California Natural Resources Agency
Department of Water Resources
Division of Safety of Dams

DIVISION OF SAFETY OF DAMS INSPECTION AND REEVALUATION PROTOCOLS

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CALIFORNIA DEPARTMENT OF WATER RESOURCES
DIVISION OF SAFETY OF DAMS

Since August 14, 1929, the State of California has regulated dams to prevent failure, safeguard life, and protect property. The California Water Code entrusts dam safety regulatory power to the Department of Water Resources, who delegates that authority to the Division of Safety of Dams (DSOD). DSOD provides oversight to the design, construction, and maintenance of approximately 1,250 jurisdictional sized dams in California.

Program Vision

To maintain a high-performance and a sustainable organization that is a leader in dam safety for the protection of life, property, and the environment.

Program Mission

To protect against loss of life and property damage from dam failure and unintentional releases.

On the Front Cover
Leroy Anderson Dam, owned by the Santa Clara Valley Water District, is an earthen dam that impounds 91,300 acre-feet of water. Photograph provided by and used with permission from the Santa Clara Valley Water District. Photography by 111th Aerial & Architectural Photography.

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Acronyms and Abbreviations

ACI	American Concrete Institute
ASDSO	Association of State Dam Safety Officials
ASTM	American Society for Testing and Materials
BPT	Becker Hammer Tests
Cal OES	California Governor’s Office of Emergency Services
CAS	Critical Appurtenant Structures
CFD	Computational Fluid Dynamics
CRR	Cyclic Resistance Ratio
CSR	Cyclic Stress Ratio
CPT	Cone Penetration Tests
DCR	Demand Capacity Ratio
DSOD	Division of Safety of Dams
DWR	Department of Water Resources
EAP	Emergency Action Plan
FS	Factor of Safety
FEMA	Federal Emergency Management Agency
FEMA Risk Tool	2008 *Risk Prioritization Tool for Dams*
GIS	Geographic Information System
HMR 58	Hydrometerological Report No. 58
k	Constant Horizontal Pseudo-Static Earthquake Inertial Load
k_y	Yield Acceleration
LEA	Limit Equilibrium Analyses
LiDAR	Light Detection and Ranging
NDA	Nonlinear Deformation Analysis
MCE	Maximum Credible Earthquake
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PI	Plasticity Index
PMF	Probable Maximum Flood
PFM	Potential Failure Mode
PMP	Probable Maximum Precipitation

PSHA	Probabilistic Seismic Hazard Analysis
RIDM	Risk-Informed Decision Making
ROV	Remotely Operated Vehicle
SPT	Standard Penetration Tests
S_r	Residual Strength
S_t	Soil Sensitivity
S_u	Undrained Shear Strength
S_{ur}	Remolded Undrained Shear Strength
TCW	Total Class Weight
USSD	United States Society on Dams

I. Introduction

This document describes how the Division of Safety of Dams' (DSOD) engineers and engineering geologists perform dam safety related inspections and reevaluations as required by the California Water Code, Division 3, Part 1, Chapter 4, Article 2, section 6103. DSOD has jurisdictional authority for dam safety for nearly 1,250 dams located throughout California that vary widely in age, design, condition, downstream hazard, loading conditions, and associated risks. Ensuring dam safety in California is a complex undertaking with its intricate geologic setting at the boundary between major tectonic plates that results in seismic and geologic hazards such as frequent strong earthquakes and large landslides, respectively. In 2016, a peer review conducted by the Association of State Dam Safety Officials named DSOD's program as being the leading dam safety program in the Nation.

These inspection and reevaluation protocols are intended to provide a general overview of the major components of work performed by DSOD related to its inspections and reevaluations. Given that each dam is unique in its design, construction, and site conditions, these protocols provide direction while allowing for sound engineering judgement, adaptation to developing best practices, and innovation for advancing dam safety. For the purposes of this document, inspections include annual maintenance, construction oversight, post-earthquake, and incident. Reevaluation studies include all engineering analyses and reviews, geologic hazard assessments, and seismic hazard assessments.

DSOD generally does not require specific approaches or methodologies to be employed by dam owners or their engineering consultants. This approach maintains DSOD's independence as a regulator; therefore, prescriptive details are not included in these protocols. Dam owners and their consulting engineers are expected to submit analyses and designs developed using state-of-the-practice analysis and techniques with sound engineering judgement. Unlike any other state regulatory programs, DSOD performs independent analyses of all proposed designs and compares its results to those submitted on behalf of the dam owner for concurrence. This provides the following benefits:

- Dam owners and their consulting engineers take full responsibility and ownership of their designs and analyses; plans and specifications must be prepared under the supervision of and stamped/signed by a Professional Engineer licensed in California.

- DSOD engineers and engineering geologists must thoroughly understand the design methodologies and assumptions used in the design of dams and their appurtenances, and the performance of these structures in the field.

- DSOD's independent validation of the adequacy of the design of dams and their appurtenances provides for the protection of life and property from dam failures and unintended reservoir releases.

- DSOD’s interactions with dam owners and their consulting engineers allow for highly sophisticated technical debates and discussions when proposed designs, analytical results, conclusions, and recommendations submitted by a dam owner differ from those obtained from DSOD’s independent analyses.

Dam owners must receive DSOD approval prior to the construction of new dams or the enlargement, repair, alteration, or removal of existing dams. DSOD also has statutory authority to require that dams be constructed, maintained, and operated in a safe manner. Ultimately, the dam owner bears the legal responsibility and associated consequences related to the failure of a dam.

II. Reevaluations and Risk-Informed Decision Making

In 1964, following the catastrophic failure of the Baldwin Hills Dam, DSOD began its reevaluation of existing dams because many of the dams in the inventory were then nearing or already older than 50 years, downstream hazard potential had increased tenfold due to population growth, and there had been significant advancements in engineering and engineering geology related to dam safety. Since the 1970s, with the advancement of understanding liquefaction following the Lower San Fernando Dam failure, DSOD has been conducting seismic reevaluations of dams and continues these efforts as the state-of-the-practice advances with respect to earthquake engineering. Dams included in these reevaluations were generally located near high-slip rate faults and could be susceptible to large deformations during a major earthquake event. As a result of these reevaluations, numerous dams have had major seismic retrofits completed over the last decades.

In California, most of the highest consequence dams are those that have large reservoirs that store water year-round and are located near highly active faults, upstream of populated areas. With the average age of California's jurisdictional dams being 70 years, many of these dams were designed before the modern era of understanding earthquake engineering. The risk of a major earthquake occurring has increased with the growing understanding that earthquakes can occur on multiple faults rupturing in a simultaneous megaquake. Therefore, the potential for seismic-related incidents is generally seen as the most likely failure mode for many of California's dams. A single, large seismic event in California has the potential to impact many dams with little to no warning, providing little time to initiate an evacuation order, if necessary, for those living downstream. A seismically induced failure mode is a regional risk, which may contrast with highly probable dam safety risks in other states where seismic events are generally less probable.

DSOD uses a qualitative approach to risk to prioritize its 1,250 jurisdictional dams and their appurtenances as part of the reevaluation process. Risk is used to guide the decision-making process regarding the safe and continued operation of those dams inspected and evaluated with respect to dam safety. Using risk, as employed by DSOD, is based on detailed reviews and results of geological and engineering evaluations, which are then used for an informed assessment of the probability and likelihood of an event and failure in conjunction with the downstream hazard potential.

For the efficiency of the program given other regulatory responsibilities and finite resources, DSOD's efforts have focused on a risk-based screening-level review of its 1,250 dams that have the highest consequence under the most probable loading conditions in California. DSOD's screening process and reevaluation programs have been failure-mode driven, focusing on specific loading conditions and associated failure modes of dams and their appurtenances with the highest consequence. The initiation of focused reevaluation programs are governed by significant advances in dam safety as a result of improvements in the state-of-the-practice or a major dam failure where a highly credible probable failure mode is identified for many of the dams in the inventory.

During the past 50 years, DSOD has conducted reevaluation programs focused on seismic-induced failure modes due to instability of dam structures, radial gate assessments associated with seismic and operational failure modes and, more recently, spillway assessments associated with hydraulic failure modes.

DSOD's use of risk is similar to the Federal Emergency Management Agency (FEMA) "Risk Tool" process, published in the 2008 *Risk Prioritization Tool for Dams* (2008 FEMA Risk Tool; URS Group, Inc., 2008). Once dams are prioritized using a screening process, reevaluations are conducted. Reevaluations begin with a comprehensive file review, followed by quantitative analyses focused on the failure modes of highest risk identified during the screening process and file review. The comprehensive file review conducted as part of these assessments can, and does, identify risks related to other failure modes; for example, outlet reliability concerns and potential flood-related deficiencies have often been identified during DSOD's seismic reevaluations.

A. Components of Risk

As a multidisciplinary team, DSOD engineers and engineering geologists consider risk as the product of the probability of the loading condition occurring, the likelihood of the failure scenario, and the consequence of failure in a mostly qualitative manner during the screening process, transitioning to a more quantitative risk assessment during the reevaluation phase to inform dam safety decisions.

Consequence of Failure

DSOD recently classified all jurisdictional dams by downstream hazard potential/ consequence using FEMA's "high," "significant," and "low" downstream hazard classifications. However, due to the highly populated communities living downstream from dams, DSOD subdivided the high-hazard classification into "high" and "extremely high." The extremely high-hazard classification generally identifies dams expected to cause an inundation area with a population of 1,000 or more persons, or the inundation of facilities or infrastructure which poses a significant threat to public safety. This creates four consequence classifications that can be broadly used for risk-based screening-level analysis (see attachment 11).

DSOD has also used a more quantitative parameter called "Total Class Weight" (TCW) for evaluating consequence on a scale of 0 to 36. The TCW is determined using four factors: height of the dam, reservoir storage, estimated downstream evacuation, and downstream damage potential. This parameter has been used to derive design-level earthquakes and floods by essentially considering the consequence to determine the load. A dam with a larger TCW would be designed to a lower probability flood event, which is analogous to looking at risk as the product of the probability of the event and the consequence of failure.

Probability of Load Conditions

Loading probability is considered for seismic and hydrologic analyses. Reservoir stage is considered at times for the limited number of dams that are used solely for flood/debris control purposes where the reservoir is generally empty.

For seismic analyses, DSOD uses deterministic methods to develop site-specific ground motions for reevaluations using a median, +½, or +1 standard deviation in ground motion prediction equations to determine target parameters. The selection of the appropriate percentile above the median ground motion is based on the downstream hazard classification and slip rate of the controlling fault informed by a site-specific Probabilistic Seismic Hazard Analysis (PSHA). For instance, dams near faults may often be designed using an 84th percentile ground motion (median plus one standard deviation) because lower levels of ground motion have a return period less than 1,000 years, while a similar dam in the Sierra Mountain Range could be designed using a 50th or 67th percentile (0 or +½ standard deviation) ground motion because the return period is on the order of 5,000 years or greater. Probability may also be considered for assessing fault rupture displacements when dams or appurtenant structures are found to intercept fault traces (attachments 3 and 4).

For hydrologic analyses, the downstream hazard classification has been used to determine the annual exceedance probability for flooding. However, for extremely high-hazard dams or dams with a TCW ≥ 30, the Probable Maximum Flood (PMF) is generally used.

Likelihood of Failure (Fragility)

The likelihood of failure is a key component in a risk-based analysis. DSOD generally does not develop fragility curves when performing a reevaluation because it is a very time- and resource-intensive process. Therefore, DSOD's reevaluations have traditionally considered the likelihood of failure semi-quantitatively including sensitivity analyses as part of the reevaluation. In addition, further information is used for qualitative considerations of the likelihood of failure:

- Age of structure, design details, and construction techniques employed.
- Adverse site geology (e.g., alluvium in the foundation, bedrock fractures, and shears).
- Known performance (e.g., seepage, deformations, or cracking).
- Sensitivity of the fragility measure (e.g., deformation, stability) to variability in the input parameters (assumed or measured) used in the reevaluation.
- Reliability of the input parameters (likelihood of a parameter to meet or exceed a value).

- Computed factors of safety for the applicable calculations.
- Level of intervention needed.

B. Screening of Dams for Reevaluation and Prioritization

More than half of DSOD's inventory (about 650 dams) is comprised of a wide variety of dams classified with a downstream hazard classification of high or extremely high. DSOD has focused on developing screening processes to efficiently identify dams in need of reevaluations and at risk for the most likely events. As previously discussed, DSOD has developed a prioritization process similar to the objectives in the 2008 FEMA Risk Tool. The following objectives represent those used by DSOD:

Screening Process:

- Uses risk-informed decision making (RIDM) tools to identify dams within DSOD's inventory that need reevaluation.
- Provides quantifiable measures to assess the relative risk associated with the screening and compares the risk across DSOD's inventory of dams.
- Is systematic and well-reasoned for prioritizing and committing resources among other regulatory responsibilities.
- Is consistent and compatible with the standards-based evaluation process used historically by DSOD, allowing previous reevaluations to inform the screening process (recognizing that the results will be updated if a reevaluation occurs).
- Is transparent, defensible, and reproducible avoiding subjectivity and bias.

Screening Tool:

- Simple, quick, and easy to implement and applicable to any type or number of dams.
- Flexible to accommodate the broad differences in dam owners and the information available for each dam.

DSOD's risk screening and prioritization process broadly focuses on looking at consequences versus the probability and associated likelihood of failure mechanisms. The most recent prioritization scheme being used for every dam in California is focused on seismic loading. It considers the TCW of the dams and a 2,500-year (embankment dams) or 5,000-year (concrete dams) Peak Ground Acceleration (PGA) developed using U.S. Geological Survey seismic hazard maps. While these PGAs are not necessarily those used for reevaluations, they efficiently identify and discretize California's dams on a consistent basis for comparison.

The prioritization is then further refined by scoring and binning dams using factors that would represent the likelihood of failure. This scoring incorporates aspects such as the age of a dam, construction techniques, foundation condition, and general condition of the dam. For example, a hydraulic fill dam built in 1915 on alluvium might receive the highest score to indicate a high likelihood of failure while a well compacted, 1995-era dam built on a rock foundation will receive a low score to indicate that failure is unlikely.

Once the scoring and screening process is completed, dams near the top of the list are selected for further review prior to evaluation. During this process, a comprehensive file review is completed by a multidisciplinary team comprised of a design engineer, field engineer, and engineering geologist to bring in specific expertise and knowledge into the decision-making process. The engineers will look closely at annual maintenance records, prior reevaluations (dams evaluated recently, that are under construction, or reviewed under prior reevaluation programs have lower prioritization pending those results), instrumentation records, performance history considering loading conditions (e.g., earthquakes), and construction history and records. The engineering geologist will focus on the foundation's geologic conditions and identify geologic hazards.

Once the process is completed, DSOD management is briefed on all aspects of how the dams were ranked and selected for reevaluation. The number of dams reevaluated each year depend on staff workload and the complexity of the reevaluations (the primary subject content of this document). As staff is available, reevaluations are conducted starting with the highest priority dams and progressing forward.

One key contrast of this prioritization process versus the 2008 FEMA Risk Tool is that it is primarily failure-mode driven. Where the 2008 FEMA Risk Tool attempts to prioritize by all potential failure modes (PFMs) at a dam to get a total risk ranking, DSOD generally focuses on specific failure modes or loading events. The 2008 FEMA Risk Tool recognizes failure mode risk as a reasonable method for prioritization, but it is presumed that all failure modes are ranked initially so there is a qualitative knowledge of other failure modes when the tool is used, regardless of sorting technique. DSOD also evaluates other risks during its reevaluations; however, other risks are not used to set priorities, which could be a limitation for cases where there are higher risks while the focused ones are considered low. Aside of this limitation, the reevaluation does look at other PFMs during dam-specific reevaluations.

C. Reevaluation Process Overview

Reevaluations are ongoing and are triggered by improved engineering and geologic standards for evaluations and analyses, or case histories and lessons learned following worldwide dam incidents. While many reevaluations are triggered through a reevaluation program using a screening and prioritization process, dams can also be selected for reevaluation by other means.

