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Calaveras Dam Replacement Project

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USSD, as the United States member of the International Commission on Large Dams, is dedicated to:

ADVOCATE: Champion the role of dam and levee systems in society

EDUCATE: Be the premier source for technical information about dam and levee systems

COLLABORATE: Build networks and relationships to strengthen the community of practice

CULTIVATE: Nurture the growth of the community of practice.

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On the Cover: Calaveras Dam Replacement Project during construction, at dawn.

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United States Society on Dams (USSD)

President's Message

"Outside of our closest friends and families, there aren't a lot of figures that we're willing to trust."

As a nation we no longer trust our government, government officials, or corporate CEOs. However, we do trust technical experts and academics. This is an interesting perspective from a book I am currently reading, *Captivology: The Science of Capturing People's Attention*, and one that resonates as I start my term as President of USSD.

USSD is embarking on a focused strategy to improve and facilitate opportunities for our members to grow their technical expertise and to serve as trusted advocates for our industry. Education and advocacy were previously identified as two crucial elements for USSD to fulfill our mission. To address the goals of the educate imperative in the past, we have relied 100 percent on the volunteer efforts of our membership to publish technical papers and develop conferences and workshops. While this has been effective, there is a need to do more to better prepare our members to serve as trusted technical experts and advocates for the "environmentally sustainable science of planning, design, construction, operation and maintenance of dams, levees, and associated civil engineering projects." To improve and facilitate educational opportunities, the Board recently took two significant steps. We established an Ad-Hoc Committee on Education and appointed board member Rod Eisenbraun to serve as the chair (see page 6 for more information); and we established the Strategic Imperatives Account. This account is primarily funded by our Life Membership Program and as it grows, it will be available to advance our education initiatives. This is an aspirational goal for USSD and one I personally supported when I elected to become a life member this year. If you are also committed to expanding and improving our education initiatives, please consider becoming a life member. This membership category is suitable no matter what stage of your career you are in.

Our advocacy efforts continue to develop under the leadership of Keith Ferguson as Chair of the Committee on Advocacy, Communication and Public Awareness. This integrated committee unites all related internal and external communication activities on behalf of USSD. You have already seen an active social media presence sharing relevant national and international information about our industry. A major new effort is the development of general position statements on issues within the scope of responsibility of USSD. These position statements will allow us to respond quickly when the news cycle requires an expert opinion related to dams and levees (see page 6 for more information).

USSD will continue to advocate for the role of dams and levee systems in society, and improve the technical content offered at our annual conference and exhibition, which remains our primary source for educational and networking opportunities. For the 2019 conference, the technical committees had a key role to review abstracts and identify session moderators, which contributed to the overall high quality of the technical content. The role of the technical committees will be strengthened for the 2020 conference. If you are interested in having a role in capturing people's attention, I encourage you to join one of our technical committees and volunteer to review conference papers and presentations, serve as a conference moderator, and collaborate on position statements.

As an elected Board member and officer, I value your support and look forward to carrying out my new responsibilities as President. I will continue to work closely with our Executive Director and the diverse and talented Board to continue to grow our organization, advance our mission, and remain a vital resource to you.

