 2003 feasibility study did not reveal any large landslide complexes that would create reservoir instability during filling. The landslides that have been mapped are mostly surficial slumps and mostly shallow (less than 20 feet thick) (DWR, 2003).

It should be noted that eight exploration gas wells have been drilled in the reservoir. Two were drilled about 500 feet west of Saddle Dam site 3, one west of the town of Sites, and six near the Salt Lake Fault. These exploration wells are assumed to have been abandoned in the proper manner, but further research is required to confirm this prior to reservoir filling.

2.3 Structure and Faulting

The project area is part of a tectonically active boundary between the Pacific plate to the west and the Sierra Nevada-Great Valley (Sierran) microplate to the east. Geodetic data show that the Pacific plate moves approximately 39 millimeters per year toward N30°W, relative to the Sierran microplate (Argus and Gordon, 2001). Because major strike-slip faults of the San Andreas system strike more westerly than average Pacific-Sierran motion north of the San Francisco Bay, there is a small component of convergence resolved across the plate boundary in the northern Coast Ranges. This overall "transpressional" (oblique shear) plate motion is accommodated by a combination of active strike-slip and thrust faulting, and over the past several million years, has produced uplift of the Coast Ranges.

Ongoing research suggests that transpressional plate motion is accommodated in part by movement on the "Great Valley fault," which is a segmented system of hidden or "blind" thrust faults beneath the western margin of the Central Valley. The western valley margin has been referred to by previous workers as the "Coast Ranges – Sierran Block Boundary Zone" (CRSBZ), and described as a belt of active crustal shortening driven by impingement of the Sierra Nevada block against the Coast Ranges (Wong and Ely, 1983). The "Great Valley fault" is the potentially seismogenic fault that accommodates most of the shortening in the CRSBZ. The Funks and Bear Valley segments are the structural segments of the Great Valley fault closest to the Sites and Golden Gate dam sites. Other segments of the Great Valley fault are known or inferred to have generated the 1983 Coalinga and 1892 Winters-Vacaville earthquakes (O'Connell et al., 2001). Neotectonic investigations have documented evidence for Quaternary growth of folds overlying segments of the Great Valley fault beneath the Rumsey Hills and Dunnigan Hills, 27 miles (44 kilometers) south of the Sites and Golden Gate dam sites. Therefore, there is a general consensus among the seismotectonic community that the Great Valley fault is an active or potentially active seismic source in the modern transpressional tectonic setting.

The proposed Sites Reservoir and dam sites have moderate topographic relief, with ridge to stream channel elevation changes of about 500 feet. In the project area, the Cortina and Boxer Formations are part of a series of an east-dipping, Great Valley Sequence of rocks exposed in the foothills bordering the eastern Coast Ranges, which have formed an intricate trellis drainage pattern. Directly west of the dam sites, at the saddle dam sites and in the reservoir, these rocks are folded about the axes of the north-trending Sites anticline and Fruto syncline. East of the Golden Gate and Sites dam sites, the rocks progressively flatten beneath the western Sacramento Valley margin. The most prominent structural geologic features in the project area are the trend of the bedding associated with folding, jointing, and faulting. Figure 2-2 shows the locations of the various structures and faults mentioned in this TM.

There are two primary folds: the Fruto syncline, and the associated adjacent Sites anticline. The Sites anticline is immediately west of the Salt Lake fault by some 1,000 to 2,000 feet. It is a doubly plunging anticline about 3 miles in length in the reservoir, dying out slightly south of the town of Sites. The anticline is interpreted to be a west-vergent fault-propagation fold developed above a blind, east-dipping thrust fault that is rooted in the flat of the Funks segment of the Great Valley fault (WLA, 2002). The anticline is a tight fold with steeply dipping and overturned strata on both limbs. East of the anticline axis, strata dip to the east like the bedding does at Golden Gate and Sites Dam sites. West of the anticline axis, strata dip to the west steeply adjacent to the axis and flattening to the west as they approach the western limb of the Fruto syncline.

The Fruto syncline is about 1 mile west of the Sites anticline near the western side of the reservoir. It is continuous for approximately 9 miles in the reservoir area, and plunges out slightly south of the town of Sites. WLA (2002) interprets the western limb of the syncline to be the forelimb of a large, east-vergent fault propagation fold above the ramp in the Funks segment of the Great Valley fault. Strata west of the syncline axis dip flatly to the west, and steepen to the east.

Based on analysis of seismic reflection data, William Lettis & Associates (WLA, 2002) interpreted that the folds and various surface faults in the Sites Project area have developed from the blind, west-dipping Great Valley thrust fault. The fault trends mostly north-south, and is located only in the subsurface about 5 kilometers below the Sites Project dam sites.

As shown in Figure 2-2, several surface faults have developed from the blind Great Valley Fault, with one set striking north, parallel to the bedding; and another striking northeast, obliquely cutting the bedding.

Based on analysis of seismic reflection data and surface geologic relationships, WLA (2002) interpreted that the Fruto syncline, Sites anticline, and surface faults described above are underlain by a blind, west-dipping thrust fault informally named the Funks segment of the Great Valley fault. The Funks segment is about 10.6 miles (17 kilometers) long, dips about 27 degrees toward the west beneath the Fruto syncline, and flattens eastward beneath the Sites anticline on seismic reflection profiles. At the latitude of the Sites and Golden Gate dam sites, the Sites anticline is interpreted to be a fault-propagation fold developed above a blind, east-dipping thrust fault that splays upward from the low-angle Funks segment. Two faults are associated with the Funks segment of the Great Valley Fault:

1) The Salt Lake fault is a bedding parallel, north-striking, high-angle thrust fault that developed adjacent to the axis of the doubly plunging Sites anticline (DWR, 1978), and can be traced confidently for about 12 miles from north of Logan Creek south to Stone Corral Creek near the town of Sites (WLA, 2002). It traverses through the reservoir and is defined by a series of salt-water springs and gas seeps that occur along the fault trace. The fault flattens at depth, and is interpreted to terminate down-dip against the gently west-dipping flat of the underlying blind thrust. The fault is about 1.5 and 1.7 miles west of the Sites and Golden Gate dam sites, respectively. It is projected as trending through the left abutment of Saddle Dam site 2. The fault was trenched in several locations by WLA (2002), and determined to be active based on the Division of Dam Safety’s criteria.
2) Brown and Rich (1961) mapped a bedding-parallel, north-striking thrust fault about 0.75 mile southwest of the Sites Dam site, referred to herein as the S-3 fault. It is similar to the Salt Lake fault, and is interpreted to be a bedding-parallel thrust fault that has accommodated shearing of the sedimentary rocks during uplift and eastward tilting along the valley margin.