Annual maintenance inspection and instrumentation reviews will identify changes in a dam from year to year. Increases in seepage, degradation of soils or concrete, deformation or displacements, or changes in piezometric conditions will cause DSOD field engineers to flag a dam for reevaluation that can supersede the screening priority or trigger an adjustment to the screening scores. An incident at a dam will necessitate a comprehensive reevaluation of the dam and, often, dam owners will implement their own reevaluations, which will start DSOD's concurrent review of the dam. These triggers are usually irrespective of a reevaluation program screening and will focus more comprehensively on all failure modes DSOD sees as a risk for a dam system.

Once a reevaluation process is begun, it generally follows through the methods outlined in the remainder of this document. Although formalized probable failure mode and quantitative risk analyses are not conducted, DSOD engineers and engineering geologists are highly experienced in dam safety and critically consider all failure modes while conducting reevaluations through regular staff-level collaboration and briefings with management throughout a reevaluation program study.

While the actual reevaluation is standards based (in line with most regulatory reviews as described in the 2008 FEMA Risk Tool), DSOD engineers and engineering geologists consider the probability and likelihood of a failure based on the results of the evaluation. This is often accomplished by considering factors such as the frequency of loads that might lead to a failure mechanism (e.g., storm frequency that would overtop a dam, ground motion intensity needed to trigger liquefaction, or piezometric conditions leading to incipient slope instability [FS = 1]). The inherent variability of parameters and sensitivity analyses may also be considered.

At the end of the reevaluation, each member of the multidisciplinary team independently documents their review within their area of expertise and provides conclusions and recommendations that will include the identification of deficiencies, any associated risks, and actions needed. Identified deficiencies, risks, and actions needed are tracked at either the section or branch level and entered into DSOD's DamPoint Database.

D. Owner Involvement

DSOD generally conducts the previously discussed processes and the following reevaluations independently from the dam owner. The screening and prioritization processes are completely internal and data availability will drive the need for involvement of the dam owner and their need to perform a reevaluation. DSOD is not the engineer of record as that responsibility lies with the dam owner.

While DSOD's process does not require dam owners to perform their own reevaluations, dam owners are often notified early in the reevaluation process when there is insufficient quality data available for DSOD to perform a reevaluation. Once dam owners are engaged in the process, they have an opportunity to conduct their own analyses, which are beneficial by providing independent verification of all conclusions and constructive discussion when results are not similar. Occasionally, DSOD completes a reevaluation without engaging the dam owner, usually because there is sufficient data for the reevaluation and findings conclusively show safe or unsafe conditions with little uncertainty.

If there are no deficiencies, dam owners may not be notified and DSOD begins the next dam reevaluation. If deficiencies are identified, dam owners are notified of the results and what is needed to mitigate the deficiencies in the interim. DSOD uses RIDM for interim risk reductions, such as restrictions, updated Emergency Action Plans, and temporary repairs based on the likelihood of the failure mode and associated consequences. Based on the size of the repair or rehabilitation project, it usually takes dam owners 5 to 20 years to design, permit, and perform permanent construction repairs thus multiple risk reduction measures may be needed in the interim.

In cases where a dam has multiple deficiencies, DSOD will also use risk to guide a dam owner to prioritize repairs by the largest risk reductions, or by those that can provide redundancy and mitigation for other risks. For instance, a working outlet is often one of the highest priorities, as a reliable outlet can mitigate other risks by helping dam owners to maintain a restriction and evacuate a reservoir quickly in the event of an emergency.

III. Comprehensive File Review

Every reevaluation begins with a thorough review of all available documents for the dam. DSOD generally has in depth records of most dams dating back to their construction. In some cases, the records may be incomplete for 1) dams constructed prior to 1929 or constructed without regulatory oversight, 2) Federal dams brought into State jurisdiction through a change of ownership, or 3) offstream dams brought under DSOD's jurisdiction in 1965 due to changes to the California Water Code. In many cases, the information available from a file review may be sufficient to initiate or conduct a reevaluation and make the needed assessments. A file review includes reviewing:

- Pre-design reports including geotechnical data reports, geologic mapping exercises, and site investigation results.
- Design reports, plans, specifications, and DSOD review memorandums.
- Construction reports, construction inspection memorandums, photographs of construction, and as-built drawings.
- Maintenance inspection and instrumentation reports.
- Subsequent dam or appurtenance construction, maintenance, repair, or alterations records.
- Records of any incidents or performance under adverse load conditions such as earthquakes or floods.

Besides design properties and parameters, a comprehensive file review includes:

- Quality assurance/quality control assessment of test data to help verify or confirm that the construction materials used met the design criteria.
    - Field changes made during construction that differ from the design criteria.
    - Foundation conditions observed during construction and if the foundation objective required by the design criteria was met.
    - Construction that was not performed in compliance with the approved plans and specifications.
    - Construction methods utilized.
- Common design practices for dams constructed in the late 1800s and early 1900s, such as leaving alluvium in place beneath a dam, hydraulic fill construction, and poor compaction techniques.

- Grouting records, especially if a foundation seepage assessment is being made. Consider grout mix design, closure criteria, geologic discontinuities such as shears, etc., that may indicate adverse foundation conditions.

- Maintenance inspections. Pay particular attention to inspections conducted when reservoirs where initially being brought into service, or after a significant change in reservoir use or operations.

    - Look at maintenance inspections' photographs over the years, noting any evolution in the performance of the dam and unusual behaviors.

    - Note repeated or extensive cracking in concrete or earthfill, swelling or heave, vegetation problems, wet spots on a dam or spillway, erosion rills, and any indication of instability in surrounding abutments and reservoir shores.

- Instrumentation data used to monitor a dam's performance.

- Local seismicity records and dam and appurtenances performance records during earthquakes or flood events that may be useful in validating reevaluations.

- Records of any adverse performance under normal and/or unusual loads.

- As-built drawings and construction specifications.

While previous reviews and analyses may be available, new reevaluations are usually conducted because of significant changes to the standard of practice. Consequently, new reevaluations need to be independent of previous analyses and not repeat findings from past reports. A reevaluation necessitates the need to go back to the original data so that independent conclusions and findings can be made. Such independent reevaluations help inform conclusions when new and past findings are inconsistent, as can occur given changed standards and knowledge of understanding with regard to loading conditions, age degradation of materials, and advancement of engineering analyses methodologies.

Engineers and engineering geologists performing file reviews are to document their independent findings in their reevaluation memorandums.

IV. Geologic Reevaluation Protocols

Understanding a dam's regional and site geology is critical. It was a lack of appreciation of the foundation geology and unrecognized foundation defects by the designers that lead to the failure of Saint Francis Dam in 1928. This failure led to the creation of California's dam safety program in 1929. Foundation defects were also responsible for the Baldwin Hills Dam failure in 1963, resulting in legislation that brought offstream dams into DSOD's jurisdiction. In general, a geologic reevaluation begins with a comprehensive file review as previously described.

A. Geologic Hazard Assessment

The reevaluation of dams and their appurtenant structures often requires a site-specific geologic hazard assessment, development of a geologic foundation model, and determination of key geotechnical input parameters for use in engineering analyses. This information can typically be compiled through a comprehensive review of DSOD's files. If, however, needed data are missing, the dam owner may be directed to perform a geologic investigation (potentially in multiple phases) to collect the missing data.

Geomorphology

Understanding the physical geography is important for providing context for the processes that influence the current topography of a damsite. An understanding of landforms and the processes that form them can be an indicator of the character of rock and soils within the surrounding geology, as well as an indicator of geologic hazards. Various interrelational processes influence the shape of the landscape, including tectonic, mass wasting, and fluvial to name a few.

To provide context to the engineers, DSOD engineering geologists couple their understanding of geologic processes with topographic data from both printed maps and airborne Light Detection and Ranging (LiDAR) when assessing the character and suitability of damsites. Additionally, geomorphology is considered when evaluating the activity of seismic sources that can influence the design of a dam.

DSOD requires dam owners to submit an exploration plan for review and approval prior to beginning any geologic investigation work. The exploration plan must explain the intent of the work and detail the scope of work, the exploration locations, and the methods and means to carry out the work. The investigation needs to be comprehensive enough to obtain the needed information. The geologic investigation must follow industry standard of practice and use American Society for Testing and Materials (ASTM) standards where applicable. Typical geologic investigations will involve both surface and subsurface methods such as field mapping, geophysical methods, trenching, drilling, sampling, and laboratory testing. Personnel performing the investigation must be experienced in the exploration techniques used and familiar with the types of geologic problems dams experience.

The selection of drilling method must be appropriate for the material encountered, the overall purpose of the boring, and the sampling methods chosen. DSOD does not typically allow down-the-hole hammers or casing advancement drilling methods within the foundations due to concern for foundation uplift and dilation if the borehole were to become plugged. Drilling through earthen embankments is allowed only if the data cannot be determined by other means. Preferred drilling methods for embankments are hollow stem auger and Sonic Core drills. Drilling with rotary wash is allowed in certain instances but must be done with extreme caution to avoid hydraulic fracture.

Soil Sampling

Soil sampling is an essential step to obtaining reliable data to define subsurface conditions, and to develop foundation and embankment fill parameters for engineering analyses. Generally, sampling and testing should conform to ASTM standards where appropriate for dam construction. Laboratory test data based on unrepresentative or incorrectly collected samples during the soil characterization phase of the reevaluations are not to be used in analyses. DSOD considers samples to be disturbed when sampling methods alter the in-situ nature of the soil. Common sampling methods that result in disturbed samples include:

- Driven samplers (e.g., standard penetration tests, California samplers)
- Vibrated samplers (e.g., sonic drilling)
- Bulk samples (e.g., retrieved samples from trench or test pit excavations)
- Cuttings (e.g., retrieved cuttings from open-bit Becker Penetration Tests)

Undisturbed soil samples are considered to have the general behavior comparable to the in-situ behavior of the soil. The common undisturbed sampling methods include:

- Thin wall push sampling (e.g., thin-walled Shelby tube)
- Rotary sampling (e.g., Denison barrel sampler, Pitcher barrel sampler, etc.)
- Block samples (e.g., carved samples)

Laboratory Testing

Laboratory testing to estimate in-situ shear strength, consolidation, permeability, and density parameters needs be performed on undisturbed samples. The adequacy and sufficiency of testing used to develop soil parameters for engineering analyses needs to be fully assessed:

- Laboratory testing needs be conducted following the most current ASTM standards and be performed by a qualified soil testing laboratory.
- During the file reviews historic laboratory testing methods need to be evaluated and compared to the current standards.

- The potential differences in testing methods must be assessed so that differences in laboratory testing results are well understood.

One primary objective in laboratory testing for embankment reevaluations is to determine a material's shear strength. Testing methods used to develop shear strength parameters need to match the expected field conditions and critical failure modes. Typical methods, their uses, and their limitations are:

- Triaxial Shear Tests – Monotonic undrained triaxial shear tests with pore pressure measurements can provide an understanding of drained and undrained soil strengths. There should be a clear understanding of the loading and consolidation methods before laboratory data are processed.

- Direct Shear Tests – These tests are one of the oldest and simplest forms of shear tests. There are several limitations associated with this type of test, and they should not be considered a reliable method to develop representative shear strength parameters for analyses.

- Cyclic Triaxial Tests – These tests were once a popular test for predicting cyclic strength and behavior. Sampling difficulty and duplication of failure modes are unresolved problems associated with these tests. These tests are now seldom used for analyzing existing dams.

- Cyclic Simple Shear Tests – These tests have similar levels of difficulty as cyclic triaxial tests and are occasionally used for predicting dynamic soil strength and behavior. These tests are costly and, often, only used for highest cost projects.

Regardless of shear strength test methods, the behavior of shearing needs to be understood and applicable to the engineering analysis.

Additional laboratory testing data that needs to be reviewed as part of an embankment reevaluation are:

- Gradation (mechanical and hydrometer)

- Atterberg limits (Plastic Limit, Liquid Limit, and Plasticity Index)

- Moisture content and dry density

- Specific gravity

- Compaction tests

- Consolidation tests

- Permeability tests

- Abrasion and soundness tests for rockfill and riprap

- Vaughan and Soares Test (address sand and gravels filter's self-healing characteristics when saturated)
- Pinhole dispersion test to ensure non-dispersive materials

In-Situ Testing

In-situ tests may be used to identify changes in embankment and foundation zoning and stratigraphy, and to obtain indirect measurements of geotechnical parameters, especially in materials that are challenging to sample. Any review of site investigations should consider whether in-situ tests have been paired with collected samples and laboratory tests to assess consistency of interpreted geotechnical parameters. Common in-situ tests for embankment dams and soil foundations include:

- Standard penetration tests (SPT)
- Cone penetration tests (CPT)
- Becker Hammer penetration tests (BPT)

Many in-situ tests have been correlated with parameters used for embankment evaluations such as shear strength, density, and behavior (e.g., clay-like versus sand-like). When such correlations are used, the engineer must verify that the correlations are appropriate, and that the appropriate corrections were used to normalize in-situ test results for use in the evaluations with an understanding of the limitations that will exist throughout the process.

Of specific interest and concern is the presence of gravels in the soils being investigated. While techniques for gravel corrections on smaller samplers exist, they can be controversial and inconclusive. To aid in the evaluation, engineering geologists logging exploration need to note sample recovery, gravel percentage, and gradation of each sample to assess the reliability of the results and their impact on the correlations. Errors resulting from gravel presence can be large thus increasing the variability of in-situ measurements, and any attempts at qualitatively or quantitatively evaluating risk will be met with significant uncertainty.

Gravel correction techniques for drive samplers, such as recording blows per inch, are not possible when gravel percentages exceed 15 to 20 percent and may not be very reliable when gravel percentages are lower. Ideally, gravelly soils would be evaluated using BPT testing, which reduces the concerns of gravel presence. However, correlations between BPT and SPT tests are not perfect, and the understanding of properties such as liquefaction resistance are poorly understood for gravelly soils.

Geophysical Testing

Geophysical tests are normally considered non-destructive as they do not change the condition of the soil, nor do they provide samples. Geophysical methods that require borings, such as cross-hole shear wave velocity tests, are not considered to be non-destructive as there is the potential for the soil to be disturbed. Since geophysical parameters are low strain, correlations for major soil characteristics, like cyclic strength, can be highly variable and unreliable. As a result, geophysical tests should typically be used as supplemental information to in-situ and laboratory testing.

B. Seismic Hazard Assessment

A key component to geologic hazard assessment is the seismic hazard. In California, earthquakes often represent the most severe loading that dams will experience. To provide a high degree of protection from earthquake-related dam failure, seismic sources that could conceivably affect the dam must be identified. DSOD classifications with regard to fault activity are:

- Active fault – A fault having ruptured within the last 35,000 years.
- Conditionally active fault – A fault having ruptured in the Quaternary, but its displacement history during the last 35,000 years is unknown.
- Inactive fault – Fault inactivity is demonstrated by a fault trace that is consistently overlain by unbroken geologic material older than 35,000 years. A fault that has no indication of Quaternary activity is presumed to be inactive, except in regions of sparse Quaternary cover (see attachment 1).

Active faults and conditionally active faults need to be used to develop the design ground motion. The faults judged to be inactive are eliminated from further consideration. When this information cannot be gleaned from previous reports or published work, DSOD will ask the dam owner to perform a fault investigation.

Design Ground Motion for a Reevaluation

DSOD's Geology Branch develops statistically-based ground motion estimates (50th to 84th percentile) for several significant seismic sources using current attenuation formulas appropriate for California's tectonic regime. All dams in California are analyzed for at least the expected 50th percentile level of acceleration associated with a maximum magnitude earthquake event at the closest distance to the controlling fault, with the exception of the minimum earthquake discussed below. In recognition that some earthquake events are more likely and that some dams have high downstream hazard potentials, many dams need to be evaluated and designed to acceleration target values greater than 50th percentile. The 84th percentile level will normally be the highest design values used by DSOD (attachment 2).

Since the conservatism associated with the deterministic approach varies regionally, an appreciation of the return period associated with a given ground motion parameter is of primary consideration in ground motion target selection. Simplified probabilistic seismic hazard analyses are used to determine the return period of the deterministically obtained target. In scenarios that allow selection of parameters between the 50th and 84th percentile levels, the selection of the 50th to 84th percentile is evaluated with consideration of return period.

For simplified analyses, target seismic parameters (PGA, spectral acceleration, Peak Ground Velocity [PGV], duration, Arias Intensity) are sufficient. For the more complex engineering analysis, spectrally matched time histories are developed that match the target parameters but still retain the fundamental shape of the seedtime history.