Denise Bunte-Bisnett
President, USSD

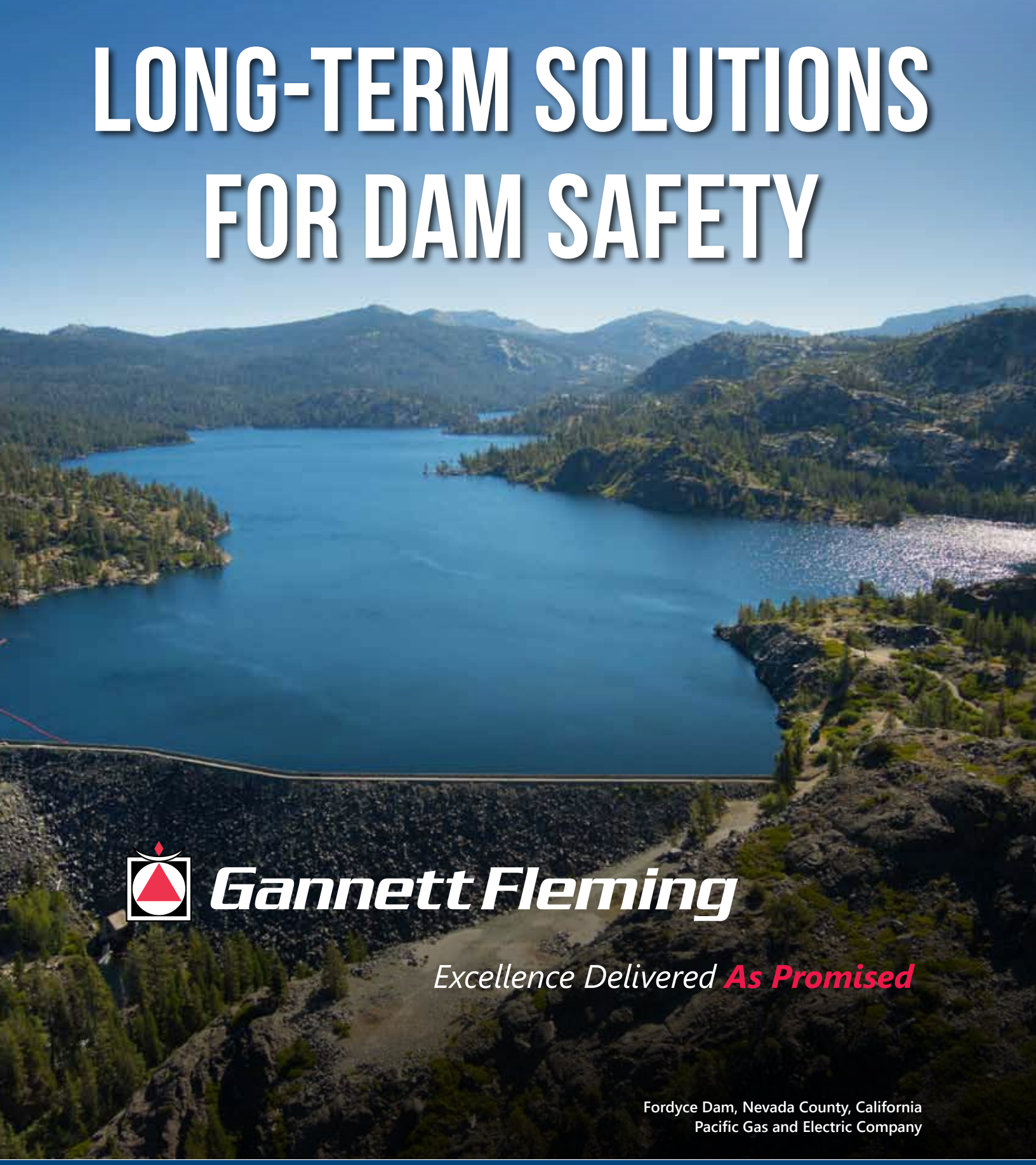
USSD

40th USSD Annual Conference and Exhibition

Denver, Colorado • April 20-24, 2020

Registration and hotel reservations will open this fall.

LONG-TERM SOLUTIONS FOR DAM SAFETY



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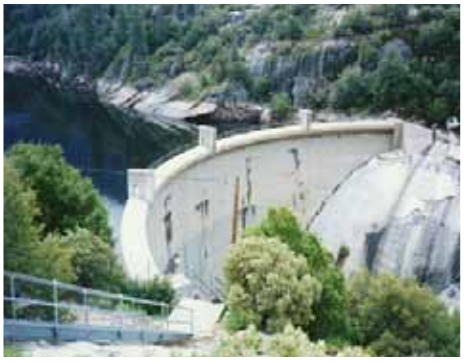

Dam Engineering

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IMPERATIVES INSIGHT

Advocate

Keith Ferguson (keith.ferguson@hdrinc.com)

The USSD ACPA Committee (Advocacy, Communication and Public Awareness) has been hard at work helping advance our visibility to membership and stakeholders, both within the U.S. and around the world. We have three major initiatives in various stages of progress.