Based on analysis of seismic reflection data, another distinct segment of the Great Valley fault is interpreted, referred to as the Bear Valley segment, and is present south of the Funks segment. The Bear Valley segment is about 14 miles (23 kilometers) long and strikes almost due north-south. Based on available reflection seismic data, the Bear Valley segment is interpreted to have a constant west dip, in contrast to the ramp-flat geometry of the Funks segment. Four surface faults are associated with this segment of the Great Valley fault: GG-1, GG-2, GG-3, and S-2. These northeast-striking, high-angle tear faults trend through the reservoir and traverse either through or near the Golden Gate, Sites Dam, and saddle dam sites, and are considered active—but are not seismic sources. These tear faults obliquely cut across the north-striking bedrock units, and consistently displace stratigraphic contacts in a right lateral sense. WLA (2002) believes that the tear faults are confined to the hanging wall block of the Funks segment, and accommodate differential northeast-directed shortening across the segment boundary (Brown and Rich, 1961; Rich, 1971). Fault locations relative to various project elements are shown in Figure 2-2; Figure 2-3 shows a typical cross section of the various faults and structure in the project vicinity.

In fault trenches excavated by WLA (2002), the fault zone widths (“gouge” zones) were observed to be approximately 1 to 3 feet wide. Some additional shear zones, likely created due to sympathetic movement, were also observed in the fault trenches.

3.0 Project Seismic Hazard

This section was excerpted from the Phase II Fault and Seismic Hazards Investigation, North of Delta Offstream Storage Integrated Storage Investigations, prepared by William Lettis and Associates, Inc. (now Lettis Consultants International, Inc.) in September 2002. Specific geologic information can be found in this reference.

3.1 Reservoir Seismic Design Parameters and Response Spectra

Numerous faults and geologic structures were investigated as seismic sources by WLA (2002). The faults and geologic structures investigated, and a summary of the findings, is presented in Appendix A, as originally produced by WLA (2002).

3.1.1 Reservoir Controlling Seismic Source and Response Spectra

Based on the analysis by WLA (2002), the controlling seismic source for both dam sites is the Bear Valley segment of the Great Valley fault system (Figure 3-1). The selection of the Bear Valley segment as the controlling seismic source was based on comparison of the response spectrum for a maximum earthquake on this fault with response spectra for earthquakes on other active seismic sources within a 31-mile (50-kilometer) radius of the dam sites. Empirical regression relations in Wells and Coppersmith (1994) give an associated characteristic earthquake of moment magnitude (M_w) 6.8 (WLA, 2002).

WLA (2002) adopted the following two-step approach for computing response spectra for earthquakes on the Bear Valley segment of the Great Valley fault:

1) Calculate the 84th-percentile, 5%-damped response spectra from the Abrahamson and Silva et al. (2014) and Sadigh et al. (1997) attenuation equations, and average the results.

2) Modify the resulting response spectrum for fault-rupture directivity effects using the procedure in Somerville et al. (1997), as appropriate.

Figures 3-1 and 3-2 show the preliminary response spectra (calculated by AECOM) to be used in design of the Sites and Golden Gate dams, along with any appurtenant hydraulic structures at those locations. Since WLA developed the response spectra at Sites and Golden Gate dams, major advances in the ground motion modeling have resulted in newer state-of-the-art ground motion prediction equations (GMPEs). GMPEs were developed as part of the Next Generation of Attenuation for the active, crustal regions (NGA-West2) project, sponsored by the PEER Center Lifelines Program. The NGA-West2 models by Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014), and Idriss (2014) were used to calculate the 84th-percentile spectra for Sites and Golden Gate dam. The models were weighted equally in the analyses. For simplicity and comparison purposes, the magnitudes and distances as determined by WLA (2002) were used for the Great Valley fault, Funks and Bear Valley segments. A V_{S30} value of 1,840 feet per second (ft/s) was used in the analyses to compare to the generic rock conditions of the models used by WLA (2002). In future calculations, the characteristic magnitude should be reviewed using newer empirical models; fault distances should be updated if necessary; basin effects may need to be considered; and fault directivity should be incorporated. Additionally, the site-specific V_{S30} needs to be determined.

Additional response spectra would need to be developed for each of the saddle dams, which would also need to examine the controlling seismic source.

3.1.2 Other Seismic Sources

The structural model adopted by WLA (2002) relates slip on northeast-striking faults (GG-1, GG-2, GG-3, and S-2) that pass through or near the dam sites to differential shortening in the upper crust above the structural boundary between the Funks and Bear Valley segments of the Great Valley fault. WLA's preferred interpretation is that the GG-1, GG-2, GG-3, and S-2 faults move sympathetically during moderate- to large-magnitude earthquakes on the Funks thrust ramp, and probably do not behave as independent seismic sources. Although WLA concludes that the northeast-striking faults are not independent seismic sources, they may be a source of aftershocks following an earthquake on the Funks or Bear Valley segments. From regression relations in Wells and Coppersmith (1994), WLA calculates an associated range of aftershock magnitudes from M_w 5.3 to M_w 5.4. WLA conservatively adopts M_w 5.4 as the maximum magnitude for aftershocks on faults GG-2, GG-3, and S-2.

It should be noted that the probability of the occurrence of earthquakes in and around a reservoir may be increased by impoundment of water. The effect of increase in elastic stress due to the load depends on the tectonic environment. An increase in elastic stress would increase the chances of failure on normal faults, and decrease the probability of failure on thrust faults (Scholz, 1990). Although much remains to be learned about the causative mechanisms for reservoir-induced (triggered) seismicity, based on previous cases, it would seem that conditions at Sites and Golden Gate do not favor the triggering of earthquakes by construction or operation of a reservoir (DWR, 2003).

3.2 South Bridge Response Spectra

Caltrans Seismic Design Criteria (SDC) 2.0 was adopted September 1, 2019. A major change in SDC 2.0 is the construction of the Design Spectrum. Previously, the Design Spectrum was constructed using the envelope of probabilistic and deterministic spectra. For SDC 2.0, the Design Spectrum is based on the U.S. Geological Survey (USGS) 975-year uniform hazard spectrum only. Effective December 1, 2019, the USGS hazard spectrum is based on the 2014 National Hazard Map per memorandum from the State Bridge Engineer. The updated Design Spectrum continues the use of near-fault adjustment factors and basin amplification factors. The only change to these factors is the use of the Campbell and Bozorgnia (2014) and Chiou and Youngs (2014) basin amplification factors, updated from their 2008 models.

Based on information provided in DWR (2003), pressure wave velocities (V_P) from seismic refraction lines vary from 3,200 ft/s (likely intensely weathered mudstone) to 13,700 ft/s (likely massive, slightly weathered or fresh sandstone) with an average of about 7,200 ft/s. Based on this information, and assuming a Poisson's ratio between 0.35 and 0.4 (typical values, not based on data), shear wave velocities in the upper 30 meters (or about 100 feet) (V_{S30}) were estimated by AECOM to range from 1,300 ft/s to 6,500 ft/s, with an average of 3,250 ft/s. Due to a lack of data in the vicinity of the proposed bridge, acceleration response spectra for several different values of V_{S30} were calculated.

Results from ARS Online V3.0.2 (Caltrans, 2019) are tabulated in Table 3-1, and presented graphically in Figure 3-3. The results show that there is a wide range of potential response spectra for the South Bridge, depending on the V_{S30} of the underlying profile. Site-specific shear-wave velocity data should be obtained before developing a final design spectrum. In addition, these spectra assume that the bridge is founded on rock. If native soil is to be left in place, the V_{S30} could be lower. The design earthquake for the probabilistic spectrum is about a magnitude 7.7, which was derived from the 2014 USGS online unified hazard tool, using the mean or mode, whichever is greater.