Minimum Earthquake

DSOD uses a minimum earthquake standard, which is intended to account for unrecognized seismic sources and is likely to be invoked in areas of low seismic activity such as the Western Slope of the Sierra Nevada Mountains, the Central Valley, and Southeastern California. The minimum earthquake applies whenever the fault source ground motion estimate is less severe than the ground motion resulting from the minimum earthquake. The minimum earthquake PGA will be within the range of 0.15 to 0.25g.

The minimum earthquake is specified as a peak acceleration value, or target response spectral curve, associated with an earthquake scenario presumed to be a magnitude 6-1/4 event at a distance, when used in current attenuation formulas, which results in the given PGA. The 0.15g PGA value is the 50th percentile peak ground acceleration for this scenario, 0.20g PGA value is the 67th percentile, and 0.25g PGA value is the 84th percentile.

Design engineers work closely with the engineering geologists to identify the appropriate level of design when using a minimum earthquake in reevaluations.

- Reevaluations of existing dams should use a minimum earthquake PGA of 0.15g, except where a higher value is indicated by a consideration of return period and consequence.

- Reevaluations of new dams/major modifications should use a minimum earthquake PGA of 0.2g, except where a higher value is indicated by a consideration of return period and consequence.

- Reevaluations for high-consequence projects should consider a PGA of 0.25 g.

Estimating Fault Displacements/Rupture

The classification of faults and fault displacement estimation approach used by DSOD is to provide consistency in the displacement estimation practice for jurisdictional dams (see attachment 3). When determining fault displacement, statistically based modern formulas appropriate for California’s tectonic regime are used to estimate the 50th to 84th percentiles displacements. Another goal is to apply the same hazard consequence philosophy, to the extent possible, used in assessing ground shaking. Therefore, a “Fault Displacement Consequence Hazard Matrix” (see attachment 4) is used to select the fault displacements level of design. Distributed displacements on well-defined secondary active faults are estimated deterministically by assuming 25 percent of the primary or principal fault displacement.

V. Hydrologic Reevaluation Protocols

Every dam system must be able to safely accommodate inflows generated by design storm events with adequate residual freeboard. Pumped inflow, stream diversions, urban drainage, and other sources must be considered along with the design storm. In general, a hydrologic reevaluation begins with a comprehensive file review as previously described.

A. Design Storm(s) Precipitation

The process of selecting and analyzing an appropriate design storm begins by making a quantitative assessment of the dam's downstream hazard potential. Spillways for dams with a low downstream hazard potential are typically designed for a return period of 1,000 years. Spillways for dams with extremely high downstream hazard potentials are designed for the probable maximum precipitation (PMP) as currently defined by Hydrometeorological Report No. 58/59 (U.S. Department of Commerce, 1999). The spillways at dams classified with significant and high downstream hazard potential are typically designed for a storm with a return period between 1,000 year storm and the PMP-based storm. It needs to be recognized that the PMP is the theoretical maximum value for a given site and that there is no specific return period for the PMP (varies from site to site).

Design storms are typically 72 hours in duration; however, 6-hour thunderstorms (short duration) need to be considered for smaller watersheds. Rainfall depth for the design storm is made for statistical storms using statistical techniques that use historical data from rain and stream gauges with over 30 years of recordings (if available) within or nearby the watershed (within preferable); depth for PMPs are defined in HMR 58. Validation of estimated precipitation data is to be conducted using smaller return period storms (e.g., 100 or 1,000 years) in conjunction with references such as the National Oceanic and Atmospheric Administration's Atlas 14 (NOAA, 2012).

Seasonal Storms

Dams and reservoirs operate differently based on the time of the year and may require developing monthly design storms. These storms can be used to assess the adequacy of a dam's spillway for a full year by considering different storage levels at various times of the year (due to spillway gates or flashboards in place), in conjunction with the probability of a storm occurring. Seasonal evaluations may also be critical in locations where snowmelt may contribute to the peak reservoir level and minimum residual freeboard, as can occur in late spring or early summer.

Snowmelt

Many dams in California have watersheds above an elevation of 6,000 feet. In these cases, the storm inflows must incorporate runoff from snowmelt when evaluating a late spring or early summer storm. Current standard techniques that consider typical snow accumulation patterns and seasonal temperature estimates need to be used. The

National Engineering Handbook (Natural Resources Conservation Service, 1994) provides one method for estimating snowmelt, as does HMR 58.

B. Watershed Characterization

DSOD engineers must characterize the watershed as part of their hydrological analyses:

- The watershed must be delineated, generally using geographic information system (GIS) software; however, hand delineation may be required if the watershed is small or if the available GIS terrain data resolution is insufficient.
- Larger watersheds need to be divided into sub-basins to more accurately model runoff characteristics resulting from differing topography, vegetation, or snow accumulation.
- If a watershed is subdivided, then the interconnecting streams need to be mapped and the stream channel routing parameters need to be estimated so that the inflow hydrograph to the dam's reservoir can be accurately determined.
- The need to estimate how much rainfall and runoff are lost due to infiltration into the soil and storage in surface depressions is also necessary. Rainfall loss rates tend to vary, with higher losses occurring at the beginning of the storm and decreasing over time. Loss considerations must take into account storm frequency, urbanization, and watershed saturation level when considering seasonal storms.

C. Routing

Once the watershed and sub-basins have been mapped, it is necessary to develop the mechanism by which rainfall is transformed into surface runoff and routed to the reservoir; this is usually done in software using unit hydrograph theory. The design storm hydrograph is routed through the reservoir and spillway to determine the maximum reservoir elevation during the storm event and, consequently, the residual freeboard as a result of the storm.

Reservoir Stage and Storage Curve

A reservoir stage and storage curve must be developed to model the volume of water that can be stored versus reservoir elevation. This curve captures the available surcharge storage during a flood event. As the reservoir is assumed to be full to the spillway lip at the start of the design storm, the storage/capacity curve needs to start at the spillway lip and extend to the dam crest.

Spillway Rating Curve

Spillway rating curves are needed for the spillway(s) at a dam to give the spillway discharge flows with respect to a given reservoir elevation. These curves need to be calculated using appropriate hydraulic principles and methods. Considerations need to be made when determining the spillway rating curve and hydraulics:

- Control structures such as gates, flashboards, and weir type.
- Location of the control point. Simple hydraulics equations may be adequate for developing a rating curve if the spillway crest structure (inlet) controls.
- Spillway contractions, submerged flow conditions, culverts, and other factors that impact the efficiency of the spillway or control structures that may necessitate a more robust hydraulics evaluation to capture the flow profile and energy through the spillway structure.
- Side-channel spillway impacts on the system, including the depth of the trough, which could reduce the efficiency of the spillway. Similarly, labyrinth weirs that may lose efficiency under large design heads over the weir.
- Complicated spillways may necessitate Computational Fluid Dynamics (CFD) modelling or physical modelling.

Inflows due to storm runoff, reservoir storage volume, and spillway discharge curves are used to determine an outflow hydrograph and the maximum resulting reservoir storage level. The routing assumes that the reservoir is full to the maximum possible storage elevation at the start of routing, without any lower-level outlet discharges from the reservoir. Additional assumptions regarding the routing process:

- Flashboards and gates need to be considered in place or closed, respectively, when the Certificate of Approval allows water to be stored against them during the design storm being considered.
- Upstream reservoirs need to be incorporated into the routing process so the evaluation accurately assesses the conditions on the full watershed.
- Other sources of inflow need to be assumed as appropriate considering the probability of their occurrence at the same time an extreme storm occurs. In small reservoirs, sources of inflow (such as pumps) may create the critical reservoir stage and may drive the necessary spillway capacities.

D. Freeboard

Freeboard is defined as the distance from lowest point along the dam crest to the reservoir elevation.

Total Freeboard

Total freeboard is the distance from the lowest point along the dam crest to the spillway crest. Typically, a minimum of 4 feet of total freeboard for dams and reservoirs built across natural flow paths (onstream) is required. A minimum of 3 feet of total freeboard for dams and reservoirs built completely offstream (no discernable watershed) is typically required.

However, adequate total freeboard must account for potential seismic deformation in areas subject to high seismic loading; this freeboard will, in theory, accommodate seismically induced deformations and cracking that cannot be fully estimated to a high level of certainty by analyses. Thus, a criterion of 5 feet plus 5 percent of the dam height is typically to be used in determining minimum freeboard for new dams subject to high seismic loads.

Finally, the amount of freeboard is also dependent upon the type of dam (e.g., earthen embankment versus concrete gravity).

Operational Freeboard

Operational freeboard is the distance from the lowest point along the dam crest to the maximum reservoir elevation allowed by the Certificate of Approval. In some cases, gates or flashboards are allowed in the spillway, which results in the operational freeboard being lower than the total freeboard. In other cases, the reservoir is certified to an elevation below the spillway crest, which results in the operational freeboard being greater than the total freeboard.

Residual Freeboard

Residual freeboard is measured from the lowest point along the dam crest to the highest reservoir elevation, as determined by routing the design storm. Generally, a minimum residual freeboard of 1.5 feet is required. However, the residual freeboard must be sufficient to account for wind and wave runup that may occur under the design storm conditions.

Parapet walls are not considered in determining freeboard unless they are a structural component of the dam. Nonstructural parapet walls should not be relied upon to impound reservoir water under any condition other than to provide additional freeboard for wind or wave runup.

E. Winterization

Dam owners that are modifying existing dams or constructing new dams need to have a winterization plan when work cannot be completed prior to the onset of winter storms/temperatures. The plan may need to include the evaluation of a flood event during construction depending on the type of dam, type of construction, outlet capacity, stream capacity, environmental constraints, watershed, and reservoir usage (what is required in a winterization plan is case-by-case). Generally, the construction site must be able to satisfactorily pass a 100-year storm, at a minimum.

VI. Hydraulic Reevaluations Protocols

In general, a hydraulic reevaluation begins with a comprehensive file review as previously described.

A. Spillways

Design storm flows need to be routed through the spillways to evaluate water depth, velocities, pressures, and spillway wall freeboard. Normally, only the peak flow is considered, but in certain spillway systems lower flows may be critical to the evaluation of the structure.

Hydraulic Routing
Spillway routing begins by locating the control point and developing the water surface profile. Flow profiles are computed depending on the location of the control point and the Froude number. Hydraulic routing should consider and include the effect of horizontal curves on water depth, the potential for cross waves, and the potential for bulking. Hydraulic routing extends to evaluate terminal structures. Downstream boundary conditions need to be assessed and appropriate assumptions made.

Cavitation
Cavitation potential needs to be estimated by computing the cavitation index along the spillway at the design flow and intermediate, more frequent, flows. If the cavitation index is relatively low, boundary layer analysis is performed to estimate an aeration point. For existing spillways, this may be calibrated by direct observation or photographs of spillway behavior during spilling events.

Water Surface Profiles
Water surface profiles are used to determine if the spillway walls overtop anywhere along the profile. Consideration needs to be given for curves in the spillway, bulking, and cross waves.

Stagnation Pressures
Spillways need to be evaluated for stagnation pressures resulting from water flowing into joints and cracks during releases. This can result in high uplift pressures beneath the spillway panels. Defensive measures can be taken to address stagnation pressures:

- Properly sealing joints and cracks.
- Installing drains beneath the spillway floor panels.
- Installing waterstops.
- Installing anchors tying the floor panels to sound rock.

Dissipation Structures

Stilling basins, dissipation structures, and flip buckets are often used at the end of a spillway to reduce flow velocities. These structures need to be assessed with consideration of the hydraulic loads. Also, the erosion potential at the terminus of these structures needs to be assessed with consideration of the site geology, including the erodibility index and discontinuities within the formations.

B. Outlet Works

Typically, DSOD requires a dam to have a dedicated low-level outlet to drain the reservoir in case of an emergency. The outlet's hydraulic capacity needs to be estimated, incorporating all head losses, to assess how long it would take the outlet to drain the full reservoir. When evaluating the minimum size of a dam's outlet, the following drawdown criteria is generally used (time ranges allow for engineering judgement):

- For reservoirs that impound 5,000 acre-feet of water or less, the outlet system should be capable of draining half of the reservoir capacity in 7 or 10 days and full contents within 20 or 30 days, respectively, depending on factors such as downstream and seismic hazard, dam construction methods and age, known deficiencies, and type of dam; as determined by DSOD.

- For reservoirs that impound over 5,000 acre-feet of water, the outlet system should be capable of lowering the maximum storage depth by 10 percent within 7 or 10 days and draining its full contents within 90 or 120 days, respectively, depending on factors such as downstream and seismic hazard, dam construction methods and age, known deficiencies, and type of dam; as determined by DSOD.

VII. Structural Reevaluation Protocols

In general, a structural reevaluation first begins with a comprehensive file review as previously described.

A. Concrete Dams

Most concrete dams under DSOD's jurisdiction can be categorized into the following three types. It should be noted that nearly all the dams are unique in geometry, with some a hybrid of multiple dam types that result in very complex three-dimensional behavior.

- **Gravity Dams:** Gravity dams rely on the weight of the structure in resisting load coming from the reservoir and other sources. Loads get transmitted through the structure and then directly into the foundation. Sliding and overturning typically control the design, not tensile or compressive stresses within the concrete. Gravity dams may include conventional concrete and roller-compacted concrete; however, older dams may include grouted masonry or cyclopean concrete.

- **Arch Dams:** Arch dams rely on three-dimensional arching action to resist loads. Arch dams can consequently be less massive than gravity dams, transmitting their loads through the arch structure and into the abutment and foundation rock. Consequently, arch dams require good foundations and abutments as loads will be more concentrated. Tensile stresses are limited given the arching geometry of the structure.

- **Multiple Arch:** Multiple arch dams consider a series of arching barrel structures, which transmit load into a series of concrete buttresses and then down into the foundation. This design also utilizes arching geometry to limit tensile stresses within the concrete.

All stress-induced failure modes that result in extensive concrete damage and the de-stabilization of a dam are evaluated as appropriate for the type of structure. Gravity dams and wall structures should always be evaluated for overturning stability and sliding. Diagonal and horizontal cracking between vertical contraction joints at arch dams can result in dislodging large concrete blocks during seismic shaking, thus this failure mode needs to be considered. Foundation geology plays a crucial role, which has led to catastrophic failures in the past. Identifying adverse foundation conditions that could result in loose foundation blocks or movement along joint sets is therefore extremely important; sliding stability at the foundation contact or at foundation discontinuities need to be considered.

Loading Conditions

Loads applied during analysis include gravity, hydrostatic pressure from the reservoir, hydrostatic pressure from tail water, uplift pressure, and earthquake load. Silt may also need to be considered in determining loading conditions. Some typical load combinations are:

- **Normal Operation** = Gravity + Hydrostatic (at certified storage level) + Uplift
- **Flood** = Gravity + Hydrostatic (at design flood level) + Uplift
- **Seismic** = Gravity + Hydrostatic (at certified storage level) + Uplift + Earthquake

Earthquake intensity is a function of seismicity at the damsite and downstream hazard. Typically, a 50th or 84th percentile acceleration response spectra are used to develop ground motion characteristics for seismic assessments. Seismic loads are typically applied in one of two different ways:

- The analysis is based on a response spectrum input at the base of the model; therefore, ground motions are not propagated through a foundation.
- More advanced analyses consider an earthquake time history where ground motions are applied deep within a foundation and the site response is captured by the model.

Characterizing Foundation Materials

Foundation conditions are evaluated to identify rock discontinuities, shears, seams, and other adverse conditions that could affect the stability of a concrete dam. Information necessary to characterize the dam-foundation interface is also reviewed and evaluated. Foundation rock may be tested in-situ, and core samples may be taken at critical locations for laboratory testing. Laboratory test results, together with information obtained from core samples, provide guidance in defining rock properties used in a numerical analysis. Instrumentation in the foundation can provide data that DSOD will review to understand and gain information related to the permeability of the rock, efficiency of the grout curtains, the performance of foundation/body drains, seepage through the foundation, and pressure distributions for uplift evaluations.

Characterizing Concrete

Concrete can be tested in-situ using various non-destructive test methods to estimate its strength and condition. Damage to the concrete from alkali-silica reaction, freeze-thaw, or construction discontinuities should be considered. In most cases, core samples are necessary to better characterize the material in conjunction with laboratory testing to estimate the concrete's compressive and tensile strengths, and lift line tensile strengths. Additional concrete properties shall be determined as required by the analyses and constitutive models used for the evaluation, such as density and elastic moduli or stress-dependent anisotropic parameters.