1. Development of Position Statements for key topics including:

- Planning and Permitting of Water Storage Reservoirs
- Evaluation of Incidents and Failures
- Using Risk to Inform the Public on Safety of Dams and Levees
- Science, Technology, Engineering and Math (STEM) Education
- Principals of Sustainability for Dams and Reservoirs
- Responsibilities for Dam and Levee Safety in the U.S.
- Dam Decommissioning

2. Development of a USSD Strategic Communications Plan.

3. Renewal of our Legislative Advocacy activities.

Our voice matters! There is no organization in the U.S. that is better positioned than USSD to speak about the full spectrum of complex technical and social issues/risks related to dams, levees, and reservoirs. A large contingent from the U.S. has just returned from the 87th ICOLD Annual Meeting in Ottawa where key public awareness and education topics were discussed. The meeting this year even included a small group of protestors against dams outside the Shaw Convention Center.

We are expecting ICOLD to release a new bulletin on the Benefits and Concerns about Dams sometime in the coming year. This document will provide a worldwide perspective on the issues related to dams, at a time when the need for power to grow economies in developing countries is driving one of the most rapid expansions of hydropower dams the world has ever seen. However along with the benefits such projects will provide, the potential impacts of these projects on rivers, floodplains and deltas, in some of the most diverse and productive ecosystems in the world, could be extraordinary. Much of our future will be focused on using our skills to help decision makers around the world reconcile the need for power and water development that includes reservoir storage, while at the same time helping to achieve sustainable project purposes that include recognition and protection of values associated with free-flowing rivers and their ecosystems.

Educate

Rodney Eisenbraun (reisenbraun@rjh-consultants.com)

To help advance the Educate Imperative, the USSD Board of Directors recently established an Ad Hoc Education Committee. After reviewing several education initiatives, the Committee has decided to focus its initial efforts on developing recurring training classes for a number of dam safety topics and re-establishing fall workshops, beginning in 2020.

Leveraging Potential Failure Mode Analyses to Perform Semi-Quantitative Risk Assessments

This course will take place over three full days in Denver, October 29-31, 2019. The course and course materials are being developed by Gregg Scott, Bill Fiedler, John France, and Mel Schaefer. USSD plans to repeat the course as needed. The course is different from the recent AEG Workshop on Risk Assessments for Dams and Levee Foundations, as it is being designed to provide a wider range of risk topics (geotechnical, seismic, hydrologic, geologic, and structural risks will be covered) and will be repeatable. For more information on this course, see page 7.

Fall Workshops

Beginning in October 2020, USSD will reinstate the annual fall workshops series. The format will allow for 4-, 8- and 16-hour workshops to be conducted simultaneously while allowing attendance at either workshop with one overnight stay, thus minimizing attendee travel time. Several USSD members have volunteered for the initial Fall Workshop Planning Committee, so expect a call for 2020 fall workshop proposals soon.

In addition to these two initiatives, the committee is investigating additional course offerings in a wide variety of dam safety topics.

Upcoming USSD Events

In a continuing effort to strengthen the Education Imperative — one of four strategic imperatives — USSD has a strong slate of events lined up. Following on the heels of a sold-out summer workshop on Static Liquefaction, USSD will offer two workshops this fall.

Leveraging Potential Failure Mode Analyses to Perform Semi-Quantitative Risk Assessments

October 29-31, 2019, Denver, Colorado. The intent of this training is to leverage and improve on the significant investment that has already been made in performing PFMAs, and use this information to perform semi-quantitative risk assessments for individual dams or dam portfolios. These assessments can then be used as a screening tool to identify PFMs and overall risks which are not likely to meet Tolerable Risk Guidelines based on life safety, and as a prioritization tool for reducing risk, performing additional investigations or studies, or performing quantitative risk assessments. A simplified method for categorizing additional consequences such as those incurred at Oroville is also presented in this training. Bill Fiedler, John France, Mel Schaefer and Gregg Scott are instructors.