Table 3-1. Acceleration Response Spectrum for Bridge Design

Period (s)	Spectral Acceleration (g) V_{S30} = 1,300 ft/s (396 m/s)	Spectral Acceleration (g) V_{S30} = 1,840 ft/s (561 m/s)	Spectral Acceleration (g) V_{S30} = 3,250 ft/s (991 m/s)
0.01	0.36	0.33	0.26
0.1	0.7	0.68	0.58
0.2	0.89	0.79	0.56
0.3	0.87	0.71	0.45
0.5	0.71	0.53	0.32
0.75	0.53	0.4	0.24
1	0.41	0.31	0.18
2	0.21	0.15	0.09
3	0.13	0.1	0.06
4	0.1	0.07	0.05
5	0.07	0.06	0.04

3.3 Conveyance Facilities Response Spectra

The structures associated with the conveyance facilities include multiple sites across the project. As stated in Section 1.1.2, the conveyance facility structures include Funks Reservoir Power Generating Plant, Terminal Regulating Reservoir Power Generating Plant, High voltage power transmission towers, GCID main canal structures (Hamilton City Head Works and Willows Railroad Siphon), Dunnigan Pipeline Intake off the Tehama Colusa Canal, Dunnigan Pipeline Colusa Basin Drain Discharge, and Dunnigan Pipeline Sacramento River Discharge. Each structure site will be evaluated for seismic hazards in accordance with the most recent California Building Code (CBC) and American Society of Civil Engineers (ASCE) 7, currently the 2019 CBC and ASCE 7-16.

For sites with significant ground motion, such as this project site area, a site-specific ground motion analysis is required by the ASCE 7 as referenced by the CBC. The site response analysis will be completed in accordance with the procedures of Chapter 21 of ASCE 7-16. The site-specific ground motion procedures, in accordance with ASCE 7-16 Sections 21.2 through 21.5, include the following steps:

- Step 1: Perform a probabilistic seismic hazard analysis to develop the uniform hazard spectrum for a 2 percent probability of exceedance in 50 years, or a return period of approximately 2,475 years. The Uniform California Earthquake Rupture Forecast will be used as the seismic source model. The next generation ground motion models for the western United States will used to obtain the spectral response for the different earthquake scenarios. The computer program OpenSHA (Open Source Seismic Hazard Analysis Software Framework: OpenSHA.org, https://doi.org/doi:10.5066/F79P2ZVV) will be used to develop the probabilistic uniform hazard spectrum.
- Step 2: Perform a deterministic seismic hazard analysis to develop the 84th percentile spectral response to characteristic earthquakes on known nearby faults. The characteristic magnitudes for each fault will be selected from the Uniform California Earthquake Rupture Forecast.
- Step 3: Apply adjustment factors for directionality and level of risk for the spectral response curves. Risk factors will be selected in accordance with ASCE 7-16 Section 21.2.1.1.
- Step 4: Select the lesser of the spectral response accelerations at each period from the probabilistic and deterministic evaluations as the risk-targeted maximum considered earthquake ground motion response spectrum.
- Step 5: Multiply the maximum considered earthquake spectral response acceleration by 2/3 to get the design response spectrum. Check that the seismic ground motion design response spectrum result exceeds the minimum required values.

3.4 Terminal Regulating Reservoir Response Spectra

For the TRR, a deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) will likely be required. The general process for performing these analyses and generating the response spectra is as follows:

- Step 1: Review of Previous Seismic Studies - Previous geologic, seismologic, and geophysical studies, including other nearby sites, will be reviewed and relevant information extracted for this proposed evaluation.
- Step 2: Seismic Source Characterization - All local and regional active faults that may be significant in terms of ground shaking hazard will be included in the site-specific PSHA. Fault parameters that will be characterized include geometry and rupture dimensions, maximum earthquake, nature and amount of slip for the maximum earthquake, and rate and nature of earthquake recurrence. The hazard from crustal background seismicity will be included in the analysis using regional seismic source zones and Gaussian smoothing.
- Step 3: Evaluation of Historical and Contemporary Seismicity - The historical and contemporary seismicity will be evaluated in the site region based on an updated seismicity catalog. Historical ground shaking at the site from past events will be evaluated. Recurrence rates of the historical seismicity for defined regional seismic source zones will be updated for input into the PSHA.
- Step 4: Site Characterization - All available geological, geophysical, and geotechnical information on the site foundation will be reviewed. Of particular importance are shear-wave velocity (V_S) data so that a VS30 (average V_S in the top 30 meters) for the site can be computed. VS30 is an input parameter into several of the ground motion prediction models.
- Step 5: Probabilistic Seismic Hazard Analysis - Based on the seismic source model for the region and ground motion prediction models, site specific probabilistic hazard will be calculated. The PSHA methodology allows for the explicit inclusion of the range of possible interpretations in components of the seismic hazard model, including seismic source characterization and ground motion estimation. Uncertainties in models and parameters are incorporated into the PSHA through the use of logic trees.

The PEER NGA-West2 models will be used in the PSHA. Hazard curves and Uniform Hazard Spectra (UHS) at 5% damping will be calculated. The hazard will be deaggregated at selected periods to characterize the controlling earthquakes.

- Step 6: Deterministic Seismic Hazard Analysis - A DSHA will be performed for the most significant seismic sources to the site using the NGA-West2 ground motion prediction models. The ground motions from the controlling deterministic earthquake will be compared to the UHS from the PSHA.

4.0 Fault Offset Potential

This section was excerpted from the Phase II Fault and Seismic Hazards Investigation, North of Delta Offstream Storage Integrated Storage Investigations, prepared by WLA in September 2002. Specific geologic information can be found in that reference.

As mentioned above and shown in Figure 2-2, several of the identified faults cross through or nearby several reservoir project elements. The location of fault crossings, particularly at the roads, are approximate, and would need to be confirmed during design if they are critical to the design.

4.1 North-Striking Faults

The Salt Lake Fault is mapped as passing through or nearby the following structures at the site:

- Saddle Dam No. 2, approximately 100 to 200 feet east of the right abutment through the slurry wall
- South Bridge between approximately stations 172+00 to 174+00
- North Road between approximately stations 554+00 to 556+00
- I/O Tower, approximately 1,000 to 2,000 feet to the west

Based on analyses by WLA (2002), during a moderate to large earthquake on the Funks Segment of the Great Valley Fault, surface displacements/offsets are likely to range from 4.5 to 16 inches. Structures crossing this fault should be designed to handle such movements, or be repaired after a seismic event.

No discussion on the S-3 fault offsets is provided in the source documents used to generate this report. However, the S-3 fault is mapped to pass through or nearby the following structures:

- I/O portal, crossing at or near the portal location
- Sites Lodoga Road between approximately stations 246+00 and 248+00

Further investigation is required, and additional analyses may need to be performed based on the selected final location of the outlet portal. For the purposes of this TM, the surface offset of the S-3 fault can be assumed to be equal to the Salt Lake Fault (4.5 to 16 inches).