Types of Analyses

The level of complexity to be used in the reevaluation of a concrete dam or structure is to be determined on a case-by-case basis:

Two-Dimensional Static and Pseudo-Static Analyses: These analyses are typically performed for gravity dams to evaluate overturning and sliding potential, often using hand or spreadsheet calculations. These analyses do not capture soil-structure-reservoir interaction and usually require conservative assumptions when estimating the shear strength of the concrete along the dam-foundation interface. These types of analyses may produce factors of safety that do not satisfy design criteria, requiring more complex analyses to understand the expected performance of the dam.

Linear Elastic Finite Element Models: These analyses can be completed in two or three dimensions. A two-dimensional analysis would be applicable to a gravity structure situated in a wide canyon. A concrete arch, multiple arch, or any other complex structure requires a three-dimensional model to provide a more realistic representation of physical problems. Analysis using linear elastic material properties can produce stresses that significantly exceed concrete strength criteria under extreme loading conditions. These stress levels are used to indirectly estimate the extent of concrete damage by considering the stress magnitude and the number of cycles where strength criteria are exceeded. The safety of the dam is then qualitatively determined, using engineering judgement, by evaluating the extent of the concrete damage and its impact dam stability. Linear elastic analyses showing extensive high stresses may require nonlinear analysis to better understand a structure's behavior under extreme loading conditions.

Nonlinear Finite Element Models: In complex cases where a dam is expected to behave highly nonlinear, these analyses can provide insight necessary to understand how the structure will perform under extreme loading conditions. These types of analyses consider geometric nonlinearities associated with lift joints and keyed contraction joints that open and close during strong shaking, accurate representations of the dam-foundation interface, nonlinear material behaviors captured through an appropriate constitutive model for the concrete and/or steel, and explicit models of the reservoir water in contact with the structure to capture the dynamic reservoir load on the structure. When nonlinear materials are used, earthquake energy input into a numerical model gets absorbed through deformations and concrete damage. In these cases, concrete elements can yield, and stresses get redistributed. The distribution of damage and post-earthquake stability of a dam is therefore better represented and understood.

Calibration is a critical step in evaluating a finite element model, and validation may be performed for static and seismic conditions using data from instrumentation at the damsite. Past earthquake recordings, along with post-earthquake observations, may be critical in validating and assessing the ability of the model to accurately recreate measured earthquake response. In cases where earthquake data are unavailable, ambient or low-level vibration testing on the dam may be requested of the dam owner to aid the model calibration effort.

Calibration using earthquake recordings and vibration-based testing is not performed for less critical cases, which rely on model verification. The verification process evaluates whether a model is mathematically behaving as it should. This procedure is based primarily on engineering judgement and considers parameters that can be estimated by the engineer. Some parameters include site response at various locations throughout the foundation, structural deformations, static/dynamic water pressures, etc. Although this verification process does not validate that a model can accurately recreate a known event, it verifies that the numerical simulations are mathematically behaving as expected and helps identify potential errors within the model.

B. Outlet Towers

Outlet towers often serve as a key component of the system necessary to dewater reservoirs in an emergency. They may also provide intakes for power generating and water supply. In general, the reevaluation of outlet towers follows what is done for concrete dams.

When reviewing the structural stability of an outlet tower, consideration should be given to such things as variable reservoir levels, accessibility, access bridges, wet verses dry towers, and clogging potential from concrete spalling during a seismic event. Outlet towers should also be reviewed with respect to the current standards for reinforcement and concrete placement techniques, such as those by the American Concrete Institute (ACI).

Traditional Analysis Techniques

In cases where extensive damage is not anticipated, DSOD relies on traditional techniques, which are based on simplified analysis methods. These types of analyses may provide conservative results and generally do not provide extensive insight into tower performance, concrete damage, or post-earthquake stability. This approach considers an elastic material model and, therefore, tower reinforcement is ignored. The analysis process is based on a user-defined response spectrum and the superposition of modal analysis results. Reservoir effects are simulated using added mass while the tower-foundation interaction is either modeled as fixed or estimated using soil springs to simulate foundation impedances. Section demands are compared to section capacities in the form of demand-capacity ratios (DCRs), which are indirect approximations of the energy ratio (total energy dissipated/elastic energy dissipated). DCRs are evaluated based on allowable ductility criteria, which is typically a function of reinforcement and the quality of detailing.

In certain cases when elastic analyses produce section demands that are several times greater than their respective calculated capacities, further insight provided by more advanced analyses is needed.

Advanced Numerical Analyses

When extensive structural damage is expected, more sophisticated analyses need to be completed. These analyses model the tower shell explicitly, along with intakes, ducts, decks, etc. The foundation is developed to accurately characterize tower embedment and the reservoir model is developed to include water surrounding the tower, inside of the ports, and within the tower interior as needed. Nonlinear behavior of concrete is characterized using a constitutive material model that allows for a pressure versus volumetric strain relationship, damage accumulation, and progressive changes in properties during the analysis. Because the material model is based on realistic concrete behavior, all longitudinal and transverse reinforcement is explicitly included.

This approach produces the most realistic mathematical representation of the physical problems, and the model is capable of tracking and responding to damage as it accumulates. The model can be subjected to an earthquake time history and will track energy dissipation, concrete damage, and changes in concrete behavior as the structure is subjected to repeated cycles of earthquake loading. Softening and changes in structural period are also captured and tracked in real-time. As the concrete begins to accumulate damage, the structural period increases and the model progressively captures this transformation. The progressive formation of cracks and energy dissipation associated with crack formation is modeled accordingly. Ultimately, energy is dissipated more realistically, and results do not have to be based on an envelope of elastic model results that consider cracked and un-cracked section properties.

These results are interpreted rather differently in the sense that they are not based on extrapolated elastic demands that approximate nonlinear behavior. Instead, the sections yield at their design load, and stresses are redistributed. Additional earthquake energy dissipation is achieved through inelastic deformation, so duration and the amount of energy being input into a system become relevant. The results provide a more direct measure of structural performance, which can be better assessed by reviewing deformation results and levels of material damage.

C. Outlet Conduits

Outlets pipes at California’s dams typically consist of welded steel pipe, reinforced concrete pipe (RCP), high-density polyethylene pipe (HDPE), cast iron pipe, and riveted steel pipe. These pipes may be fully encased in reinforced concrete, cradled in reinforced concrete, encased in low strength concrete, or unencased. The type of pipe and its encasement often depend on the era when the dam was constructed. When evaluating an outlet conduit, the construction and backfill techniques need to be fully reviewed. Some pipe assessments may require detailed inspections, which could be performed via a remotely operated vehicle (ROV) inspection. When evaluating an outlet conduit, the following items need to be assessed:

- Potential for seepage and erosion with consideration given to leakage at joints (e.g., double gasket on RCP) and along the outside of the pipe (full encasement).

- Pipe condition should include an assessment of the thickness of the pipe (loss due to corrosion), or other discontinuities such as cracks or collapse.

- Pipes must be evaluated for all internal (hydrostatic) and external (soil overburden and transient) loading conditions. Loads within embankments can be significant, and some designs may have used standards that are not appropriate under the expected loads. Review of pipe strength and encasement should consider placement method (positive, negative, trench placement) and its impact on the evaluation.

- Corrosion protection (e.g., coatings) needs to be considered.

- Thrust blocks must be included in designs to accommodate hydraulic loads.

- Filter diaphragms are determined on a case-by-case basis, but, must maintain filter compatibility with surrounding fill material.

- Seepage collars are not allowed for new construction as compaction around them may not be uniform, leading to a possible increased risk for seepage and piping around a conduit.

- Corrugated metal pipes are not allowed for new construction.

Outlet Foundations
The following items should be considered:

- If the foundation of an outlet is not fully founded on bedrock, the outlet conduit and its encasement should be assessed for its ability to accommodate differential movement resulting from compression/settlement.

- For outlet systems, a review of the geology should be performed to assess changes in foundation quality, transition between rock and soil areas, and the need for lean concrete in areas where voids may have been encountered.

- Joints and articulation at locations where deformations may be possible, such as at intake structure and outlet pipeline interfaces.

- Potential fault movement and faults crossing an outlet conduit.

Outlet Valves and Controls
An upstream control gate or valve should be provided to eliminate hydraulic pressure within a pipe located in a dam’s foundation. A downstream control adds needed redundancy and allows the outlets to be cycled with minimal water loss. All valves should be designed for the expected maximum head, including the maximum reservoir surface as determined during hydrologic routing. Air vents need to be adequately designed and provided in the proper location to eliminate adverse conditions that can damage the outlet system and its controls. The need for a backup method to operate

valves and gates (e.g., backup generators) needs to be evaluated to ensure reliable operation during an emergency.

Trashracks

Outlet conduits are expected to be equipped with a trashrack at the pipe entrance to prevent material from entering and clogging the outlet conduit. The structural capacity of trashracks need to be evaluated considering a partially blocked condition, a load equivalent to 25 percent of the total reservoir head is used to represent a partially blocked trashrack. Trashracks also need to be evaluated for vibration under the typical range of discharge flows as failure may occur due to fatigue.

Slip-Lining

Slip-lining is a common means of rehabilitating pipes in disrepair. The evaluation of slip-lining should include a review of construction records and specifications. Items that are important for slip-lined outlets include:

- Shrinkage potential for grout surrounding pipes. This material must be non-shrink or slightly expansive. Some non-shrink grouts may show shrinkage, which could lead to seepage.
- Type of grout pumps used. Moyno-type pumps should always be used to avoid high pressure pulsations.
- Construction process and verification techniques. Bulkheads often need adequate ventilation to allow grout to displace the air surrounding new pipes. Additionally, ports are needed to verify that grout has completely filled the void surrounding slip-lined pipes.
- Change in hydraulic capacity. Slip-lined pipes are smaller than the original conduit and will diminish the capacity of the outlet system. Slip-lining pipes will also change the Manning's n Value. An assessment should note the changes to the drawdown capacity.

The cured-in-place method of slip-lining an existing pipe is also acceptable. However, it is very important to ensure that the manufacture's guidelines are strictly followed during construction.

D. Spillways

Normally, spillways are located away from earthen dams. Exceptions to this are for dams used solely for flood control or offstream dams where there are no other suitable locations. Spillways should be non-erodible, either hewn from non-erodible bedrock or constructed of reinforced concrete. Reinforced concrete spillways typically require a competent foundation, preferably bedrock.

Uplift Pressure Loads

Quantification of uplift pressures is difficult and highly uncertain, thus a qualitative evaluation is performed instead. Potential uplift pressures derived from stagnation pressure analysis are evaluated based on surface water velocity, but, considered only as an index. Conditions that would promote the development of uplift pressures, open joints and cracks, high flow velocities, and saturated foundation need to be considered. Conditions that would lead to foundation saturation are identified on a case-by-case basis. These include adequacy and conditions of the slab drain system and walls drain system, and potential for surface water penetration under the slab from either side of the spillway or spillway invert. To prevent hydrostatic uplift, waterstops should be installed and an underdrain system placed beneath the spillway floor to collect and discharge any ground water or seepage that may accumulate.

Special consideration is given to observation of water flowing into or out of joints and cracks at existing spillways. Water stains on slab and wall joints are considered good evidence for flow through cracks and joints. To increase stability, steel anchors can be grouted into bedrock at regular intervals and embedded in the channel floor slabs. If anchors are present under the slab, construction records are reviewed to search for any testing done as part of the acceptance criteria during construction. However, anchor capacity is evaluated based on anchor penetration into the foundation and anchor details (dimension, grout characteristics). Details of anchor bar embedment into the concrete slab are also considered. Reasonable assumptions need to be made regarding shear strength at the grout-rock interface.

Spillway Drain Systems

Spillway drainage systems need to be designed to address potential uplift pressures. Special attention is devoted to drain outfalls, drain pipe sizes, drain slopes and travel lengths, drain material filtering capability, and collector and conveyance pipe material durability. Modern spillway design details that should be considered when reviewing an existing spillway’s drain system design include:

- Pipe materials need to be strong and chemically inert for the local conditions and have continuous joints (welded).

- Pipes must be sized so they accommodate the maximum estimated flows.

- Drain rock should be composed of durable and resistant material and sized for compatibility with the openings in drain collector pipes. Drain rock material must be protected during slab concrete pouring to prevent contamination.

- Multiple drain discharge points are needed for redundancy and to help locate where water is entering the drainage system.

- Walls should have at least one continuous longitudinal drainage line near its base. Ideally, wall and slab drainage should be separated.

- Drainage systems need to have frequent cleanout ports and be designed to facilitate internal inspection.

- Drain holes should not be used in the spillway slab for drainage and are discouraged.

- Drain outfalls need to be protected to prevent wildlife from entering the drain system as well as from vandalism. Drain outfalls should also be observable during spilling events to verify, or measure, presence or absence of flow.

Structural Evaluation of Spillway Concrete Lining

Evaluation of spillway concrete lining adequacy starts by reviewing as-built drawings. Design and construction documentation is reviewed to identify potential issues in spillway linings due to construction methods or geologic hazards identified during design or construction. Special attention is devoted to the design features of slab panel joints (both transverse and longitudinal) to identify potential deficiencies when compared to current design practice. The following items need to be considered when reviewing spillway concrete lining:

- Spillway slabs need to be reviewed for thermal stresses, uplift, and spillway flows to verifying concrete and reinforcement per ACI standards.

- Slab joints should have been designed with special attention to safety features such as shear keys, and doweled bars to prevent vertical offsets.

- Joint details such as waterstops and filler materials.

- Moment and shear capacities of slabs should be computed to assess the maximum unsupported length the slabs can take under full water load if presence of potentially erodible material under the slabs is verified or suspected.

    - The potential unsupported length is considered a vulnerability index and not a measure of the slab bridge over unsupported gaps.

    - Dual-layers of reinforcement are the current standard of design, but the evaluated moment and shear capacities will provide an indication of the performance for thin or singly reinforced slabs.

Spillway Walls

Structural adequacy of walls depends on the function of the wall. Lining of trapezoidal channels, where the walls do not function as a retaining structural element, are evaluated similarly to spillway slabs. Vertical spillway walls act as retaining structures and, for these cases, both global and internal stability are to be evaluated. Vertical walls are evaluated for overturning and sliding by computing shear and moment demand-capacity ratios. Demands are estimated under different loading conditions:

- Hydraulic loads during the maximum spillway discharge.

- Lateral earth loading under static and seismic load conditions. Load evaluations for a retaining wall must consider the adequacy of drainage behind the wall and the potential for pore pressures to contribute to the load.

- Since it is uncommon to have specific information on the shear strength of retained material, reasonable assumptions are normally made, which are aided by a review of construction specifications and field inspections.

- For sloping backfill, simple static and pseudo-static techniques may be too conservative, and limit-equilibrium slope stability analyses may need to be considered.

- Seismic loads in California can be significant and current empirical techniques for assessing the lateral loads on retaining walls should be used as appropriate.

- For spillways where wall footings are separated from spillway slabs by longitudinal joints, global stability against overturning and sliding are also performed considering potential uplift and saturated conditions.

Other Spillway Features

Grout curtains or cutoff walls are constructed at the upstream entrance to prevent seepage and erosion. At the downstream end of the spillway, energy dissipaters are often constructed to prevent stream erosion downstream, or headcutting erosion that could undermine the spillway channel. Features such as these, or their absences, need to be considered as part of a reevaluation.

E. Spillway Gates and Controls

Radial (Tainter) Gates

There are 57 dams under DSOD's jurisdiction that have radial gates in operation. Following the radial gate failure at Folsom Dam in 1995, a radial gate reevaluation program was initiated in 1996. Climb teams of engineers first conducted detailed field inspections, and then structural analyses were performed for all radial gates at all State jurisdictional dams. The program was completed in 2005, resulting in more than 40 gates being replaced or retrofitted. Radial gate assessment and reevaluation generally focus on the potential for corrosion of steel members, increases in trunnion pin friction, and deterioration of the integrity of the gate anchor system. A reevaluation of a gate is to be conducted when a performance anomaly is detected during gate operation, or when visual inspection indicates excessive deterioration of gate members or anchor system component.