Public Safety and Security around Dams

November 12-14, 2019, Vallejo, California. This workshop is designed for all security and dam industry professionals, and any dam and hydropower professional with a requirement to manage public safety and security for dam and/or water retention structures. The three-day course will offer an in-depth review of the requirements for public safety and security programs and assessments. It will also offer instruction on public safety and physical security concepts and technologies, as well as the integration of the process. Included will be site visits to the City of Vallejo's Lake Curry earth embankment dam and Monticello Dam (concrete) as part of the practical exercise component. Instructors include William Foos and Paul Schweiger.

2020 USSD Annual Conference and Exhibition

April 20-24, 2020, Denver, Colorado. Join us in the Mile High City for the 2020 USSD Annual Conference and Exhibition. Be a part of this premier technical event for dam and levee professionals. Learn from industry experts, gain expertise, share experiences, connect with colleagues, build new relationships, and collaborate with other world-class professionals dedicated to advancing the role of dam and levee systems in society. The technical program chair is Elena Sossenkina, HDR.

Venue

Conference activities will take place at the Hyatt Regency Denver at Colorado Convention Center. All sessions and the exhibition will take place in the hotel. The hotel is centrally located in the heart of Denver's restaurant and entertainment district.

Workshops

Several workshops, organized by USSD Technical Committees, will be held during the conference.

Exhibition

At press time, the exhibition was nearly sold out. Act now to secure your space!

Registration

Registration and hotel reservations will open this fall.

For more information, visit www..ussdams.org or email 2020conference@ussdams.org.

Research Articles Sought

The journal *Infrastructures* (ISSN 2412-3811) is preparing a Special Issue entitled "Advances in Dam Engineering." Original research articles focused on the state-of-the-art techniques and methods employed in the design, construction, and analysis of dams are sought. Both theoretical and application papers of high technical standard across various disciplines are welcomed, thus facilitating an awareness of techniques and methods in one area that may be applicable to other areas.

The submission deadline is October 31, 2019. Submitted papers should not be under consideration for publication elsewhere. For detailed information, please follow the link to the Special Issue Website at: https://www.mdpi.com/journal/infrastructures/special_issues/dam_engineering. For further details on the submission process, please see the instructions for authors at the journal website (http://www.mdpi.com/journal/infrastructures/instructions).

FEATURE

AWARD OF EXCELLENCE IN THE CONSTRUCTED PROJECT

Calaveras Dam Replacement Project

Note: The following article is based on the award nomination submitted by Dan Wade, San Francisco Public Utilities Commission.

All images (unless otherwise noted) courtesy of San Francisco Public Utilities Commission, Robin Scheswohl.

Project Description

Calaveras Dam and Reservoir, located approximately 38 miles southeast of San Francisco, California, are owned and operated by the San Francisco Public Utilities Commission (SFPUC) as part of the Hetch Hetchy Regional Water System. The Reservoir is the system's largest source of water in the Bay Area. The original Calaveras Dam was a 220-foot-high hydraulic fill embankment completed in 1925. Due to seismic stability concerns, the reservoir level behind the dam was restricted in 2001 to approximately 39 percent of its total storage capacity of 96,850 acre-feet.