4.2 Northeast Striking Faults

The northeast-striking faults include the GG-1, GG-2, GG-3, and S-2 faults. These faults cross or pass nearby the following structures:

- Golden Gate Dam, through the right abutment (GG-2) and approximately 500 to 1,000 feet north of the left abutment (GG-1)
- I/O Tower cut slope, with GG-2 passing within about 500 feet of the I/O tower through or near the cut for the approach channel
- I/O portal, with GG-3 passing within about 1,000 feet east of the portal, potentially effecting downstream structures
- South Bridge at approximately Station 172+00 to Station 174+00 (G-2)
- Sites Lodoga Road between approximately Station 273+00 and Station 275+00 (S-2)

Based on analyses by WLA (2002), maximum surface displacements from these faults would not exceed about 8 inches, and are likely to be lower (more on the order of 2.4 to 4 inches). Structures crossing this fault should be designed to handle such movements, or be repaired after a seismic event.

4.3 Other Faults

Other faults are shown by WLA (2002) and DWR (2003) as passing near or through various other project elements, as shown in Figure 2-2. Many of these require further investigation, additional analyses, and/or interpretation. Of these, the most notable is the LSSD5-4 fault (DWR, 2003), which passes through the center of Saddle Dam No. 5 and the North Road, downstream of Saddle Dam No. 5.

No calculated estimates of fault surface displacement are provided in the source documents. Although many of these faults pass through a road and may not be considered critical, LSSD5-4 potentially passes through the center of Saddle Dam No. 5, and should be investigated further.

5.0 References

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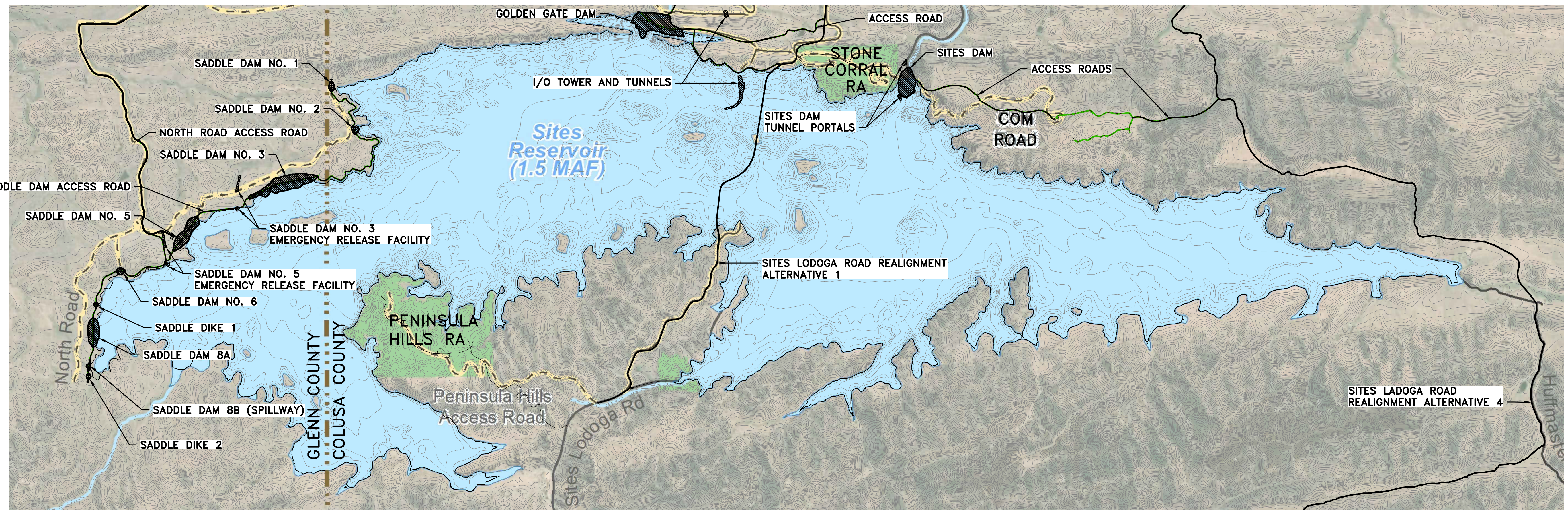
Figures



0 1/2 1

1" = 1/2 MILE

NORTH

Sites

AECOM

Project Number 60632561

SITES RESERVOIR PLAN

Figure 1-1

VERIFY SCALES
BAR IS ONE INCH ON ORIGINAL DRAWING. ADJUST SCALE FOR REDUCED PLOTS

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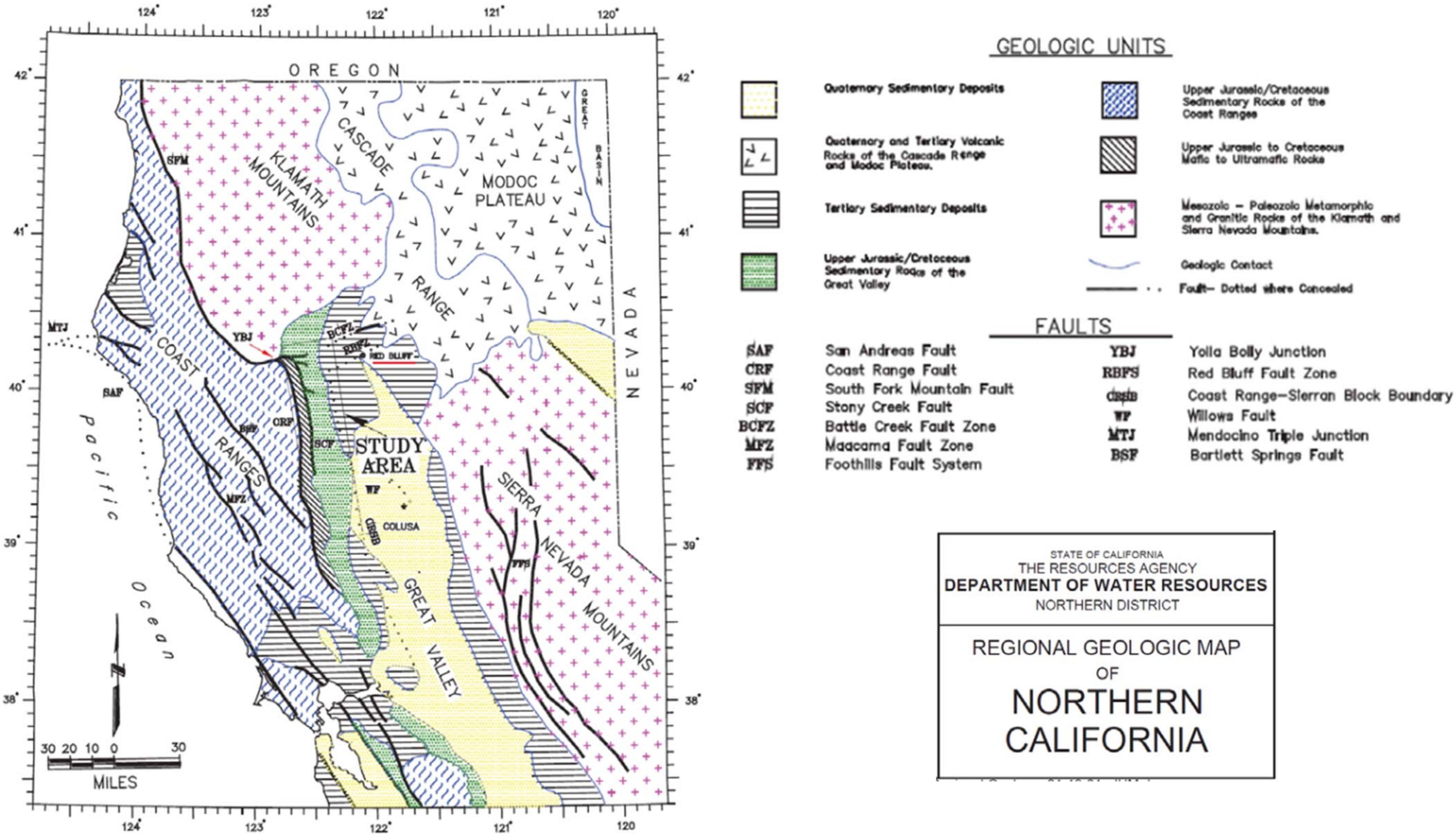
DRAWING: pw:\\aecom-na-pw.bentley.com:AECOM_DS20_NA_2019\Documents\60632561-Sites Reservoir TO 1\900-CAD GIS\910_CAD\20_SHEETS_FIGURE 1-1_60632561.dwg