Structural analyses of radial gates are conducted using a linear three-dimensional finite element model of the gate. Loads applied during analysis include gravity, hydrostatic pressure from the reservoir, lifting, and earthquake load. Some typical load combinations are:

- **Normal Operation** = Gravity + Hydrostatic (at certified storage level)

- **Gate Lifting** = Gravity + Hydrostatic (at certified storage level) + Lifting

  The lifting force is computed using a trunnion friction moment based on a minimum trunnion friction coefficient of 0.3. Higher trunnion friction coefficients may be used when excessive corrosion is suspected, or when it is indicated from the in-situ trunnion friction test.

- **Seismic** = Gravity + Hydrostatic (at certified storage level) + EQ

  The seismic evaluation typically uses a 50th percentile peak ground acceleration to estimate the hydrodynamic pressure from the reservoir.

The structural evaluation is typically conducted using the Load and Resistance Factor Design Methodology with appropriate load factors and strength reduction factors. Allowable combined stress ratio is 1.0 for all load cases. Critical member connections, as well as the trunnion anchorage, are checked to ensure adequate capacities. The condition of the gates (including maintenance concerns, corrosion, and other damage) should be assessed and addressed in the evaluation. The anchorage system also needs to be assessed for any degradation that may impact the gates structural stability.

Drum Gates

Drum gates are operated hydraulically by filling and emptying the flotation chamber beneath the gates, thereby raising and lowering the gates. The structural analysis of a drum gate system will be similar to other structural analyses described, especially for radial gates, except load conditions will only consider aspects applicable to the system. Additional load conditions should consider the hydraulic loads when the reservoir is at a maximum level over the gates that may be based on the design flood or seasonal storm conditions.

Obermeyer Gates

Obermeyer gates are typically being used as adjustable spillway control structures for seasonal storage. The gate system consists of ribbed steel panels that are hinged at their base and are supported on the downstream side by inflatable air bladders clamped to a floor slab. The use of these gates is discouraged for sites susceptible to strong seismic shaking, harsh climates, known vandalism problems, or other conditions that could adversely hamper day-to-day monitoring and operations. These types of gates tend to use sophisticated operating systems, requiring demonstrated resources by the dam owner. The structural analysis of an Obermeyer gate system will be similar to other structural analyses described, especially for radial gates, except load conditions will only consider aspects applicable to the system.

Flashboards and Stoplogs

Flashboards usually consist of boards or structural panels anchored to the crest of the spillway, and stoplogs are boards or structural panels spanning horizontally between slots or grooves recessed into the sides of the supporting piers. Structurally, flashboards and stoplogs are evaluated as discussed above. However, other considerations should be included as part of the reevaluation:

- Methods and equipment for installing and removing these barriers and the reliability and accessibility to removing these gates under potential flood conditions.
- Risks associated with the sequence needed to remove these barriers as well as the risks associated with the potential non-removal.
- Time of use, such as, during the summer season when there is a low probability of design storm events occurring. However, snowmelt may be a factor at higher elevations where peak reservoir inflow can occur in the summer months.
- Structural stability under various loading conditions including seismic loads and overtopping (similar to other gate structures).

VIII. Geotechnical Reevaluation Protocols

DSOD’s inventory of jurisdictional dams are approximately 80 percent earth-type dams, which include earthfill, earth and rockfill, rockfill, and hydraulic fill dams. In general, dams that have a high likelihood of being exposed to strong seismic shaking and a high downstream damage potential are considered to have a higher risk/vulnerability. Flood control and debris dams with temporary storage are considered lower risk/vulnerability since they either impound water for a very short period or maintain a shallow conservation pool. These qualitative vulnerability assessments are independent of the downstream hazard classifications, which do not incorporate probability of the extreme load occurring.

A. Reevaluation Process

In general, a reevaluation of an embankment will first begin with a comprehensive file review as previously described. Common potential failure modes and hazards that a reevaluation will focus on include:

- Dams with a potential fault rupture hazard and potential failure modes caused by embankment cracking resulting from differential lateral and vertical movements, and possible piping and internal erosion if the embankment is not adequately filtered.
- Upstream and downstream slope instability under reservoir operation, including upstream instability due to rapid reservoir drawdown.
- Dam instability and severe deformation during the design earthquake loading (high and low recurrence earthquakes).
    - Significant emphasis will be the potential for liquefaction and general strength degradation of materials under cyclic loading.
- Internal erosion or material migration (piping) potentially caused by:
    - Insufficient filtering and drainage within the embankment.
    - Ineffective cutoff of seepage including grouting, cutoff walls, and the keying in of core materials.
    - Poor compaction and material placement around conduits or other embedded structures, especially around collars.
    - Inadequate treatment of shears and joints and the dam-foundation interface.
- Surface erosion resulting from:

  - Dam overtopping.
  - Inadequate slope protection for potential wind-wave action.
  - Direct rainfall on cohesionless materials.
  - Erosion resulting from inadequate slope protection at the discharge point of spillway or outlet structures.

Material Characterization and Foundation Assessment

Prior to conducting a geotechnical evaluation or assessment, the adequacy of existing geotechnical data and its coverage for characterizing the embankment structure and its foundation must be determined.

Liquefaction and Cyclic Softening

Dynamic soil strength is an important consideration when analyzing the stability of embankment dams subject to seismic loads. Strength loss associated with liquefaction is one of the most critical factors in deficiencies at dams. Evaluating potential for strength loss of soils under dynamic loading primarily considers fines content (percent passing No. 200 sieve) and plasticity index (PI) to determine if a liquefaction or cyclic softening evaluation should be conducted. Estimating a saturated soil's dynamic strength consists of:

- Selecting the applicable evaluation procedure for the soil type.
- Determining the cyclic resistance ratio (CRR) and cyclic stress ratio (CSR) to identify the potential for strength loss.
- Estimating the residual or remolded strength if strength loss is expected, and understanding the extent of potential strength loss in the foundation or fill materials.

The evaluation procedure is based on whether a material is sand-like (liquefaction evaluation) or clay-like (cyclic softening evaluation). This requires determining if the material is fines-controlled (sand-like or clay-like) or coarse-controlled (sand-like) and, if fines-controlled, determining if the material is sand-like or clay-like based on its PI. Consideration must also be given to the degree of saturation, keeping in mind that saturation levels can cycle with reservoir levels. The probability of saturation may be considered to inform a qualitative risk assessment of the likelihood of saturation. Soils known to be dense, heavily over-consolidated, or well-compacted are not likely to be susceptible to liquefaction or cyclic softening.

Details of the evaluation procedure are based on literature related to liquefaction susceptibility from Bray and Sancio (2006) and Boulanger and Idriss (2006 and 2008). While literature often suggest a hard line where materials switch from clay-like to sand-like, it is expected that material properties and behavior might transition from sand-like to clay-like, which is suggested by the differences in the interpretation presented in literature. Materials that may be interpreted as both clay-like and sand-like based on multiple methodologies may be considered transitional or intermediate. DSOD either evaluates these soils conservatively (generally a liquefaction evaluation) or requires additional testing to improve the interpretation.

Coarse-Controlled Soils

A liquefaction triggering evaluation is performed if a soil is likely to be saturated and determined to be coarse-controlled or is fines-controlled with sand-like behavior. This evaluation is usually based on in-situ tests such as SPT, CPT, and BPT because of the difficulty in collecting undisturbed samples of these materials. However, other methods, including cyclic strength testing, may be performed if samples can be obtained. Influence by gravels must be considered when assessing in-situ data. In-situ penetration data will be corrected as required for specific liquefaction evaluations for items such as fines influence, energy, overburden, and static shear stresses.

Numerous liquefaction triggering curves can be used to relate the in-situ data, which provide an estimate of the cyclic resistance ratio (CRR) to the seismic load that can be used to estimate the cyclic stress ratio (CSR). If CSR is larger than CRR, then liquefaction is possible. Recent publications provide means to estimate the probability of liquefaction based on the case-history database that has been used to develop the triggering curves. This may be used to inform a risk assessment with consideration of the probability of the seismic load and the downstream hazard.

If liquefaction triggering is expected, then residual strengths (S_r) will be estimated using correlations between corrected penetration data and S_r. Two forms of empirical relationships have been developed to evaluate residual strength; the first form estimates S_r directly and the second form estimates a ratio of residual strength to the vertical effective stress (stress normalized S_r). Often, both forms of empirical relationships, along with static undrained strengths (to ensure S_r does not exceed the static strength), will be compared to develop a representative S_r and to understand the sensitivity of the analyses to the strength interpretation.

Fines-Controlled Soils

A cyclic softening evaluation is necessary if the soil is determined to be fines-controlled and the embankment is in a seismic area. Retrieval of undisturbed fines-controlled soil samples is possible; therefore, laboratory data can be used to estimate the level of potential cyclic softening. Cyclic softening potential can be determined from direct measurements of cyclic laboratory testing (estimated as a function of the undrained strength determined from monotonic laboratory tests) and in-situ tests that might be correlated to either of the previous measurements through site-specific correlations with the in-situ tests, which require laboratory testing as described above.

A similar method to the liquefaction method will be performed for cyclic softening evaluations in which CRR and CSR are compared (as described by Boulanger and Idriss [2006 and 2008]) to be analogous with liquefaction evaluations although CRR and CSR are estimated differently.

If cyclic softening is expected, then remolded undrained shear strengths (S_{ur}) will be estimated using laboratory data and/or in-situ data. S_{ur} will be developed based on one or more of the following methods:

- Post-cyclic strengths from undrained cyclic laboratory tests.
- Estimated soil sensitivity ($S_t = S_u/S_{ur}$) correlations with vertical effective stress and liquidity index.
- Estimated S_t from CPT or Vane Shear Test data.

Slope Stability Analyses

Slope stability analyses of dams will initially be performed using Limit Equilibrium Analyses (LEA):

- One or more cross sections of the dam will be selected that represent the most critical sections with the least favorable conditions. Cross sections will be developed based on as-built and design drawings, LiDAR, bathymetry, and geotechnical investigations.
- The location and shape of the slip surface will also be considered during analysis. The typical shape of a slip surface is circular. However, other shapes such as piece-wise linear segments or combined curved and linear segments may be considered depending on features that may contribute to preferred failure planes.
- The extent of the slip surface will be limited to critical conditions that impact the safety of the dam and will not consider shallow “maintenance-type” repairs, unless there is concern over progressive slope instability.
- LEAs will be evaluated under normal and critical reservoir operations.
- Pore pressures and the phreatic line within the embankment will be estimated using available piezometric data, seepage observations, and by performing seepage analyses.
- Any potential surcharge loads imposed on the dam should be accounted for in the analyses.

The stability of embankment dams will be analyzed for multiple potentially critical loading conditions that may occur during the life of a dam. These loading conditions will include:

- Steady-State Seepage: This condition represents the long-term, static stability of a dam when the phreatic surface within the dam has been fully established and soil is expected to behave drained. A resulting factor of safety is acceptable if it is greater than 1.5.

- Rapid Drawdown: This condition occurs during a rapid drop in the reservoir elevation where pore pressures within the dam do not have time to dissipated. This evaluation only applies to the upstream slope and is completed using a three-stage approach, which is standard of practice. The resulting factor of safety is acceptable if it is greater than or equal to 1.25.

- Pseudo-Static: This condition is a simplified standard assessment for embankment dams under earthquake loading. The assessment considers a constant horizontal inertial load (k) to represent the effects of earthquake loading. This method is applicable for dams not susceptible to liquefaction and can be used to determine a yield acceleration (k_y) that results in a factor of safety equal to 1.0. A factor of safety of 1.1 is considered acceptable with k = 0.15g, although k_y will often be used to assess the vulnerability of the dam to failure and estimate the potential for deformation.

    - It is important to establish whether drained strengths or undrained strengths should be used. If there is doubt as to whether undrained or drained conditions are applicable, both conditions are considered

- Post-Seismic: This condition predicts if a dam is stable (factor of safety greater than unity) or unstable (factor of safety less than unity) following an earthquake and expected strength loss of soils.

    - If the post-seismic factor of safety using applicable residual strengths is less 1.0, the dam is considered unstable and major reservoir operating restrictions or embankment modifications are required.

    - If the embankment is found stable for post-seismic conditions, the analysis proceeds to an evaluation of the potential deformation that will result from seismic loading.

    - It is possible that an embankment will be found stable under post-seismic conditions, but judged deficient with respect to safety because calculated deformations are deemed unacceptable.

B. Deformation Analyses

Deformation analyses are performed to understand the extent of movement, potential failure mechanisms, and dam and foundation behavior under seismic conditions. Analyses are completed for all slope stability evaluation when the factor of safety or yield acceleration estimated by LEA under seismic conditions is considered marginal.

Deformation analyses may also be performed when dynamic strength loss is expected, due to liquefaction or cyclic softening. The analyses are performed in a sequenced and logical progression starting with simplified evaluations that can be performed quickly, followed by more sophisticated evaluations if deemed necessary.

Simplified analyses are used to estimate a range of deformation using Newmark displacements. These evaluations can be completed using empirical predictive models based on regressions of Newmark deformation analyses using k_y and ground motion intensity measures such as peak ground acceleration, Arias Intensity, spectral acceleration at a given period of interest, and peak ground velocity. A traditional Newmark sliding block analyses can also be completed using selected site-specific time history records; however, this is not generally done as it provides deformations that fall into the range estimated by empirical methods.

Nonlinear deformation analyses (NDA) using numerical methods such as finite element or finite difference may be required if the simplified deformation analyses estimates are considered borderline, if liquefaction or cyclic softening is expected, or if there are other mechanisms that a limited equilibrium analysis cannot capture. NDAs for embankment dams are typically modeled using two-dimensional finite element or finite difference numerical models unless unique embankment, foundation, or abutment geometries exist that warrant three-dimensional modeling. Critical steps for the deformation analyses include:

- Characterizing the embankment zones and foundation with the soil parameters that capture the overall materials behavior.

- Choosing an appropriate constitutive model for each zone along with relevant properties. Constitutive models for dams can typically be categorized into three major models: linear elastic, simple elastic-perfectly plastic, and more complex plasticity models that capture cyclic behavior such as strength loss, shear modulus reduction, and hysteretic damping.

- Considering variability within embankment zones to ensure the modeled parameters are representative of the zone and whether additional sensitivities should be considered.

- Ensuring that the relevant element behavior in the constitutive model is calibrated to laboratory tests and published relationships for the range of conditions expected, and considering monotonic drained and undrained conditions, changes in shear modulus and damping ratio with strain, and cyclic element behavior under uniform loading with a range of overburden stresses and initial static shear stresses.

- Developing the vertical and lateral extents of the model to ensure that the boundaries do not influence the expected behavior of the model, and assessing and balancing the element sizes to sufficiently model the dynamic conditions and provide reasonable computation time.

- Developing time histories for the design earthquake.
    - The number of time histories developed depend on expected embankment behavior and the impact that variability in the results may have on the final assessment.
    - A minimum of three time histories spectrally matched to the maximum credible earthquake (MCE) level will be considered to determine the average response.
- Typically specifying time histories as “outcrop” motions and inputting them at the base of the model using boundary conditions appropriate for the model configuration and site geology.
- Tracking the model behavior at several key locations (at least the model base, embankment base, upstream and downstream slope, and dam crest) to understand the embankment response, the development of excess pore pressure with time (to observe liquefaction); and the stress-strain response and shear strain development.
- Assessing the imposed stresses as they relate to soil strengths, particularly for zones which are expected to lose strength due to cyclic softening and liquefaction.

The general deformation behavior will be assessed as it relates to the available freeboard, the reasonableness of the response, and the impact of deformation on nearby appurtenant structures. In general:

- Deformations of less than 5 feet are considered sustainable provided they are not too large a percentage of the total dam height and do not seriously compromise freeboard.
- Deformations of more than 5 feet are considered serious and may require implementing defensive measures or a reservoir restriction.
- If deformations approach 10 feet, the accuracy of the results become unpredictable and adverse conditions such as transverse cracking become likely yet unpredictable.
- Crest width, zoning, adequacy of filter and transitions zones, available defensive design measures, and embankment slopes will all need to be considered before final decisions are made.

C. Seepage Analyses

Seepage analyses are performed for new and existing dams to assess internal erosion protection measures, and pore pressures within the embankment and foundation for slope stability analyses. Seepage analyses are performed on two-dimensional cross sections using simple, commercial finite element analysis software. Piezometric data within the embankment and foundation are used to supplement or calibrate permeability data for the different embankment zones.