Award Recognition

Owner/Operator: San Francisco Public Utilities Commission

Design Consultant: AECOM

Construction Management Consultant: Black & Veatch

Contractor: Dragados USA/Flatiron West/Sukut Construction Joint Venture

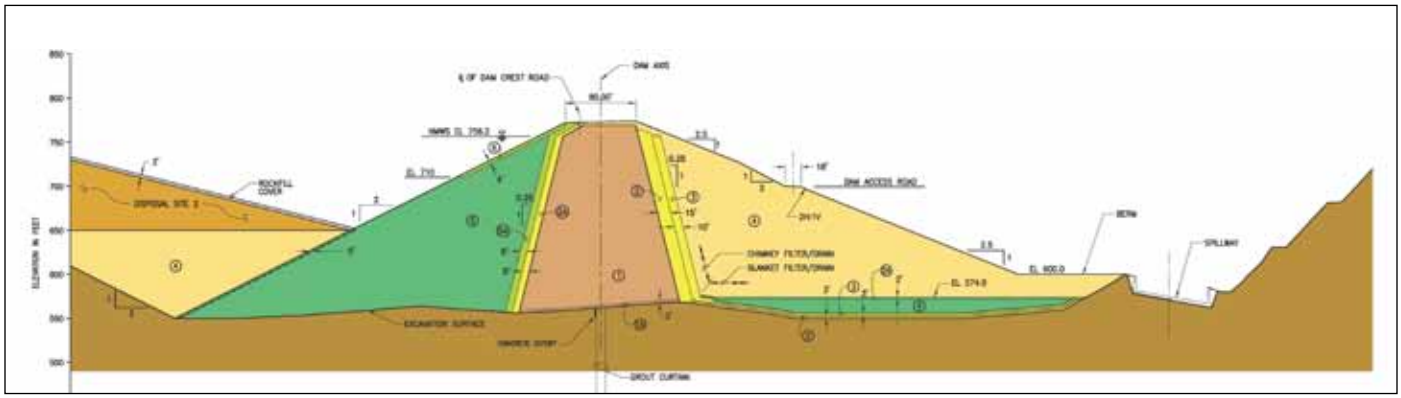
Construction of the Calaveras Dam Replacement Project to restore the full storage capacity of Calaveras Reservoir started in 2011, and the new dam was approved by the California Division of Safety of Dams (DSOD) to start impounding water in fall 2018. The major features of the project include a new 220-foot zoned earth and rock fill embankment dam located immediately downstream from the existing dam, a new 1,550-foot-long reinforced concrete spillway, a new intake tower, and a new 78-inch diameter outlet conduit extending beneath the new dam. The replacement dam is designed to withstand and remain functional after a magnitude 7.25 maximum credible earthquake on the Calaveras Fault (located 0.3 mile from the dam) and a peak ground acceleration of 1.1 g. The spillway has a capacity of 40,000 cfs and is designed to safely pass the probable maximum flood.

New dam rendering.

The Challenges

The project faced many challenges, starting from the environmental review and permitting process, and continuing through the design and construction phases.

The project authorization involved a lengthy consultation process to address environmental impacts associated with the original dam construction and other project-related features. Extensive environmental commitments including modifications to existing facilities, revisions to standard operating procedures, and on-site mitigation measures during construction were required to obtain certification of environmental review through the California Environmental



Maximum cross section.

Quality Act (CEQA) and multiple local, state and federal permits, culminating in a permit from the U.S. Army Corps of Engineers under Section 404 of the Clean Water Act.

Calaveras Dam is located in a highly seismic and complex geological setting that presented significant challenges during both design and construction. The new dam embankment design had to comply with current seismic and flood control standards and be constructed while maintaining continued operation of the existing facilities. Multiple differing site conditions were encountered during construction including a large ancient landslide complex and secondary faulting located within the limits of excavation for the spillway, dam foundation, and outlet conduit. These geologic complexities required expeditious evaluation of the conditions during excavation and design of remedial measures to minimize cost and schedule impacts. The project site is underlain by the Franciscan Complex with various rock types containing both federally regulated and non-regulated forms of naturally occurring asbestos (NOA).

These conditions necessitated an integrated program of dust control and air monitoring related to NOA disturbance to comply with regulatory requirements and protect public and worker health.