Project No. 60632561	Sites Reservoir Project	Geologic Setting of Project Area (USBR, 2017)	Figure 2-1
	AECOM		

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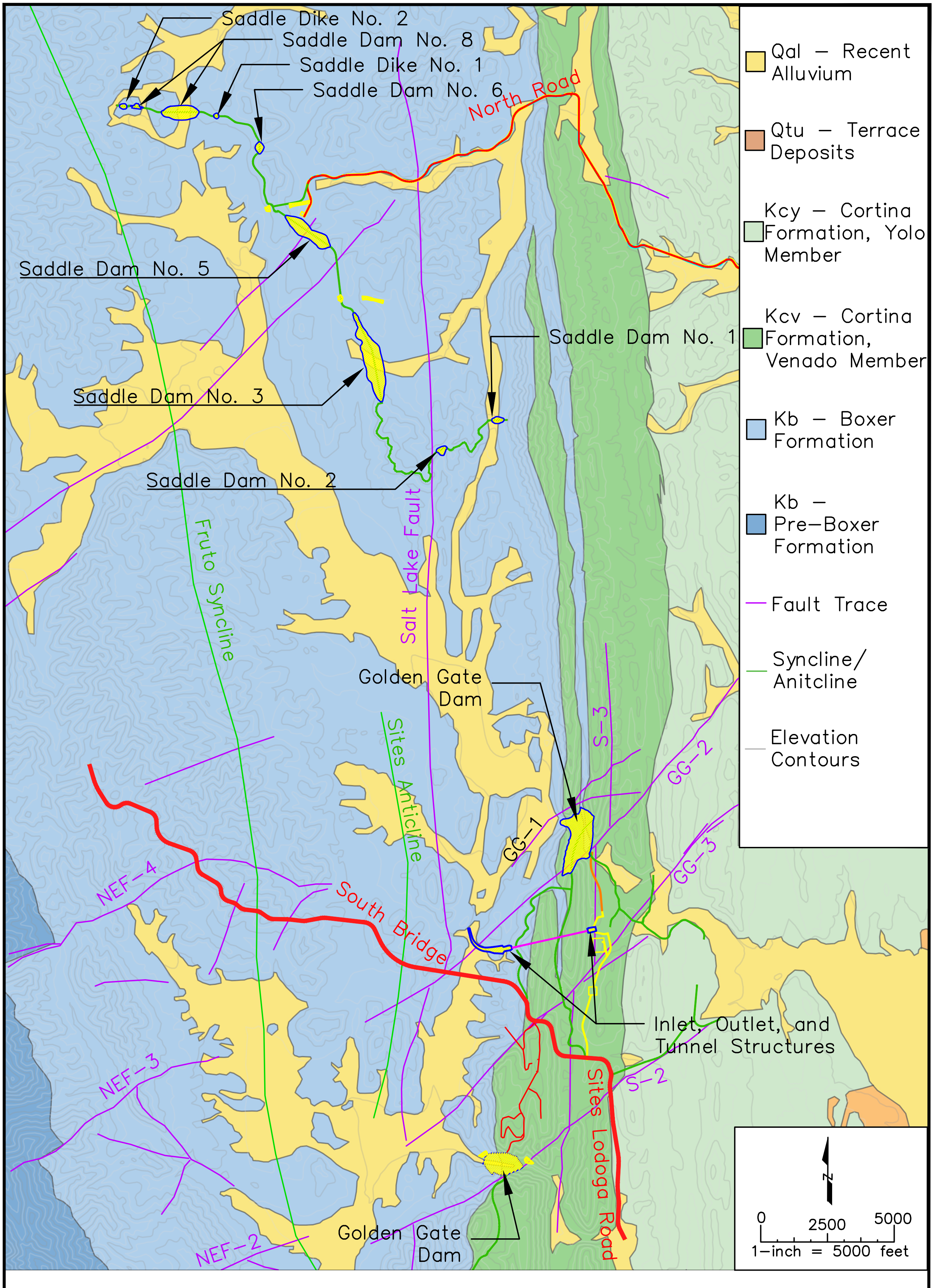