The accuracy of seepage analyses relies heavily on understanding the existing site conditions. Limitations in assessing internal erosion exist where two-dimensional seepage models and/or instrumentation is not located at specific critical areas. Contributing factors to internal erosion should be well understood when performing seepage analyses. Uncertainties in the seepage analysis and instrumentation data must be identified and parametric studies should be employed to better understand the potential impact to seepage results.

Impacts to dam safety when conditions suggest there is potential for internal erosion to occur in the embankment or foundation must be evaluated. Generally, internal erosion is initiated by either backward erosion, concentrated leaking, suffusion, or heave within the embankment or foundation. Conditions that could increase the likelihood of internal erosion include:

- Core zones that have a narrow geometry, are poorly compacted, or placed with a dry of optimum water content (i.e., brittle core zone).
- Foundations with high irregularities, differential settlement, jointed rock, or very steep abutments.
- Presence of conduits through an embankment that have open joints within the conduit or poorly compacted soil around the conduit. The age of conduit and type of conduit (e.g., masonry, brick, corrugated steel) are also critical factors.
- Concrete walls abutting the core zone (e.g., spillway wall, transition from embankment dam to concrete dam).
- Gap-graded soil gradations with a wide percent passing finer particle sizes susceptible to suffusion.
- Cohesionless soils along the downstream slope of an embankment that can be vulnerable to particle movement under high gradients.

Whether internal erosion continues and progresses to a breach after it has initiated depends on multiple factors that should be considered during reevaluation. For example, initiation of internal erosion may be more likely to continue if:

- There is an unfiltered exit point of seepage.

- There are high gradients with dispersive soils, poorly compacted, or cohesionless soils that progress to an enlarging pipe.

- The pipe remains open due to materials supporting the roof of a pipe.

- Upstream zones cannot fill the forming pipe due to homogenous zoning or high permeability upstream zones (e.g., upstream concrete element for seepage control of a homogenous dam).

To prevent internal erosion, adjacent materials and embankment zones must meet filter criteria to ensure that soil particles will not migrate due to seepage forces and, at the same time, allow adequate drainage of seepage. Critical filter zones are typically located at the downstream face of a core zone, at the foundation-downstream shell interface, and possibly at the upstream face of a core zone if drawdown seepage conditions are expected. The suitability of the filter and drain design is reviewed following current state-of-the-practice filter compatibility design requirements.

High phreatic surfaces within the downstream shell of an embankment represent increased pore pressures and may lead to downstream slope instability. It is common to lower the phreatic surface in the downstream shell by designing steep drainage layers of processed materials at the downstream face of the core zone (chimney drains) and horizontal drainage layers at or near the base of the downstream shell (blanket drains). These drainage zones act by intercepting seepage flows from a zone typically containing high gradients and reducing the gradients within the drainage system. The drainage and filter zone must contain a permeability higher than the neighboring upstream zones and must be filter-compatible.

IX. Inundation Map Protocol

Senate Bill 92, signed into law on June 27, 2017, added new sections to the California Water Code requiring owners of all State jurisdictional dams, except low-hazard dams, to prepare inundation maps and Emergency Action Plans (EAP) for their dams and critical appurtenant structures (CAS). Dam owners must submit inundation maps for dams and CAS to DSOD for review and approval. California Water Code, section 6161(a)(3), requires dam owners to develop an EAP based on the DSOD-approved inundation map(s) and submit the EAP to the California Governor's Office of Emergency Services (Cal OES) for their review and approval. Section 6161(d) specifies the following EAP submission deadlines:

- On or before January 1, 2018, if the hazard classification of the dam is extremely high.
- On or before January 1, 2019, if the hazard classification of the dam is high.
- On or before January 1, 2021, if the hazard classification of the dam is significant.

Section 6161(e) also requires dam owners to update the inundation maps and EAP for each dam at least every 10 years or, sooner, when there are significant changes in the dam, CAS, or downstream hazard. Requirements for submitted inundation maps are provided in the California Code of Regulations, Title 23, Division 2, Chapter 1, Article 6, "Inundation Maps."

A. Review and Approval

DSOD engineers review inundation maps to ensure they meet what is required by regulations, and that they are useful for emergency responders and emergency planning purposes. The following steps are typically followed when reviewing inundation maps for a given dam:

Critical Appurtenant Structures Determination

The assigned engineer first conducts a CAS determination based on the available information in DSOD's files and then confirms the CAS determination with the Area Engineer who is generally more familiar with the dam. CAS are barriers or hydraulic control structures that impound the same reservoir as the dam and meet any of the following conditions:

- Is 25 feet or more in height.
- Impounds a minimum of 5,000 acre-feet of water at the maximum possible storage elevation.
- Poses a significant or higher downstream hazard, as determined by DSOD.

Typical critical appurtenant structures include emergency spillways, gated spillways, and saddle dams. In addition to the dam, all CAS are required to have their own inundation map.

Inundation Map Review

DSOD engineers typically use the DSS-WISE Program (Developed by the University of Mississippi's National Center for Computational Hydroscience and Engineering, with funding from FEMA) to verify inundation maps submitted by dam owners. The engineer performs independent analyses to confirm the inundation boundaries and the other pertinent information provided by the submitted maps. The engineer also confirms that the submitted maps meet all the requirements set by the regulations.

In cases when there is a downstream dam that could possibly fail (or overtop) due to the failure of an upstream dam, submitted inundation maps must include the inundation area downstream from the downstream dam. Engineering judgement is used in these cases to determine if the downstream dam (or CAS) will fail, or safely pass flows from the upstream dam failure based on such factors as the height and duration of overtopping.

The engineer reviewing the map also needs to check the dam's downstream hazard potential classification (attachment 11) using the inundation maps and reclassify the dam if warranted. The dam owner is to be informed about the hazard classification change.

If it is determined that submitted inundation maps do not meet requirements set forth by the regulations, the dam owner is informed that revised maps need to be resubmitted for review and approval.

Approval and California Governor's Office of Emergency Services Coordination

The dam owner and Cal OES are notified by letter when DSOD approves a dam's submitted inundation maps.

X. Inspection Protocols

The State is divided into three regions overseen by supervising engineers (Regional Engineers). Each region is further divided into three areas, with each area containing between 100 to 200 dams. The areas are managed by senior engineers (Area Engineers) who are assisted by one or more associate engineers (Field Engineers). Attachment 5 shows the current "Regional and Area Engineer Assignments" by county. The Regional and Area Engineers are required to be registered civil engineers in California.

A. Maintenance Inspections

The California Water Code, Division 3, Part 1, Chapter 4, Article 1, section 6075, provides DSOD with the regulatory authority to supervise maintenance and operation of dams and reservoirs insofar as necessary to safeguard life and property from dam failure or uncontrolled release. This is carried out, in part, through periodic dam inspections conducted by DSOD engineers of all dams under state jurisdiction. Assembly Bill 1270, signed into law on February 26, 2018, amended section 6102 of the California Water Code to require inspections of jurisdictional dams that have a downstream hazard classification of significant, high, and extremely high once every fiscal year (July 1 to June 30). Low-hazard dams must be inspected at least once every 2 fiscal years.

Engineers make contact and arrangements with the dam owners for these inspections. Typically, an attempt is made to vary the inspection time-of-year so that dams are seen under differing storage and seasonal conditions. However, access may be restricted at times of the year due to snow or impassable roads. Specific arrangements may be necessary for safe access to various dam features, particularly large spillway chutes. DSOD's policy is to perform inspections with the dam owner (or representative) and/or their engineer, if they have one employed, whenever possible. This allows the initial findings of the inspection and any recommendations or necessary actions to be discussed in person. The face-to-face contact is also important in establishing relationships so that dam owners know who to contact if they have questions regarding their dam, or in the event of an emergency.

Attachment 6 provides a "DSOD Inspection Protocol Task Checklist," which is described in more detail in the following sections.

Pre-Inspection File Review

Prior to conducting a maintenance inspection, the engineer needs to be familiar with the dam and appurtenances, the history, as-built drawings, key design and construction details, geological data and existing geological conditions, previous inspection observations or required work, ongoing work or studies, and work hazards that will be encountered during an inspection.

Becoming familiar with the dam and its appurtenances, as well as the history of the dam, is the general background information that provides an overview of the performance of the structure and explains the reasons for various features or treatment of past problems. This should include a review of past comprehensive reviews and reevaluation reports, as well as the most recent hydrologic/hydraulic study for the spillway, stability analyses, and instrumentation reports. The design and construction details are important information to help diagnose or anticipate problems with the dam and appurtenances. Deviations from the current state-of-the-practice should be noted; additional analysis may be necessary to determine if a change has resulted in a potentially unsafe dam.

Reviewing the geological data and understanding the geological conditions provides important context for the design and performance of the dam, as well as informing the engineer of geologic hazards (landslides, for example). The engineer will pay attention to the foundation materials, the variability of the foundation, and how the foundation was prepared for the construction of the dam or appurtenances. Adverse or unusual foundation conditions should be noted for follow-up during the file review.

The previous inspection reports are reviewed for trends or conditions that need to be noted, like seepage areas and quantities at similar reservoir stage, descriptions of ongoing problems, and the completion or progress of requested actions. Recurrent problems need to be understood, or investigated, to determine the potential cause(s) and remediation(s).

A thorough review of DSOD's files on the dam is also necessary to ensure that the engineer is aware of the status of any ongoing studies or projects involving the dam, as well as the conclusions of previous work. Temporary or permanent restrictions, or any seasonal restrictions, should be noted so that the engineer can ensure the dam owner is in compliance with the terms and conditions of the Certificate of Approval.

Lastly, DSOD's documentation on site-specific personnel safety hazards for each dam needs to be thoroughly reviewed before leaving the office and heading out to the field so the engineer is aware of potential hazards at the dam and any special safety equipment that is needed to carry out the inspection.

Inspection

The weather conditions at the time of the inspection are noted (and preceding it if it has a bearing on the observations such as ponded water at the toe of the dam following recent precipitation or snowmelt). The reservoir level during the inspection is recorded, as are any contacts made during the inspection.

The field inspection involves a thorough walkover of all the accessible features of the dam and appurtenant structures (e.g., spillways, saddle dams). The walkover needs to be systematic so all the exposed features are viewed. At a minimum, the dam crest, downstream groins, and downstream toe area are walked over, assuming adequate personnel safety. If portions of the dam cannot be inspected and are not viewable, arrangements are made for special inspections of these features on a set schedule (for example, at a concrete arch dam the owner may be required to have a boat available so the upstream face can be closely inspected). When necessary, the dam owner is required to employ a specialty contractor to perform ROV, drone, climb/rope, or dive inspections of normally inaccessible features. The dam owner is then required to formally submit the findings along with an engineer's evaluation for DSOD's review and concurrence.

Special attention is given to previously noted defects, areas of distress, and any changed conditions. The observation of changed conditions is an important aspect of any inspection, followed by the application of engineering judgement to evaluate the consequences and necessity for action. The dam owner (or representative) is asked about any differences and about general performance since the last inspection.

Embankment and rockfill dams are evaluated for consistency of line and grade, presence of slumping or cracking, material erosion or slides, and other evidence of structural distress. If present, slope protection measures are evaluated for uniformity. For rockfill dams, the upstream liner is inspected for signs of deterioration and leakage. Where some portion of dam freeboard is provided by a parapet wall, the wall panel surfaces and joints are evaluated for deterioration and differential movement. Embankment drains and seepage locations are inspected and compared to prior measurements or descriptions. New or changed seepage conditions are investigated and documented, and additional monitoring is prescribed as necessary. The dam, abutments, toe area, and foundation are evaluated for stability as well as seepage, based on the review of geologic data and conditions.

Concrete dams are evaluated for alignment, visible concrete deficiencies, cracking, or other signs of structural distress. The exposed surfaces are checked for deterioration from age and weathering, for structural cracking caused by overstress from applied loads, and evidence of shrinkage or differential movements. Movement along vertical and horizontal axes, and along joints, is checked for and evaluated. The abutments are checked for instability or excessive weathering, and the accessible portions of abutment contacts are inspected. If present, galleries are inspected and evaluated for visible deterioration, structural cracking, and differential movements. It is verified that internal drainage features are functional and performing as designed. Drains and seepage areas on the downstream side of the dam are also inspected, and comparisons are made to past inspections. Additional monitoring is prescribed as necessary. If accessible, the foundation is examined for undercutting at the downstream toe. The assessments made during the inspection are based on knowledge of the geological data and conditions.

Vegetation management is evaluated at all dams. All woody vegetation must be removed from the dam crest and faces, and within at least 5 to10 feet of the dam groins and downstream toe contact. Vegetative root systems can be detrimental to the safety of the dam, and excessive vegetation prevents a thorough inspection. Mature trees that have been present for many years are evaluated during inspections on a case-by-case basis and are generally allowed to remain, provided they are maintained by pruning and remain healthy. DSOD's experience is that removal of large, established, healthy trees can be more detrimental to the dam than good. If a tree is dying, or there is potential for it to fall and uproot, the dam owner is required to remove it, the root ball, and roots down to ½-inch diameter, then properly backfill the disturbed area with compacted fill. Landscaping with ivy or ice plant is no longer allowed because their thick growth prevents an inspection of the embankment for seepage and instability; the necessary irrigation also masks seepage. Grass can remain on embankment dams as it provides good erosion protection, but if it becomes too tall, periodic mowing is required to allow a proper inspection of the embankment and discourage rodent activity.

At concrete structures, vegetative growth in joints, behind walls, and in drain or weep holes can cause movement, spalling, and increased water pressures. Vegetation that appears in these areas is to be periodically removed. All woody vegetation near concrete structures must be removed within, at least, 5 to 10 feet.

The dam is inspected for evidence of rodent activity. Generally, rodent activity is only a concern or problem at embankment dams. DSOD does not direct dam owners on how to control rodents, but requests that they address identified rodent activity and break up and backfill existing dens with compacted fill. Many dam owners employ professional rodent abatement specialists to periodically visit their dam. Fencing large animals (such as cattle) off the dam and appurtenances is encouraged, particularly in the wet months as they can cause damage to structures and embankment erosion that can lead to instability.

Spillway approaches, control sections, and downstream channels must be clear and unobstructed by vegetation, soil/rock deposits, or debris to ensure full passage of flood flows. Concrete spillways are inspected for conformance to line and grade, evidence of distress or movement, and severity of cracking and spalling. Panel alignment and joint condition is evaluated, and grinding or sealing may be prescribed based on local conditions. It is verified that all drains are clear and flowing as intended. The foundation at the toe of the spillway structure is examined for evidence of undercutting. For spillways with gates or other control features, the gate faces, structural members, connections, seals, and protective coatings are visually inspected for corrosion and deformation from a safe vantage point; more detailed climbing inspections may be periodically required of the dam owner. The hoists, cables, and operating equipment, including backup or auxiliary devices and power, are evaluated for general condition and operability.

Outlet systems are evaluated for general condition and for operability of the upstream and downstream control(s). The integrity of the controls and trashrack, when visible, are evaluated. Where present, outlet tunnels and headwalls are inspected for stability and integrity. Pipes in carrier tunnels are inspected for corrosion and deformation, and any structural saddles, hangers, joints, wrappings, or coatings are inspected for damage and wear. Camera inspections inside outlet conduits are requested when judged necessary to ensure that the outlet is not creating an unsafe condition beneath or within the embankment. The need and frequency for such inspections are determined by DSOD engineers based on conduit age, construction details (i.e., type of pipe, encasement, etc.), historical performance, and other factors. The downstream outlet channel must be kept free draining and clear of vegetation or debris to ensure the maximum possible release can be made in an emergency.

DSOD has historically required dam owners to operate yearly all outlet valves and gates necessary to draw down the reservoir in an emergency, and in the presence of a DSOD engineer every 3 years. Assembly Bill 1270 now requires dam owners to operate “critical outlet and spillway control features” on an annual basis and to demonstrate their full operability in the presence of DSOD engineers every 3 years, or as directed. Dam owners are encouraged to keep a log documenting when controls were last cycled for quick reference. When the dam owner must operate a control feature in DSOD’s presence, arrangements are made in advance to avoid disturbing the dam owner’s reservoir operations or to accommodate any permitting constraints.

