Memorandum

To: Mr. Paul Dunlap, California Department of Water Resources

From: Oroville Dam Spillway Incident Independent Forensic Team

Date: September 5, 2017

Re: Interim Status Memorandum

Introduction – The Independent Forensic Team (IFT)[1] is conducting a thorough review of available information to develop findings and opinions on the chain of conditions, actions, and inactions that in February 2017 caused the damage to the service spillway[2] and emergency spillway at Oroville Dam, and why opportunities for intervention in the chain of conditions, actions, and inactions were not realized.

On May 5, 2017, the IFT published a memorandum presenting its preliminary findings concerning candidate physical factors potentially contributing to damage of the service and emergency spillways. At that time, the IFT was still in the information gathering and early review stages of its work, and had not developed any conclusions. The preliminary lists of candidate physical factors that were being considered by the IFT were presented in May to provide input to the ongoing repair efforts, so that those physical factors could be considered in the repairs.

The IFT has subsequently progressed its investigation of both physical factors and human and organizational factors. The IFT has noted that efforts have been initiated in California and elsewhere to evaluate spillways at other dams. Although the IFT's work will not be completed and its final report will not be issued until fall 2017, the IFT wanted to share some of its findings to date, so that they may inform the ongoing spillway evaluations at other projects.

In this interim status memorandum, the IFT's findings to date are presented in only summary form. All of the findings are supported by detailed evidence, which will be compiled and presented in the IFT's final report.

Work Completed and In Progress – The IFT has carefully reviewed extensive documentation related to the geology and subsurface conditions of the spillway foundations; design and construction of the spillways; inspection, evaluation, maintenance, and repair of the spillways; the California Department of Water Resources (DWR) dam safety program management; and the regulatory framework for the project.

In addition, the IFT has studied photos and videos of the spillways, and post-incident forensic field investigation reports related to the failure and post-failure conditions. The post-incident studies include geologic investigations, ground penetrating radar (GPR) studies, video inspections of the remaining drainage system of the service spillway, evaluations of local trees and tree root growth, field inspections of the damaged areas of the service spillway chute, and forensic excavation and removal of portions of service spillway chute slabs in the sections of the chute remaining after the chute failure.

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[1] Resumes for members of the IFT can be found at the following link: https://damsafety.org/sites/default/files/Oroville%20Investigation%20Team%20Resumes%20FINAL.pdf

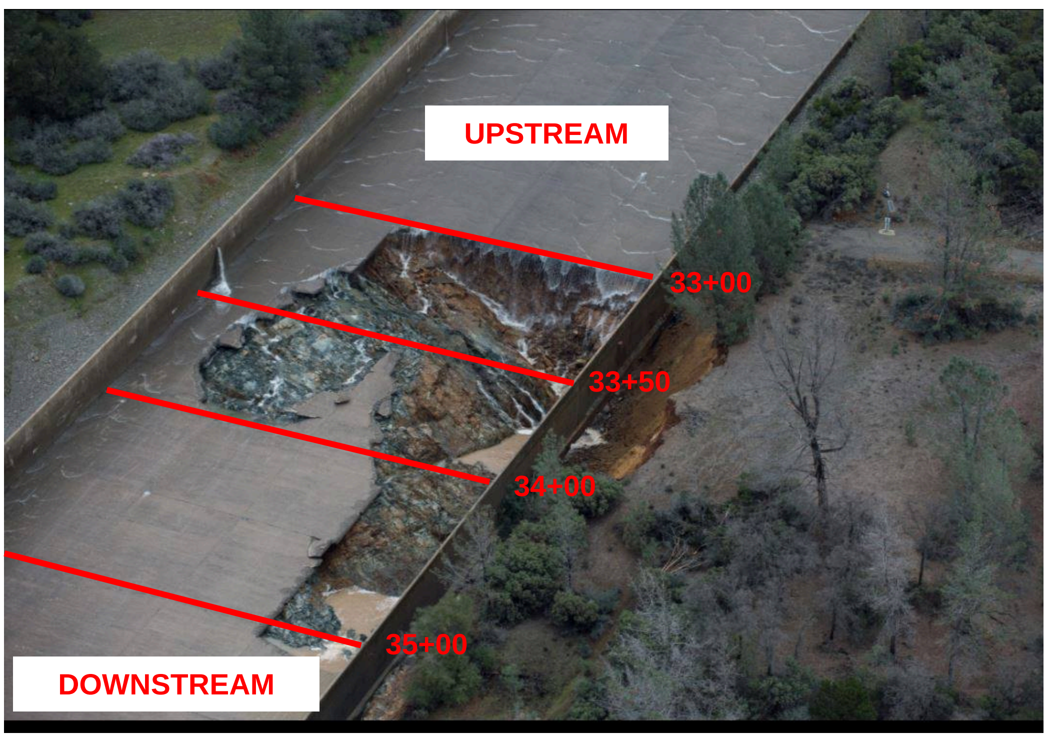
[2] The service spillway has historically been referred to as the flood control outlet (FCO) or flood control outlet spillway or gated spillway.