Justification for Nomination

Sustainable Water Resources Management

The original Calaveras Dam provided 96,850 acre-feet storage of water originating in the Alameda Creek Watershed. The reservoir level restriction in 2001 was in response to seismic stability concerns and reduced the storage capacity to approximately 39 percent capacity. This restriction significantly degraded the water system's overall reliability related to water quality and the ability to provide uninterrupted delivery of drinking water to approximately 2.7 million customers. With increasing droughts and potential loss of alternative water supplies, remedial measures were critical to restore the water system's storage capacity and reliability. Locating the replacement dam immediately downstream of the existing dam allowed continued water storage and delivery capability during construction. The new replacement dam not only restores the reservoir storage capacity but also provides improved reliability of the water supply and long-term performance by remaining operational after a major seismic event. As an additional effort towards sustainable water resources management, the replacement dam was designed and constructed to accommodate a future height increase allowing for increased reservoir storage capacity and growing water demands.

Innovative Design and Construction Techniques

Curved Spillway — The spillway consists of an L-shaped side channel weir about 285 feet long and a chute about 1,000 feet long. To conform to the site topography and reduce excavation volume, the chute was designed with a unique horizontal bend. The performance of the spillway was evaluated during the design phase with physical model testing. This testing allowed adjustment of the side channel weir geometry to maximize capacity. The layout of the bend in the chute was also optimized to distribute the flow evenly along the chute which reduced the height of cross-waves and thus of spillway walls required. The analyses also confirmed effective dissipation of energy in the stilling basin prior to discharge to Calaveras Creek.

Conveyor Delivery System — The material used for the downstream shell of the embankment (Zone 4) was quarried and stockpiled upstream of the dam, creating potential complications in hauling this material across the core for placement. The average scheduled placement rate for the Zone 4 was over 6,000 cubic yards per day, requiring approximately 300 truckloads daily. To expedite construction and improve site safety, the contractor installed a conveyor approximately 4,000 feet in length to transport the Zone 4 material from the upstream stockpile and down the completed spillway, and to deposit it in a stockpile

Calaveras Dam under construction. Also shown are the curved spillway, stilling basin, and Zone 4 conveyor system. Photo courtesy of DFSJV, Structures Engineer Marlon Delgadillo.

located near the downstream edge of the work area. The material was then placed and compacted from this stockpile without haul trucks having to cross the core. The use of this conveyor also made placement and compaction of the core zone significantly safer and more efficient by not having to work around frequent truck traffic.

Outlet Conduit Design at Fault Crossings — Geologic mapping during excavation of the dam foundation identified several bedrock faults crossing the alignment of the new 78-inch steel outlet pipe both upstream and downstream of the dam core. An evaluation of these faults indicated a potential for up to six inches of sympathetic movement on these features during a maximum credible earthquake on the nearby Calaveras Fault. Several design features were implemented to accommodate this movement and possible rupture of the outlet pipe. Upstream of the dam core, a sequence of clay, filter, and drain materials was placed surrounding the pipe to reduce leakage into the pipe in the event of a rupture and facilitate repairs. Downstream of the core, rupture of the pipe at the faults could result in high-pressure water leakage into the downstream shell. At these locations, the steel outlet pipe and reinforced concrete encasement design were modified to accommodate greater deformations. A waterproofing membrane was also provided around the concrete encasement to reduce leakage from the pipe in the event of a rupture.

Combination Earthfill/Rockfill Embankment — The potential for increased seismic deformation of the embankment related to potential strength loss in a saturated upstream earthfill shell was reduced by using a free-draining rockfill material quarried on site instead of the earthfill material used for the unsaturated downstream shell. This design allows seismic deformations of the embankment under the design earthquake (PGA = 1.1g) to occur in a manner that would not require emergency repairs following the earthquake.

Foundation Grouting Approach — Foundation grouting was on the construction schedule critical path. The sequence and staging of the grouting operation was adjusted to allow grouting work to begin while the foundation excavation was still underway. Grouting work began midway down the right abutment with a short transverse grout curtain, and then proceeded up to the top of the right abutment while excavation work continued to the valley floor. On the valley floor, the grouting was performed in two stages. The first

Panorama photo of construction of the zoned embankment.

stage was done through approximately 40 feet of overburden while foundation excavation was ongoing elsewhere. A shallow second stage was then done after the foundation grades were achieved to verify acceptance of the grouting work. This innovative grouting approach was successful and avoided critical path impacts.