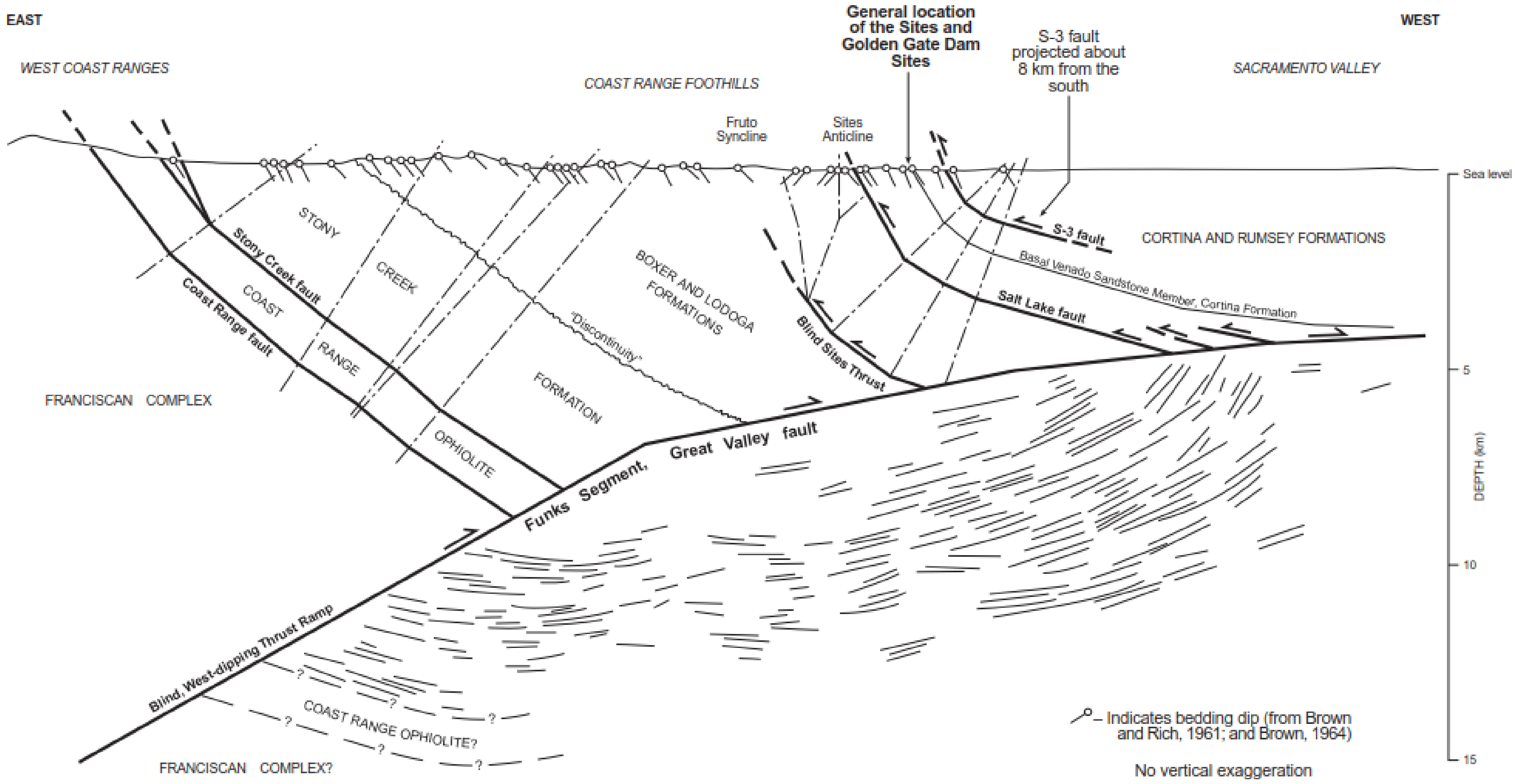
AECOM

Project No. 60632561

Site Reservoir Project

REGIONAL GEOLOGIC MAP AND PROJECT ELEMENTS

Figure 2-2

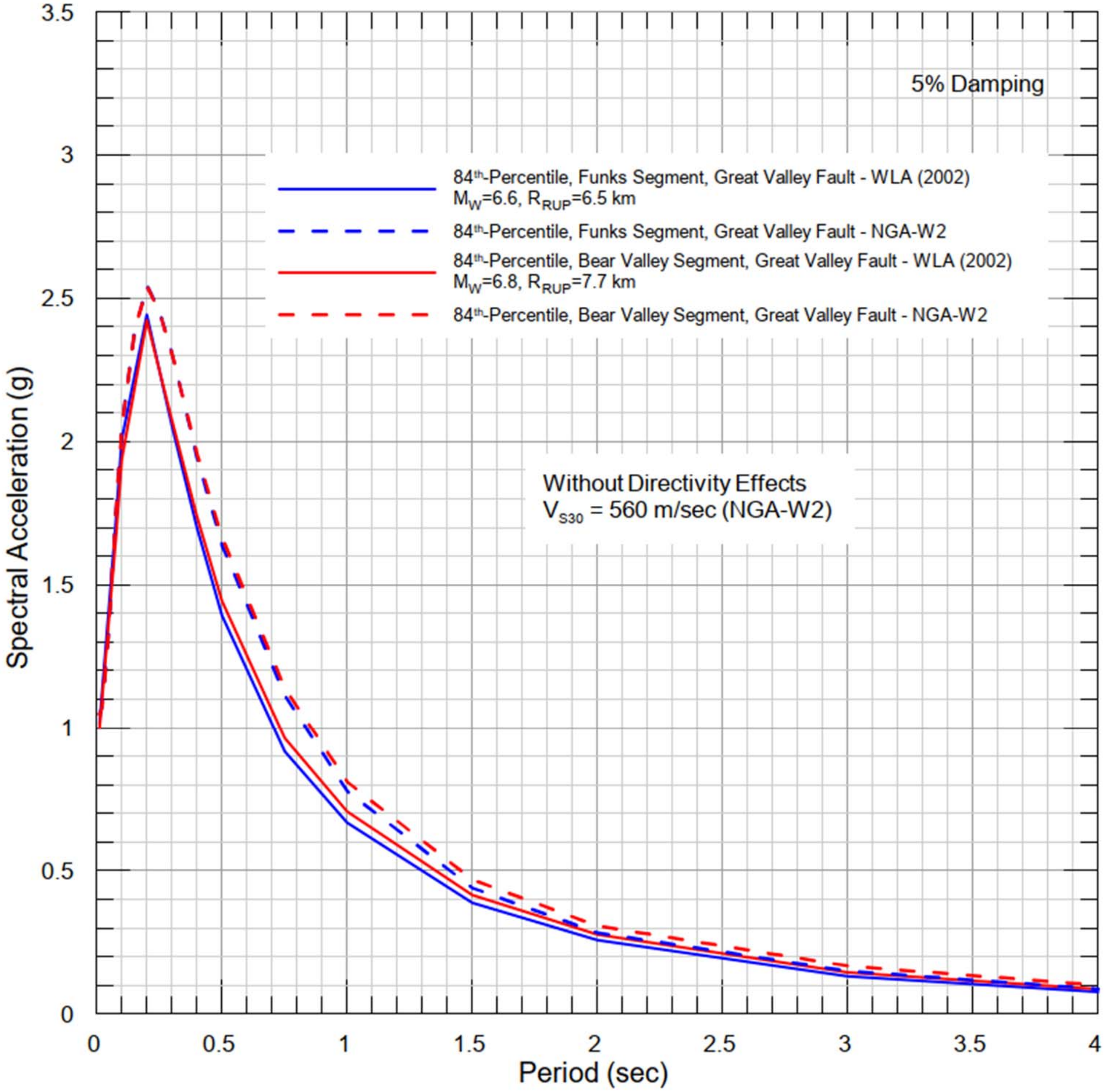


PHASE 2 FAULT AND SEISMIC HAZARDS INVESTIGATION
NORTH OF DELTA OFFSTREAM STORAGE
DWR-INTEGRATED STORAGE INVESTIGATION

Cross Section Showing Major Map-scale Structures in the Study Area, and their Relationship to Structures Imaged by Seismic Reflection Profiles

WLA William Lettis & Associates, Inc. | Figure E-2

Project No. 60632561	Sites Reservoir Project	Structure and Faulting Typical Cross Section (WLA, 2002)	Figure 2-3
	AECOM		