The California Department of Water Resources (DWR) has made available a very large volume of information for the IFT to review, and the IFT has interviewed personnel on site at the time of the service spillway chute failure, personnel involved in emergency management efforts and recovery efforts, and personnel involved in dam and spillway engineering and safety at DWR, the DWR Division of Safety of Dams (DSOD), the Federal Energy Regulatory Commission (FERC), and several consulting firms.

The IFT is continuing review of documents, photos, and videos, and conducting additional interviews. In addition to reviewing information provided by others, the IFT has completed independent analyses, provided direction for certain aspects of the post-incident field investigations, completed reviews of historical spillway design and construction practices, issued a public call for pertinent information, and established an email box for receipt of comments. As information has been collected and reviewed, the IFT has held eight meetings, some multi-day, to discuss and evaluate the collected information.

The IFT is nearing completion on its deliberations regarding the physical factors involved with the spillway incident and has substantially progressed its investigation of human and organizational factors. The IFT is now focusing most of its efforts on completion of the investigation of human and organizational factors and compilation of its findings in a final report.

***Update on Initiating Event of Service Spillway Chute Failure* –** The IFT believes that the service spillway chute failure most likely initiated by the uplift and removal of a section of the slab in the chute downstream of Station 33+50 at shortly after 10:00 am on February 7. Once the initial section of the chute slab was removed, the underlying moderately to highly weathered rock and soil-like material beneath the slab in this location was directly exposed to high-velocity spillway flow. The high-velocity flow rapidly eroded the foundation materials at this location, removed additional chute slab sections in both upstream and downstream directions, and quickly created the erosion hole that was observed by 12:30 pm on February 7, as flows diminished following spillway gate closure – see photo below. These findings are based on eyewitness accounts, and photo and video records.



Update on Physical Factors Evaluation for Service Spillway Chute Failure – While there are numerous physical factors that contributed to the failure, which the IFT has studied in detail, the IFT has focused on the critical factors that it believes likely played the most significant roles in the failure of the service spillway chute. As noted above, the IFT had previously prepared a list of potential physical factors under consideration, and now has a more refined view of these factors.

The IFT has concluded that the initial uplift and removal of the slab section downstream of Station 33+50 was most likely caused by water uplift pressure beneath a sufficiently large area of the slab, producing an uplift force that exceeded the uplift capacity of that particular section of slab. The resistance to uplift is provided by a combination of the weight of the slab, the weight of the water above the slab, the structure of the slab, and the uplift resistance provided by the foundation anchor system. Once the upstream end of the slab section lifted into the flow, the pressure under the slab rapidly increased and produced the sudden failure of the slab.

The excessive uplift pressure was mainly due to high-velocity spillway flow injecting water into slab surface features, such as open joints, unsealed cracks over the herringbone drains, spalled concrete at either a joint or drain location in either a new or previously repaired area, or some combination of these features. Localized slab deterioration and repairs pre-existed in this area prior to February 7, and these deteriorated and repaired locations may have been vulnerable to damage during high-velocity spillway flow.

During spillway releases, the slab chute surface features allowed water to flow into the foundation. The resulting flow was observed at the collector drain outfalls. Once the inflow exceeded the local drainage capacity, the flow backed up around the drains. Water that collected around the herringbone drains would have increased the pressure under the slab.

Since all physical evidence at the point where the failure initiated was destroyed, it will never be possible to confirm exactly where the initiating event occurred. Others have suggested that the uplift initiated at Station 33+00 (see photo above). However, the IFT has concluded that, although there may have been water injection along the Station 33+00 joint, that was almost certainly not the location of the initial failure. Had the failure initiated along that joint, the concrete keys at the joint would have been damaged, and this was not observed when the spillway gates were closed, and the eroded hole was inspected on February 8 by a climb team engaged by DWR. The slab section downstream of the joint at that location could not have lifted without shearing the concrete key in the upstream slab section, and this condition was not observed in the photos and videos taken by the climb team, which were carefully reviewed by the IFT.