Efficiency of Design

Use of Onsite Materials — The replacement dam volume is approximately four million cubic yards, of which about 90 percent was obtained at the site. Rockfill material was produced in a quarry downstream of the dam, earthfill material was obtained from the foundation and abutment excavations, and clay core material was obtained from a borrow source upstream of the reservoir. The onsite materials were not suitable to produce sand and gravel for the filter and drain elements of the dam, so these materials were imported from offsite commercial sources.

Onsite Disposal of Excess Material — Approximately ten million cubic yards of earth and rock materials had to be excavated to reach acceptable foundation conditions for the dam and the spillway. These materials in excess of those used for the embankment dam construction were all placed on site in disposal sites near the dam and adjacent to the reservoir. The use of nearby disposal sites saved time and truck traffic that would have been required to haul the materials elsewhere.

Use of Existing Dam and Appurtenances — The replacement dam was constructed immediately downstream of the existing dam. This design allowed the existing dam to serve as a cofferdam and Calaveras Reservoir to remain in operation during construction of the replacement dam. In addition, portions of the existing outlet works, including the outlet works intake piping extending into the reservoir and the outlet conduit running through the abutment of the existing dam, were able to be used for the project.

Overcoming Significant Challenges

Many significant challenges had to be overcome during construction of the project including unanticipated geologic conditions, presence of natural occurring asbestos, and adverse weather.

Unanticipated/Differing Geologic Conditions

The project encountered several major and extensive unanticipated geologic conditions during construction. Design modifications, construction resequencing, and special construction means and methods were implemented to reduce impact to the project's schedule and cost. These unanticipated/differing geologic conditions were presented by SFPUC and the Designer during USSD conferences in 2014, 2015, and 2016, and include the following:

Early construction phase of the replacement project, showing the original dam.

- A large ancient landslide complex was encountered during excavation on the left (west) side of the valley above the new spillway location. Excavation came to a halt immediately due to slope stability concerns. To address the issue, extensive geotechnical investigations were performed to define the actual conditions and limits of the landslide. The left abutment slope required an increased layback, resulting in approximately two million cubic yards of additional excavation to remove the unstable landslide formation so as to allow work to continue. This differing site condition necessitated the development of additional onsite disposal areas and resequencing of the foundation excavation, spillway construction, and embankment construction.
- During geotechnical investigations and excavation of the landslide on the upper left abutment, a second ancient landslide complex was identified extending further down into the valley, inside the spillway and dam foundation limits. Approximately one million cubic yards of additional excavation was required to achieve acceptable foundation conditions for the spillway and dam. The final foundation excavation conditions required placement of approximately 12,000 cubic yards of backfill concrete to reestablish the spillway foundation. A tie-back wall was constructed near the spillway inlet to reduce the amount of landslide material removed and provide the necessary staging area for the spillway construction.
- During excavation of the rock quarry for the upstream shell material in the dam embankment, curvilinear discontinuities and unstable blocks were encountered. An exploratory drilling program was initiated immediately to evaluate the extent of these geologic conditions. The drilling program also identified two large shale formations with materials unsuitable for use in the dam embankment. To provide adequate slope stability and ensure a sufficient quantity of rock for the

dam embankment, additional rock slope support was installed during the quarry excavation and the removal/disposal of the unsuitable shale material was planned and monitored carefully.

- The depth to competent bedrock beneath an earthen containment dike required for one of the designated disposal sites was much deeper than anticipated at the beginning of construction. Cement deep soil mixing shear wall treatment was developed for the foundation that allowed construction of the dike to continue as planned.