“Critical outlet controls” are defined by DSOD policy as all outlet valves and gates that are associated with the outlets, pipes, or tunnels that would be used to drain a reservoir in an emergency. These can be either high- or low-level controls that discharge water at or from different elevations within the reservoir. Many dams (particularly larger dams) have redundant valves and gates in series as an added safety measure. For these cases, all valves and gates must be fully cycled. Partial cycling of valves and gates is not generally allowed, even if a dam owner can show through engineering calculations that DSOD’s drawdown criteria can be met, since this is not a good maintenance practice. In DSOD’s experience, controls that are not operated fully cycled experience long-term maintenance issues. If fully opening a control presents downstream flooding issues, DSOD works with the dam owner to come up with a solution to meet the cycling requirements. A possible solution often includes installing a temporary or permanent redundant control so a control can be fully cycled while maintaining downstream releases at an acceptable level. Small dam owners are encouraged to routinely fully cycle the outlet controls during every inspection.

“Critical spillway controls” are defined as gates, stoplogs, or other obstructions that are installed in the spillway to raise the maximum storage level seasonally (spring through fall months), or year-round. Dam owners with seasonal spillway controls can usually and easily meet the cycling requirements, as they are required to fully open/remove the controls before every winter. For large control features that impound water year-round, such as radial gates, full cycling can cause downstream flooding or severely impact reservoir operations. In these cases, the dam owner is required to install temporary stoplogs, cycle the feature at a time of year when the reservoir level is low, or make operational arrangements to temporarily lower the reservoir to prevent downstream flooding. DSOD will allow some adjustments to the annual full cycling requirement on a case-by-case basis after considering factors such as reliability, age, and overall condition of the control feature, as well as to the extent that the control feature is necessary for passing flood flows and emergency drawdown.

A final item to review during the inspection is the observable condition of any instrumentation. The most common instruments at dams are survey monuments, piezometers, and seepage measuring devices (weirs or flumes). DSOD engineers investigate any instruments that were identified during their pre-inspection file review of instrumentation reports that may be showing unusual data or trends. DSOD engineers also inquire with the dam owner if there are any instruments that are acting erratically or providing abnormal data. Typically, instruments are spot-checked, survey monuments are observed for signs of disturbance, piezometers are inspected to ensure they are secure and protected, and seepage measuring devices are evaluated for damage, silt accumulation, and leakage or bypass flows. Seepage measuring devices are generally read during the inspection; piezometers are periodically read with the dam owner during the inspection.

At the end of the inspection, findings are reviewed in the field with the dam owner (or representative) to explain and make clear what actions are required. In addition, the implications for dam safety of any action item are explained to the dam owner (or representative) so they have a clear understanding of why the work is needed. The engineer also gathers general information on changes of ownership or staff, changes in the normal operation of the dam and reservoir, and asks about any unusual events since the last inspection.

Maintenance Inspection Report

Following the inspection, a report (attachment 7) is prepared containing all the factual observations, conclusions, recommendations, comments, photographs, sketches, and any other pertinent information. DSOD policy is to comment on all the features that were observed, both positively and negatively, as well as mentioning what was not reviewed and why. The report contains general information on the dam, the weather during the inspection, reservoir water surface elevation, and who was contacted during (or before and after) the field inspection.

The report contains a section summarizing important observations resulting from the inspection, recommendations made, and any actions taken or required. These summarizations are supported in the body of the report. Timelines for completing the work are given, from immediately to within a specific period, depending on the implications that not completing the work has on the safety of the dam. For example, an inoperative outlet will need to be repaired immediately, but a dam owner may be required to remove sparse vegetation growth every few years. Important ongoing work (applications, studies, etc.) is typically also mentioned. All recommendations, actions, and ongoing work are tracked until each item has been satisfactorily addressed by the dam owner.

The overall conclusion of the inspection report is generally one of the following (i.e., “The dam is <u>judged</u> to be”):

1. Safe for continued use,

2. Safe for continued use with some qualifying statement (i.e., pending the review of some aspect such as seismic stability, etc.),

3. Safe for continued use at a restricted level, or
4. Unsafe to store water with some qualifying statement of reason.

The following wording is typical: "From the known information and visual inspection, the dam, reservoir, and appurtenant structures are judged safe for continued use."

In the body of the report, the inspection observations of the various dam features are documented and compared with those of past inspections. Statements are made about defects judging whether they are stable and unchanged or progressing, and whether observations are within the anticipated or design limitations.

About 450 jurisdictional dams have instrumentation, and dam owners are required to submit instrumentation reports to DSOD with the data and an engineer's evaluation. As part of the maintenance inspection report, the engineer conducts an in-depth review of the data contained in the instrumentation report. The number and type of instruments are documented, along with the monitoring frequency. The engineer evaluates any short- and long-term trends, performance relative to design benchmarks (e.g., phreatic surface), and any concerning measurements. Obsolete or nonfunctional instrumentation is noted. The review also incorporates into their report any information learned during the inspection through observations or discussions with the dam owner.

The engineer makes an overall statement assessing whether the instrumentation data indicates the dam is performing satisfactorily or unsatisfactorily. An overall assessment of the instrumentation network's adequacy is also made and, if necessary, requires that additional instruments be added. Finally, further evaluation and/or action items are requested of the dam owner. These requests can vary from the dam owner correcting formatting errors in the instrumentation report to requiring an evaluation of an unusual instrument reading by the dam owner's engineer. If the additional information is learned during the inspection, in regard to instrumentation, or the in-depth review of the instrumentation data indicates an immediate dam safety concern, a letter is sent requiring action by the dam owner.

Maintenance Inspection Follow-up

A copy of the reviewed and approved inspection report is mailed (and/or emailed) to the dam owner (or representative). The report serves as the notification to the dam owner of items that need action at their dam. A follow-up letter may also be warranted depending on the type and severity of action items noted in the report. A letter is normally sent for recurring routine maintenance items that are not being satisfactorily addressed between inspections, or if there is dam safety deficiency identified that requires immediate attention by the dam owner. If necessary, the dam owner is ordered to complete work in accordance with the California Water Code, and a reservoir restriction may also be ordered until the deficiency is corrected.

If conditions are noted during the inspection that warrant additional or immediate technical investigations or analyses, DSOD Branch Chiefs and the Division Chief are informed by the Regional Engineer and appropriate actions taken.

Lastly, the engineer ensures that the dam owner's contact information, the dam's condition assessment, and hazard classification are current or updated, if needed. Definitions for condition assessment and hazard classifications are in attachments 10 and 11, respectively. In order to ensure DSOD engineers are aware of personnel safety hazards and special safety equipment needed for future inspections, documentation on site-specific safety hazards is also reviewed and updated, if needed.

B. Construction Inspections

California Water Code, Chapter 4, Article 1, section 6075 states "The department, under the police power of the state, shall supervise the construction, enlargement, alteration, repair, maintenance, operation, and removal of dams and reservoirs for the protection of life and property as provided in this part." Section 6400, further states "the department shall make continuous or periodical inspections at state expense for the purpose of securing conformity with the approved plans and specifications..."

DSOD engineers perform construction inspections on a periodic or as-arranged basis to ensure that work is being constructed per the approved plans and specifications. The dam owner's resident engineer will contact DSOD to request inspections of certain critical items such as foundations and concrete reinforcing steel. A 72-hour (3 business days) advance notice to schedule an inspection is typically required. Design engineers and engineering geologists are consulted throughout construction to provide additional technical expertise. The number of construction inspections for any given project is dependent upon the complexity of the project, the quality of oversight by the dam owner's resident engineer, and the contractor's demonstrated compliance with the approved plans and specifications.

When conducting construction inspections, DSOD engineers determine whether the contractor is complying with the approved plans and specifications. Critical project elements related to dam safety are inspected regularly to ensure work is progressing in a satisfactory manner. Earthwork and concrete placements are monitored on a periodic or continuous basis, depending on the complexity of the project or the critical nature of the feature being constructed. The engineer works with the dam owner's staff to correct deviations or address minor changes that need to be made due to differing site conditions or other issues. Major changes to the plans or specifications are made via a formal submittal and must be approved by DSOD's Chief. Severe non-compliance issues can result in a "Stop Work" order pursuant to section 6406 of the California Water Code. The DSOD engineer also monitors the dam owner's quality control program to ensure that material properties are meeting the criteria laid out in the approved specifications.

The "Inspection of Dam Construction" report (attachment 8) documents contacts made, important recommendations or approvals that were made, and a narrative of the inspection that describes in greater detail the work that was inspected and/or approved. Photographs of key features or conditions are provided for future reference.

C. Post-Earthquake Inspections

DSOD engineers and engineering geologists receives earthquake notifications via the U.S. Geological Survey "ShakeCast" software, which has been customized to provide notifications based on the estimated level of shaking at damsites. Fragility levels are assigned to each dam so that dams more vulnerable to earthquake damage have a lower action-level threshold. The software generates a list of dams in general order of priority for contact and inspection. Emails are automatically sent to the relevant Area and Regional Engineers, in addition to DSOD Branch Chiefs and Division Chief.

When notified, the Area Engineer(s) immediately begin contacting the dam owners. Based on the severity of the shaking estimated for a given dam, the dam owner may be required to make an immediate inspection, make an inspection in the next several hours, or make an inspection within the next day. Dam owners are then required to report back to DSOD with their inspection findings. DSOD personnel may accompany the dam owners on these inspections, depending on availability and access, or may make a follow-up inspection. For larger earthquakes, inspection teams are assembled that consist of field and design engineers, and engineering geologists.

Post-earthquake inspections focus on earthquake-induced damage, signs of structural distress, and any changes to the foundation or dam that could indicate a hidden problem. Embankments are evaluated for cracking, slumping, and other signs of movement. Concrete dams are checked for signs of structural distress (cracking, spalling) and any signs of movement. Spillways are checked to verify there are no signs of instability and that they are clear and fully functional. It is verified the outlet works remain fully functional. Seepage is evaluated for changes in quantity, quality (cloudiness), and if any new seepage locations are identified. If a dam is equipped with instrumentation, readings are taken and evaluated. It is common for seepage and piezometer levels to change suddenly after an earthquake, even at relatively distant dams. Enhanced monitoring is often necessary in the days and weeks following an earthquake. A "Post-Earthquake Inspection Checklist" (attachment 9), includes a list of items that need to be checked during an inspection.

If a dam has been damaged, it will be judged whether it is still safe to continue impounding water. The dam owner may be required to immediately lower the water level or drain the reservoir entirely. A temporary reservoir restriction will be put in place until the damage has been investigated and repaired. Follow-up inspections and communications with dam owners of damaged dams is as needed.

In addition, a Memorandum To File that includes a summary of post-earthquake inspections, including a summary of the overall DSOD response, is created to document earthquake events that require action by DSOD.

D. Incident Inspections

Incident inspections are often initiated following the discovery of significant dam safety concerns. Dam incidents are generally reported to DSOD by the dam owner, an emergency management agency, or by concerned citizens. Generally, a multidisciplinary team of engineers and engineering geologists is promptly dispatched to the dam. Following the incident, a memorandum or report is written that documents the inspection findings, recommendations, and any actions taken.

XI. References

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XII. Attachments

Attachment 1
DSOD Fault Activity Guidelines for use in Deterministic Fault Activity Assessments

Active Seismic Sources (considered seismic sources for dam design or reevaluation)
A Holocene Active Fault is a fault on which surface or subsurface displacement has occurred within the Holocene epoch. Holocene activity is demonstrated by one or more lines of evidence including the following: Holocene (last 10,000 years) stratigraphic displacement; Geomorphic evidence of Holocene displacement or tectonism; Geodetically measured tectonism or observations of fault creep; or Well-located zones of seismicity.

Latest Pleistocene Active Fault is a fault on which no evidence of Holocene displacement is known, but which has experienced surface or subsurface displacement within the last 35,000 years. Latest Pleistocene activity is demonstrated by one or more of the following lines of evidence: Stratigraphic displacement to units 11,000 to 35,000 years; or Geomorphic evidence of Latest Pleistocene displacement or tectonism.

A Conditionally Active Seismic Sources (treated as a seismic source for dam design or reevaluation because of incomplete or inconclusive evidence, with the understanding that additional investigation or analysis could change the designation)

A Conditionally Active Fault meets one of the following criteria: A Quaternary active fault (one that has experienced surface or subsurface displacement within the last 1.6 million years) with a displacement history during the last 35,000 years that is not known with sufficient certainty to consider the fault an active or inactive seismic source; A pre-Quaternary fault which can be reasonably shown to have attributes consistent with the current tectonic regime. *Example...* In the foothills of the Sierra Nevada geomorphic province Mesozoic faults are considered Conditionally Active Seismic Sources unless proven otherwise.

Inactive Seismic Sources (not considered for dam design or reevaluation)

Inactive Fault: a fault that has had no surface or subsurface displacement within the last 35,000 years. Inactivity is demonstrated by a confidently-located fault trace, which is consistently overlain by unbroken geologic materials 35,000 years or older, or other observation indicating lack of displacement. Faults that have no suggestion of Quaternary activity are presumed to be inactive.

WAFraser 10/1/95

Attachment 2

DSOD Earthquake Hazard Matrix

		SLIP RATE			
		Very High 9 mm/yr or greater	**High** 8.9 to 1.1 mm/yr	**Moderate** 1.0 to 0.1 mm/yr	**Low** Less than 0.1 mm/yr
HAZARD CLASS	**Extremely High**	84th	84th	67th to 84th	50th to 84th
	High	84th	84th	50th to 84th	50th to 84th
	Significant	67th to 84th	50th to 84th	50th to 67th	50th
	Low	50th	50th	50th	50th

Used to Select the Appropriate Safety Evaluation
Earthquake (SEE) Deterministic Level of Design
September 2017

Attachment 3

Classification of Faults and Fault Displacements

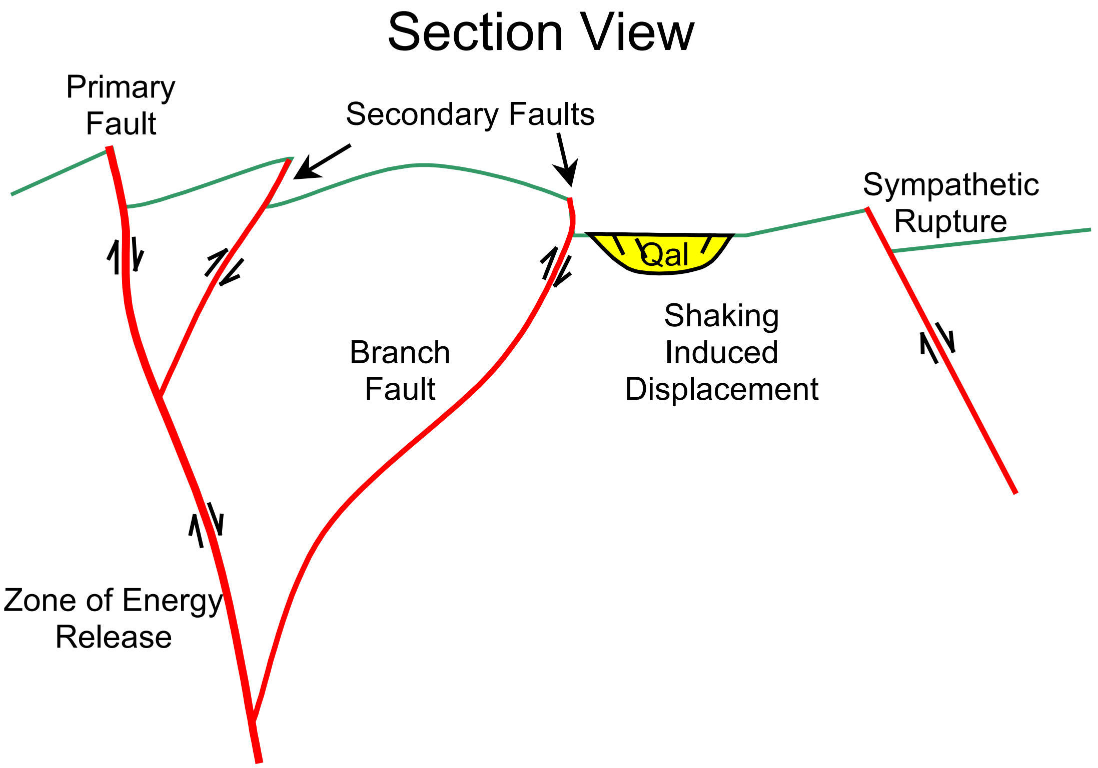
Primary Fault and Primary Fault Displacement: The primary or principal fault is the zone of energy release of an earthquake where the majority of coseismic displacement occurs. Primary fault displacement is the amount and direction of slip which has occurred or is expected to occur on the primary fault in a single earthquake.