Flows into the foundation would generally increase as flow velocities near the chute surface increased. The failure occurred immediately after the gates were opened further to increase flow down the spillway chute, which likely led to higher surface flow velocities, injection flows, and uplift pressures. There are a number of possibilities as to why this flow resulted in chute slab failure on February 7 when, historically, the chute had survived much larger flows, the last time being about eleven years before the chute failure. The IFT believes that some combination of the following factors most likely was involved:

- New damage and/or deterioration of slab repairs that resulted in more potential flow disturbance locations and more flow into the foundation than during the prior spillway discharge events.
- Possible expansion of relatively shallow void(s) under the slab due to long-term erosion under the slab. The IFT found that the available evidence does not support the hypothesis that a deep void formed beneath the spillway chute due to foundation erosion, resulting in subsequent slab collapse, but shallow voids are conceivable.
- Corrosion of the rebar across the concrete cracks or joints, as evidenced by post-failure investigations and previous repair photographs.

- Reduction in anchor capacity due to erosion around anchors beneath the slab or anchor corrosion where anchors were not properly encapsulated in grout, also as evidenced post-failure.

The IFT continues to study the spillway chute underdrain system. However, it can be confidently concluded at this time that flows observed exiting from the spillway chute drain outfalls are almost entirely from leakage through joints and cracks when water flows through the chute, and that the volumes of drain flow during spillway operation are much larger than intended in the design. Significant flows through the drains have been observed whenever there is flow in the chute, beginning with the first spillway discharge in 1969. Quantitative data concerning chute drain flows are limited, however, records and photos of drain flows from 1969 to present show that flows from individual outfalls vary over time, the most extreme example being drains that flow at some times but not at others. The IFT is continuing to evaluate possible reasons for variations in drain flows, including potential tree root intrusion, with results of a study on tree root characteristics expected soon from experts engaged by DWR, in part at the request of the IFT.

The IFT believes that moderately to strongly weathered rock and soil-like foundation conditions beneath the failed chute reduced effectiveness of slab anchorage, allowed for at least some under-slab erosion, and certainly dictated the extent of the ensuing damage. Areas immediately downstream from the initial damage area have much less weathered foundation rock conditions, where both bonding of the concrete slab and bonding of the anchor bars to the foundation rock offered significantly greater resistance to uplift, and some sections of these slabs remained in place when the gates were closed after the initial chute failure.

The IFT believes that the following factors were either not involved or had only a small effect in contributing to the failure:

- Cavitation: The conclusion that cavitation was not a significant factor is based on computations for historic flows and visual observations of the remaining downstream chute, where telltale indicators of incipient cavitation were not found.
- Groundwater: The geological features and visual evidence of groundwater flow indicate that the amount of groundwater flow was minor, and could have easily been accommodated by the slab underdrain system.
- Seismic damage: A review of seismic activity in the project region, since the last larger flow in 2006, indicates no ground motions large enough to have significantly affected the stability or condition of the spillway chute.

Update on Design and Construction Factors Evaluation for Service Spillway Chute Failure – The IFT has identified a number of design and construction fragilities which lead to vulnerability to uplift. These include:

- Underdrains that intruded into the chute slab section, reducing the thickness of concrete above the drains to 7 inches or less (compared to a design minimum thickness of 15 inches elsewhere), resulting in cracks above most of the herringbone drains; the cracks allow water to pass through the slab and also led to a propensity for concrete spalling.
- Absence of waterstops at contraction joints, and a less than optimal shear key configuration.
- The specified foundation preparation and treatment, which was followed for the headworks and emergency spillway crest structures, was relaxed during construction of the spillway chute slab. Up to 50 percent or more of the foundation in some areas was not properly treated by removal of weathered materials and cleaning of soil-like materials from the surface.
- Shallow rock anchorage of 5-foot embedment length, and possibly less where the slab was thicker than the minimum of 15 inches, as well as inadequate development of the anchors in the slab. In addition,

some anchors in the failed area were installed in highly weathered and fractured rock that was unlikely to develop the intended pull-out strength.

- A drainage system with many deficiencies, such as no filtering, possibly broken or disconnected pipes caused by the method of placement, and likely inadequate collector drain capacity for the flow that occurred through the slab.
- Single top layer of nominal reinforcement bars.
- A relatively large concrete aggregate size, resulting in a propensity for cracking and spalling at keys and over drains, and damage to drain pipes.

***Update on Physical Factors Evaluation for Emergency Spillway Damage* –** In the May 5, 2017 memorandum, the IFT identified the following four candidate physical factors for the damage at the emergency spillway:

- Significant depth of erodible rock and soil in orientations that allowed rapid headcutting toward the crest control structure; these materials also appear to be associated with geologic features such as shear zones.
- Hillside topography that concentrated flows and increased erosive forces, facilitating headcut formation.
- Insufficient energy dissipation at base of the spillway crest.
- Absence of erosion protection downstream of the crest structure.