AECOM	Project No. 60632561	84th Percentile Response Spectra, Sites Dam	Figure 3-1
	Sites Reservoir Project		

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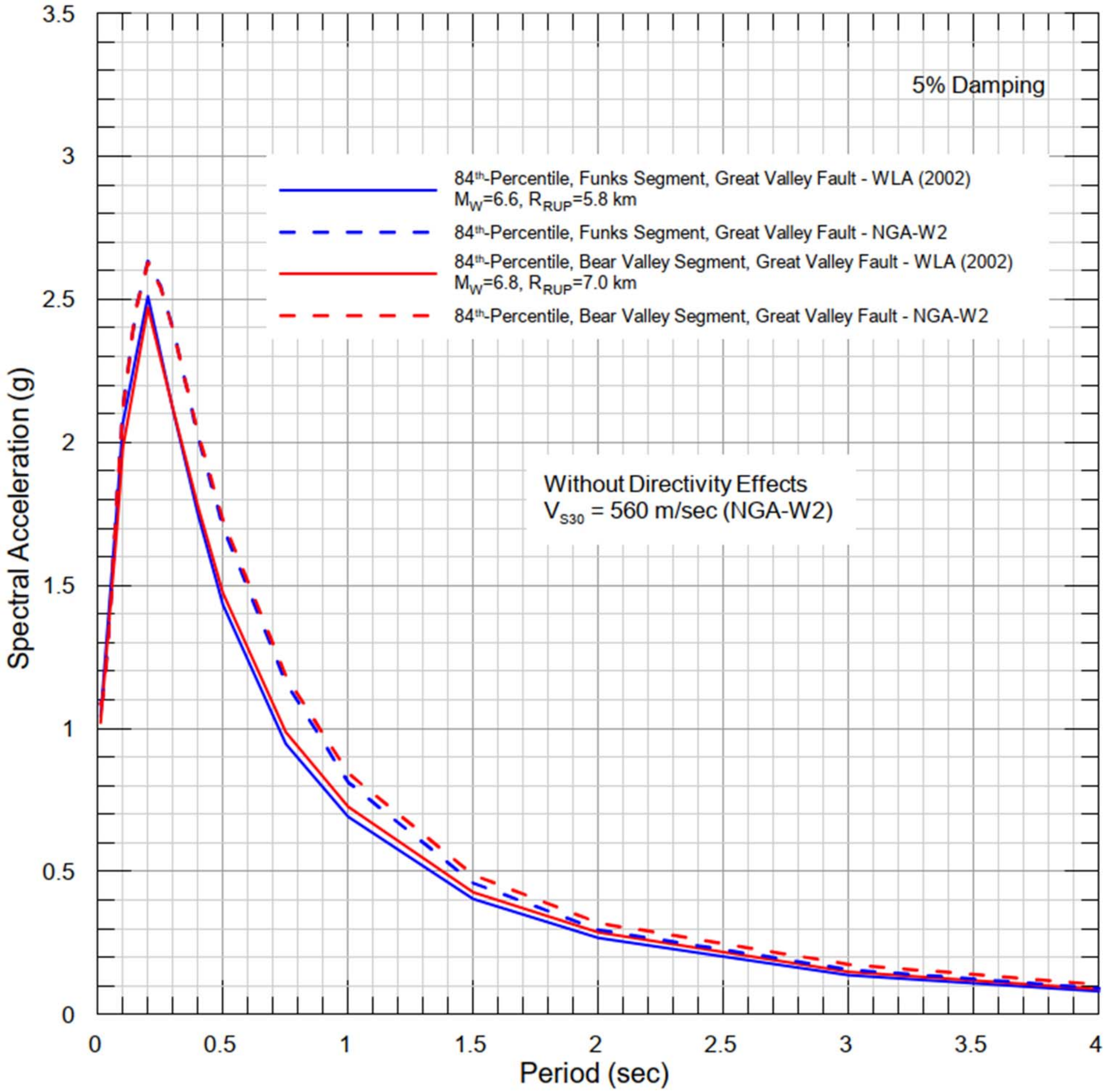
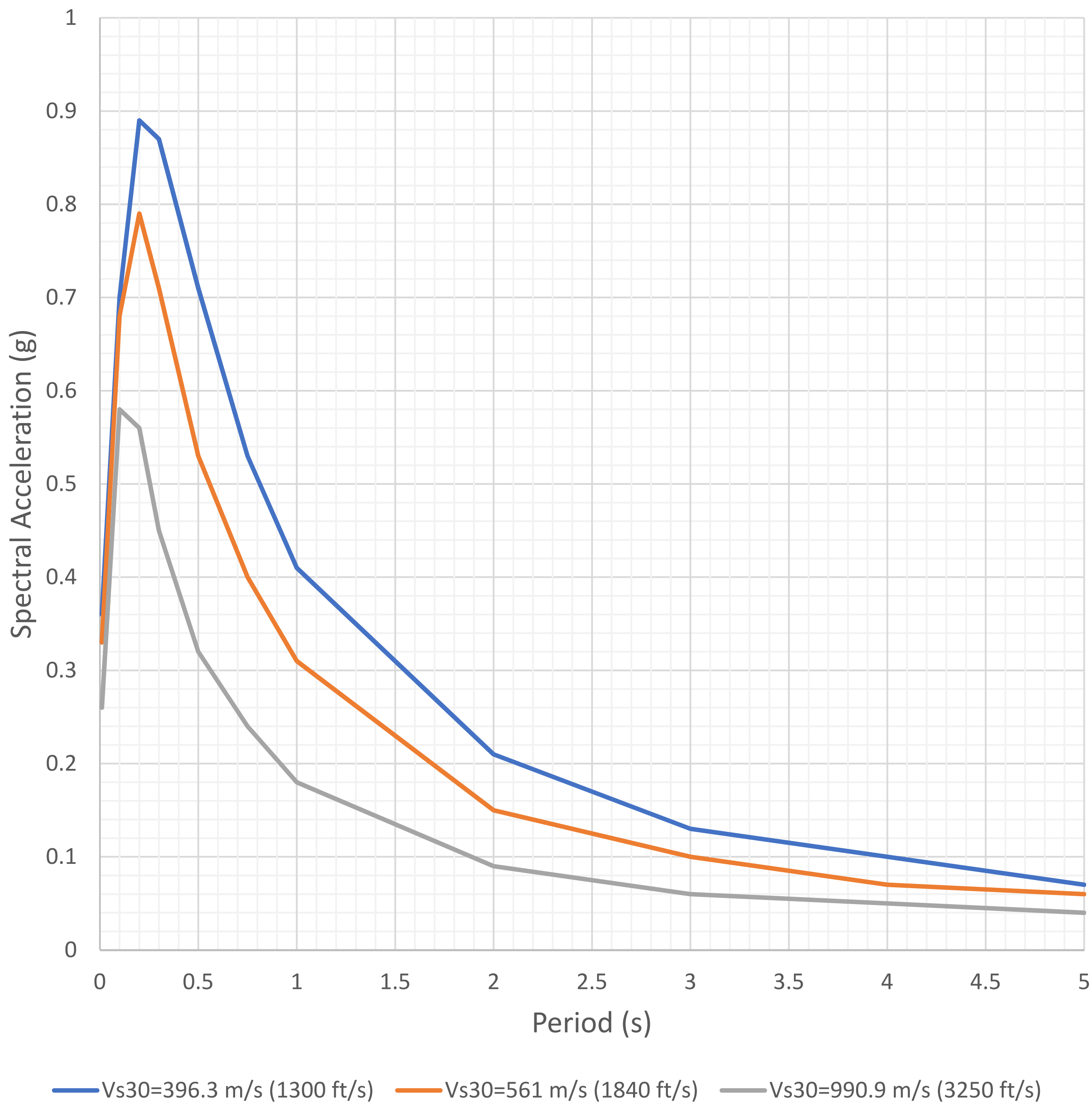