Secondary Fault and Secondary Fault Displacement: Secondary faults are subordinate fault traces closely related to the primary fault in either plan or at depth. Secondary fault displacement is the amount and direction of slip which has occurred or is expected to occur on the secondary fault in a single earthquake. A Branch fault is secondary fault trace at some surface distance from the primary fault.

Sympathetic Fault Rupture: is a passive displacement *triggered* along a pre-existing fault that is completely isolated from the primary fault.

Shaking-Induced Displacements: are ground cracks produced by intense shaking or compaction of unconsolidated sediments due to earthquakes. Shaking-induced displacements can include landslides in natural material and liquefaction settlements.

Fault Creep: is the continuous strain release along the near-surface portions of a fault.



Attachment 4

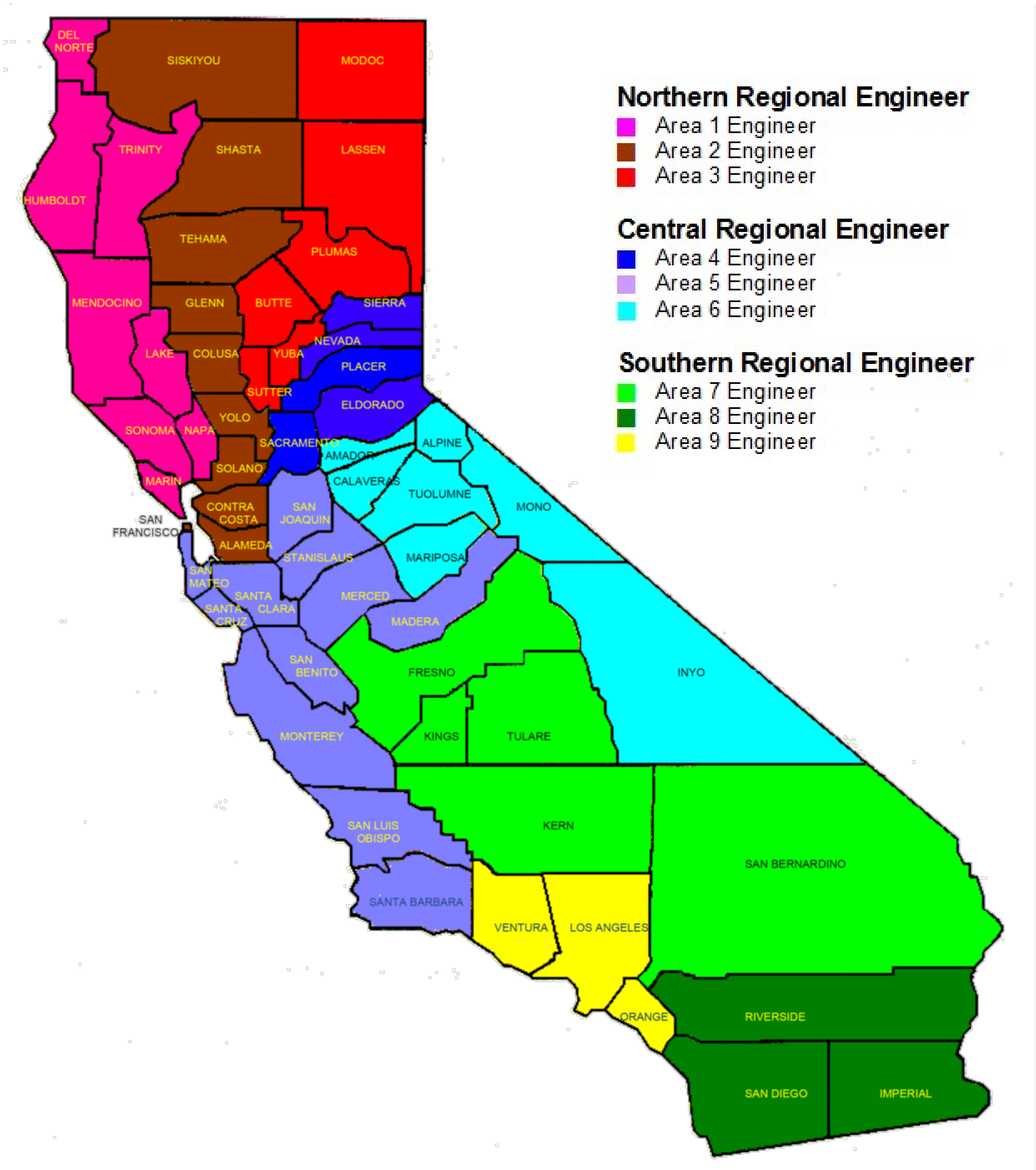
DSOD Fault Displacement Consequence Hazard Matrix

	Very High Slip Rate 9 or greater mm/yr	**High Slip Rate** 8.9 to1.1 mm/yr	**Moderate Slip Rate** 1.0 to 0.1 mm/yr	**Low Slip Rate** less than 0.1 mm/yr
Hazard Class **Extremely High**	Average Displacement to mean plus ½ sigma of Average Displacement	Average Displacement to mean plus ½ sigma of Average Displacement	Average Displacement	Average Displacement to mean minus 1 sigma of Average Displacement
Hazard Class **High**	Average Displacement to mean plus ½ sigma of Average Displacement	Average Displacement to mean plus ½ sigma of Average Displacement	Average Displacement	Average Displacement to mean minus 1 sigma of Average Displacement
Hazard Class **Significant**	Average Displacement	Average Displacement	Average Displacement to Mean minus 1 sigma of Average Displacement	Mean minus 1 sigma of Average Displacement
Hazard Class **Low**	Mean minus 1 sigma of Average Displacement	Mean minus 1 sigma of Average Displacement	Mean minus 1 sigma of Average Displacement	Mean minus 1 sigma of Average Displacement

Used to Determine the Appropriate Fault Displacement
September 2017

Attachment 5

DIVISION OF SAFETY OF DAMS
REGIONAL AND AREA ENGINEER ASSIGNMENTS



Attachment 6

DSOD Inspection Protocol Task Checklist

Scheduling		
	Task	**Notes**
☐	Contact Owner/Representative	Every effort must be made to have Owner/Representative present
☐	Discuss special arrangements needed with Owner Representative (cycle outlet controls, safe access)	
☐	Discuss access issues and any weather concerns	
Pre-Inspection Review		
	Task	**Notes**
☐	Familiarize with dam and appurtenances as well as history	Construction issues and long-term maintenance issues need to be reviewed
☐	Review of past comprehensive and reevaluation reports.	Note any items that require special attention/inspection
☐	Review hydrology and Spillway Summary Sheet	Note type of design flood used and residual freeboard
☐	Review latest instrumentation report	Note unusual readings or potential problems with instruments
☐	Review as-builts and key design and construction details	Particular attention is spent on construction joint and drainage system details
☐	Review geologic data and existing geologic conditions	Review foundation/abutment conditions/preparation, variability in foundation materials, compaction, etc.
☐	Review of past inspection reports	Recurrent problems need to be understood, and investigated, if needed
☐	Review and familiarize with ongoing studies/work	
☐	Review Certificate of Approval for approved seasonal water levels.	Cross-check with correspondence file for temporary restrictions.
☐	Review Workplace Assessment Form	Note any safety concerns or equipment needed for inspection
☐	Review Inundation Map	Check for new downstream development
Field Inspection		
	Task	**Notes**

☐	Note reservoir level and weather conditions	
☐	Visual inspection of dam faces, crest, abutments, toe areas.	Note defects, changed conditions, maintenance required.
☐	Vegetation Control	
☐	Rodent Control	
☐	Visual inspection of spillway(s)	No obstructions, cycle “critical” controls (1-year, 3-year), compliance with seasonal restrictions
☐	Visual inspection of outlet controls(s)	Cycled controls (1-year, 3-year)
☐	Visual inspection of all other appurtenances	
☐	Seepage	Note seepage areas and drain measurements
☐	Instrumentation	Spot check condition of instruments
☐	Review inspection findings with owner or representative.	Make requests for additional maintenance or monitoring, as needed. Explain reasons for recommendations and actions.
☐	Review owner contact information	
☐	Review EAP information with Owner	Suggest EAP updates to owner if needed.
Inspection Report and Follow-up		
	Task	**Notes**
☐	Complete Inspection Report (DWR Form 1261)	
☐	Mail/email inspection report, if letter is not required.	
☐	Engage DEB and GB if deficiency is identified during inspection that requires immediate action and/or technical consultation is needed.	Branch and Division Chief is kept apprised of developments.
☐	Write maintenance or deficiency/ordered/restriction letter to send with report, if necessary	Generally warranted for recurrent maintenance issues and deficiencies that require immediate attention
☐	Area Engineer tracks work needed at dams and timelines for completing by own processes	Schedule follow-up inspection(s) when needed.
Inspection Report and Follow-up (cont.)		
☐	Verify/Update Responsible Persons Sheet with Dam Owner Information	
☐	Verify/Update Workplace Hazard Form	
☐	Update Downstream Hazard and Condition Assessment Classification, if needed	

Attachment 7

STATE OF CALIFORNIA
CALIFORNIA NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
DIVISION OF SAFETY OF DAMS

INSPECTION OF DAM AND RESERVOIR IN CERTIFIED STATUS

Name of Dam ______________________________ Dam No. ________________________ County ________________________

Type of Dam ______________________________ Type of Spillway ____

Water is ________________ feet ________________ spillway crest and ________________ feet ________________ dam crest.

RWS – 2,915

Weather Conditions ____

Contacts Made ____

Reason for Inspection ____

Important Observations, Recommendations or Actions Taken

Conclusions

From the known information and visual inspection, the dam, reservoir, and the appurtenances are judged safe for continued use.

Observations and Comments

Dam

Spillway

Outlet

Seepage

Instr.

Inspected by ______________________________

Photos taken? Yes _____ No _____

Date of Inspection ______________________________

cc for ______________________

Date of Report ______________________________

Attachment 8

STATE OF CALIFORNIA
CALIFORNIA NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
DIVISION OF SAFETY OF DAMS

INSPECTION OF DAM CONSTRUCTION

Name of Dam: Dam No.

Contacts Made: County:

Stage of Construction:

Important Observations, Recommandations, or Actions:

Conditions Noted and Remarks:

Inspection by:
Date of Inspection:
Date of Report: 12/25/19
Photos Taken? Yes/No

DWR 624 (sub) (Rev. 1/98)

Attachment 9

STATE OF CALIFORNIA
CALIFORNIA NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
DIVISION OF SAFETY OF DAMS

POST-EARTHQUAKE INSPECTION CHECKLIST

Name of Dam ______________________ Dam No. ________________ County __________________

Type of Dam ______________________ Type of Spillway ______________________________

Water is ________ feet __________ spillway crest and _______ feet __________ dam crest. WSEL: ________

Earthquake Date ______________ Magnitude ____________ Instrumental Intensity at Dam ______________

Weather Conditions ____

Contacts Made ____

IMPORTANT OBSERVATIONS, RECOMMENDATIONS, OR ACTIONS TAKEN		
Select one		*Descriptions, actions, and recommendations:*
☐	No damage	
☐	Minor damage	
☐	Major damage	

DAM(S)*		
Item		*Description of damage*
Transverse Cracking	Y ☐ / N ☐	
Longitudinal Cracking	Y ☐ / N ☐	
Spalling	Y ☐ / N ☐	
Offsets	Y ☐ / N ☐	
Slumps/Slides	Y ☐ / N ☐	
Sinkholes/Depressions	Y ☐ / N ☐	
Settlement	Y ☐ / N ☐	
Horizontal Displacement	Y ☐ / N ☐	
Abutment Contacts	Y ☐ / N ☐	
Abutments	Y ☐ / N ☐	
Toe Area	Y ☐ / N ☐	
Galleries	Y ☐ / N ☐	
Adits	Y ☐ / N ☐	

Other	Y ☐ / N ☐	

*Note if other than main dam.

SPILLWAY(S)*		
Item		*Description of damage*
Blockage	Y ☐ / N ☐	
Cracking	Y ☐ / N ☐	
Spalling	Y ☐ / N ☐	
Offsets	Y ☐ / N ☐	
Slumps/Slides	Y ☐ / N ☐	
Settlement/Movement	Y ☐ / N ☐	
Control Structure(s)	Y ☐ / N ☐	
Gate Controls	Y ☐ / N ☐	
Operability	Y ☐ / N ☐	
Other	Y ☐ / N ☐	

*Note if other than primary spillway.

OUTLET		
Item		*Description of damage*
General Condition	Y ☐ / N ☐	
Offsets/ Cracking	Y ☐ / N ☐	
Leakage	Y ☐ / N ☐	
Controls	Y ☐ / N ☐	
Operability	Y ☐ / N ☐	
Other	Y ☐ / N ☐	

SEEPAGE		
Item		*Description of damage*
New Seepage	Y ☐ / N ☐	
Boils	Y ☐ / N ☐	
Seepage quantity vs typical	Y ☐ / N ☐	
Seepage turbidity vs typical	Y ☐ / N ☐	
Other	Y ☐ / N ☐	

INSTRUMENTATION	
Item	*Description of damage*
Readings taken Y ☐ / N ☐	
Settlement Y ☐ / N ☐	
Change in Seepage Y ☐ / N ☐	
Change in pore pressure levels Y ☐ / N ☐	
Other Y ☐ / N ☐	

OTHER	
Item	*Description of damage*
Access Y ☐ / N ☐	
Other Y ☐ / N ☐	

Diagram showing location of noted areas:

Attachment 10

Dam Condition Assessment Definitions

California DSOD uses the U.S. Army Corps of Engineers' National Inventory of Dams (NID) condition rating definitions, with additional criteria, as a guideline in assigning condition assessments. The NID database condition assessment rating definitions, with DSOD's additional criteria, are as follows:

- **SATISFACTORY** – No existing or potential dam safety deficiencies are recognized. Acceptable performance is expected under all loading conditions (static, hydrologic, seismic) in accordance with the applicable regulatory criteria or tolerable risk guidelines
- **FAIR** – No existing dam safety deficiencies are recognized for normal loading conditions. Rare or extreme hydrologic and/or seismic events may result in a dam safety deficiency. Risk may be in the range to take further action. Additional DSOD criteria can include the following:
    - Dam has a long-standing deficiency that is not being addressed in a timely manner
    - Dam is not certified and its safety is under evaluation
    - Dam is restricted and operation of the reservoir at the lower level does not mitigate the deficiency
- **POOR** – A dam safety deficiency is recognized for loading conditions that may realistically occur. (Loading conditions refer to the stress to a dam from seismic activity or major storm events.) Remedial action is necessary. A poor rating may also be used when uncertainties exist as to critical analysis parameters that identify a potential dam safety deficiency. Further investigations and studies are necessary. The DSOD also requires that a dam with multiple deficiencies or a significant deficiency that needs extensive remedial work will be rated poor.
- **UNSATISFACTORY** – A dam safety deficiency is recognized that requires immediate or emergency remedial action for problem resolution.
- **NOT RATED** – The dam has not been inspected, is not under State jurisdiction, or has been inspected but has not been rated.

Attachment 11

Dam Downstream Hazard Potential Classifications

The downstream hazard is based solely on potential downstream impacts to life and property should the dam fail when operating with a full reservoir. This hazard is not related to the condition of the dam or its appurtenant structures.

- **LOW** - No probable loss of human life and low economic and environmental losses. Losses are expected to be principally limited to the owner's property.
- **SIGNIFICANT** - No probable loss of human life but can cause economic loss, environmental damage, impacts to critical facilities, or other significant impacts.
- **HIGH** - Expected to cause loss of at least one human life.
- **EXTREMELY HIGH** – Expected to cause loss of at least one human life and one of the following:
    - Result in an inundation area with a population of 1,000 persons or more.
    - Result in the inundation of facilities or infrastructure, the inundation of which poses a significant threat to public safety as determined by the department on a case-by-case basis.