Based on further evaluation completed to date, the IFT believes that all four of these factors contributed to the observed damage at the emergency spillway.

Update on Human and Organizational Factors – Human and organizational factors which potentially contributed to the chain of conditions, decisions, actions, and inactions resulting in the spillway damages are being investigated by various methods, including extensive review of technical and historical documents, numerous interviews within and beyond DWR, online surveys, and solicitation of public input.

The IFT is considering a broad scope of human and organizational factors spanning various categories. A list of these human and organizational factors is provided below.

- Pre-design investigations
  - Scope and methods of pre-design investigations for spillway location selection and evaluation of foundation conditions
  - Characterization and communication of findings of the pre-design investigations
- Design aspects, considered in the context of standards of practice of the era
  - Composition and processes of design teams
  - Design methodologies and reference resources
  - Design budgets and schedules
  - Characteristics of the spillway designs
- Construction aspects
  - Construction budgets and schedules

   - Differences between observed spillway foundation conditions and the foundation conditions assumed in the spillway design, and how those differences were addressed, including relaxation of specification requirements for foundation weathered rock removal and cleanup
   - Other deviations from design plans and intent during construction
   - Relationships and communications between designers, geologists, construction contractors, construction inspectors, consultants, and other parties during construction
   - Potential inadequacies of slab anchor testing
   - Documentation of the construction process and as-built conditions

- Operations and maintenance
   - Programs for spillway chute inspections, maintenance, and repairs, including their intentions, efficacy, budgets, and schedules
   - Technical background, expertise, training, and continuing education of individuals involved in dam and spillway engineering and safety decision-making
   - Systems and processes for managing and sharing the large volume of information related to the Oroville facilities
   - Regulatory reviews and processes, including DSOD and FERC inspections and Potential Failure Mode Analysis (PFMA) evaluations

- Organizational aspects, including their evolution from pre-design until the spillway incident
   - Organizational structure, culture, policies, communications, and coordination
   - Priority placed on dam and spillway safety versus other organizational goals
   - Organization and functioning of DWR's dam safety management program, in the context of DWR's overall organizational structure and its interactions with regulators

The IFT's findings with respect to these human and organizational factors will be presented in its final report.

Lessons to be Learned – There will be numerous lessons to be learned in terms of current DWR and industry dam safety practices, and these lessons will be developed and presented in the IFT's final report. At this time, the IFT shares three higher-level lessons that have been identified so far:

1. Physical inspections, while necessary, are not sufficient to identify risks and manage safety. At Oroville Dam, more frequent physical inspections would not likely have uncovered the issues which led to the spillway incident.
2. Comprehensive periodic reviews of original design and construction, taking into account comparison with the current state of the practice, are needed for all components of dam projects. These reviews should be:
   - Thorough, taking advantage of all available information
   - Critical and independent, rather than relying largely on the findings of past reviews
   - Completed by people with appropriate technical expertise, experience, and qualifications to cover all aspects of design, construction, maintenance, and failure modes of the assets under consideration

   The IFT has not seen any indication that such a review for the service spillway chute at Oroville Dam has ever been conducted since original construction. Such a review would likely have "connected the dots" and informed the PFMA process, by identifying the physical factors that led to failure of the service spillway chute, including:

- Design shortcomings relative to current state of the practice
- Construction procedures, decisions, and changes to the designs that exacerbated the shortcomings of the design
- Drain flows well beyond what were intended in design and beyond observed drain flows at other spillways
- Subsurface geologic conditions that left portions of the spillway susceptible to uplift and subsequent foundation erosion
- Chute slab repairs that were generally limited in extent, rather than designed to reliably and durably withstand high-velocity flows, thermal effects, and other loading conditions

3. Compliance with regulatory requirements is not sufficient to manage dam owners' and public risk.

   - Current regulatory requirements are generally focused on preventing failures involving uncontrolled releases of stored water. Serious incidents can occur that do not necessarily lead to uncontrolled release, but still have significant impacts to the owner and public, such as a) limitations on an owner's ability to control the reservoir, b) costs of emergency management and repairs, c) damage to or loss of resources and project benefits, d) environmental damage, e) impacts on society, f) damage to reputation, and g) potential legal liability.
   - Current PFMA and risk analysis processes are also focused on uncontrolled release of reservoir water and generally do not include development of scenarios for non-release incidents that can result in the same impacts noted in the previous bullet point.
   - Regulators have an essential role in management of dam safety, but do not have the resources nor the primary responsibility for managing dam safety. That responsibility, both ethically and legally, rests with dam owners, and dam owners must, therefore, develop and maintain mature dam safety management programs which are based on a strong "top-down" dam safety culture.