AECOM	Project No. 60632561	84th Percentile Response Spectra, Golden Gate Dam	Figure 3-2
	Sites Reservoir Project		



AECOM	Project No. 60632561 Sites Reservoir Project	975-Year Response Spectra, South Bridge	Figure 3-3

Appendix A

Table 1 from William Lettis & Associates (2002)

Table 1 Faults and Geologic Structures Investigated in this Report

Fault Name	Fault Type	Activity	Seismic Source Characterization				Closest Approach		Comments
			Fault Length	Fault Width	Rupture Area	Maximum Magnitude	Sites	Golden Gate	
GG-1	Right Lateral, Strike Slip	No Holocene Activity	1.1 mi (1.8 km)	Not a seismic source			3.1 mi (4.1 km)	<0.5 mi (<1 km)	GG-1, GG-2, GG-3 and S-2 are interpreted to be shallow tear faults along Funks/Bear Valley Segment boundary. Conservatively assumed to be sources of aftershocks. Possible surface-rupture hazards.
GG-2	Right Lateral, Strike Slip	No Holocene Activity	3.7 mi (5.9 km)	Faults GG-2, GG-3 are S-2 are considered potential sources of shallow aftershocks. Maximum earthquake magnitude for these structures is M_w 5.4.			1.7 mi (2.3 km)	<0.5 mi (<1 km)	
GG-3	Right Lateral, Strike Slip	No Holocene Activity	3.0 mi (4.8 km)				0.4 mi (0.7 km)	<0.5 mi (<1 km)	
S-2	Right Lateral, Strike Slip	No Holocene Activity	2.4 mi (3.9 km)				<0.5 mi (<1 km)	2.2 mi (3.5 km)	
Salt Lake Fault	Thrust	Multiple Late Quaternary Surface Ruptures	12 mi (20 km)	Not a seismic source			1.5 mi (2.4 km)	1.7 mi (2.7 km)	Interpreted to accommodate triggered, aseismic slip
S-3	Thrust	No Holocene Activity	≥4.25 mi (6 km)	Not a seismic source			0.9 mi (1.5 km)	600 ft (200 m)	May accommodate triggered aseismic slip
Funks Segment, Great Valley Fault	Blind Thrust	Late Quaternary Activity	11 mi (17 km)	14 mi (22 km)	146 mi^2 (374 km^2)	M_w 6.6	4.0 mi (6.5 km)	3.6 mi (5.8 km)	Indirect evidence of late Quaternary activity
Bear Valley Segment, Great Valley Fault	Blind Thrust	Assumed to be Active	14.4 mi (23 km)	14.4 mi (23 km)	207 mi^2 (529 km^2)	M_w 6.8	4.8 mi (7.7 km)	4.4 mi (7.0 km)	Conservatively assumed to be active
San Andreas Fault	Strike Slip	Active	650 mi (1,050 km)	Maximum magnitude = M_w 8 (WLA, 1997)			70 mi (113km)	70 mi (113 km)	Assumes maximum earthquake will rupture 272 mi (435 km)
Maacama Fault	Strike Slip	Active	84 mi (135 km)	Maximum magnitude = M_w 6.5 (WLA, 1997)			45 mi (72 km)	45 mi (72 km)	Too far from sites to dominate hazard
Bartlett Springs Fault	Strike Slip	Active	70 mi (113 km)	9.4 mi (15 km)	117 mi^2 (306 km^2)	M_w 6.6	20 mi (32 km)	22 mi (32 km)	Maximum rupture length of proximal Coyote Rocks Segment is 11 mi (18 km)
Stony Creek Fault	Thrust (?)	Not Active	63 mi (100 km)	Not characterized			10 mi (16 km)	11 mi (18 km)	Interpreted to be a deformed Mesozoic fault

Table 1 Faults and Geologic Structures Investigated in this Report

Fault Name	Fault Type	Activity	Seismic Source Characterization				Closest Approach		Comments
			Fault Length	Fault Width	Rupture Area	Maximum Magnitude	Sites	Golden Gate	
Coast Range Fault	Normal	Not Active	Not a continuous fault trace	Not characterized			12.4 mi (20 km)	12.4 mi (20 km)	Interpreted to be a deformed Mesozoic fault
Green Valley Thrust Fault and related faults	Thrust	Not Active	11 mi (17 km)	Not characterized			8 mi (12.5 km)	9 mi (15 km)	Bedding-parallel thrust fault confined to the upper 3 mi (5 km) of the crust
Paskenta Fault	Normal	Not Active	28 mi (45 km)	Not characterized			25 mi (41 km)	23 mi (37 km)	Interpreted to be a deformed Mesozoic fault
Rumsey Hills Fault	Blind Thrust	Active	16 mi (25 km)	Not characterized			28 mi (45 km)	30 mi (49 km)	Too far from dam sites to dominate hazard
Sweitzer Fault	Thrust	Active	11 mi (17 km)	Not a seismic source			28 mi (45 km)	30 mi (49 km)	May accommodate triggered aseismic slip
Valley Side Fault	Thrust/Reverse	Active	10.5 mi (17 km)	Not a seismic source			16 mi (26 km)	18.6 mi (30 km)	May accommodate triggered aseismic slip
Black Butte Fault	Bedrock Escarpment	Not a Fault	10.5 mi (17 km)	Not characterized			30 mi (48 km)	27 mi (44 km)	
Southern Reach, Corning Fault	Oblique-Reverse	Active	13 mi (21 km)	13 mi (21 km)	182 mi^2 (462 km^2)	M_w 6.7	20 mi (32 km)	18 mi (29 km)	Associated with clusters of seismicity
Cascadia Subduction Zone	Megathrust Fault	Active	620mi (1,000 km)	74.5 mi (120 km)	46,310 mi^2 (120,000 km^2)	M_w 9	100 mi (160 km)	100 mi (160 km)	Geologic evidence for giant Cascadia earthquakes
Intraplate (Gorda slab) Faults	Probable Strike Slip	Active	Source dimensions not directly observed; maximum magnitude adopted from empirical observations			M_w 7.5	53 mi (85 km)	53 mi (85 km)	1922 Gorda plate earthquake estimated to be M_s 7.6