Naturally-Occurring Asbestos

The project is underlain by the Franciscan Complex, a geologic unit comprised of complexly mixed sedimentary and metamorphic rocks. Naturally Occurring Asbestos (NOA) is present in the Franciscan rock units mined to construct the upstream rockfill shell of the dam embankment. Certain forms of NOA found in the rock types at the project site are federally regulated as asbestos while other forms are currently non-regulated but have characteristics suggesting a cancer potency comparable to regulated asbestos types. Construction of the replacement dam required the excavation, processing, and placement of over three million cubic yards of NOA containing material. The significant amount of work in NOA containing materials was anticipated to produce asbestos containing dust. An integrated program of dust control and air monitoring was implemented during construction to protect the public and workers' health and verify the effectiveness of the dust control measures.

Dust control measures implemented during construction included:

- Speed restrictions for all onsite vehicles
- Continuous wetting of NOA containing materials during disturbance
- Suspension of ground disturbance activities during periods of high winds
- Covering or wetting material stockpiles
- Vehicular wheel wash and track-out stations
- Drilling with water in NOA containing materials
- Wetting of blast areas before, during, and after each blast
- Capping roads with non-NOA containing material

Air monitoring was performed in the active construction areas, at designated locations around the boundary of the project site, and at designated off site locations. Continuous air sampling was conducted in 24-hour cycles throughout the seven-year construction project, and the samples were analyzed using Transmission Electron Microscopy to provide accurate and reliable data. The air monitoring data was used to verify the effectiveness of the dust control measures, to evaluate NOA emissions from the various construction operations, to select the appropriate level of personal protective equipment (which included Tyvek coveralls and respirators), to establish the boundaries of regulated work areas, and to develop alternative dust control methods for specific operations and equipment. Nearly 120,000 man-hours were expended on the NOA inspection and air monitoring program with over 70,000 air samples being collected and analyzed. The results of these air monitoring tests from various stations were presented to the nearby community and posted on the SFPUC website (sfwater.org) throughout the active construction for the project as part of the outreach program.

Adverse and Extreme Weather Conditions

The project site experienced unusually severe weather including heavy rains during the 2016/17 winter season, which caused a portion of Calaveras Road near the site to fail in a landslide. Calaveras Road is owned by another county and provides the only access to the site. Importation of the filter and drain material required for the embankment construction was not possible without the road in service. To reduce the amount of access outage, SFPUC mobilized the entire team and issued an emergency contract to design and construct a road realignment around the landslide area. Through a collaborative effort by the entire project team and with outside stakeholders, Calaveras Road was back in service by May 2017 and an extended schedule delay was avoided.

Project Benefits

The original Calaveras Dam completed in 1925 reportedly trapped ocean-run steelhead trout above the reservoir and blocked fish migration into spawning and rearing habitat. Calaveras Reservoir also receives water from Alameda Creek by way of the Alameda Creek Diversion Dam (ACDD) and a 1.8-mile-long tunnel. The ACDD was constructed in 1931 and is considered an artificial barrier to the natural migration of Central California Coast steelhead into the upper reaches of Alameda Creek. The construction of the project provided an opportunity for the SFPUC, regulatory agencies, and non-governmental organizations to address fish population restoration and enhancement through the environmental review and permitting process. To restore and enhance fish habitats within the Alameda watershed, this project included installation of sleeve valves to allow year-round scheduled release of water from Calaveras Reservoir to Calaveras Creek to maintain streamflow, construction of a fish ladder at the ACDD, installation of fish screens on the existing outlet works intakes at Calaveras Dam, and revised operating criteria for ACDD.

Reservoir near operating elevation.

Dedication of the new Calaveras Dam, July 23, 2018.

Calaveras Dam and Reservoir play a crucial role in the SFPUC's continuous efforts to provide a safe and reliable water supply to the Bay Area's growing population. Upon completion of the replacement dam and removal of the reservoir restriction in fall 2018, the original operating capacity of Calaveras Reservoir was restored, helping to ensure the SFPUC has sufficient storage for its 2.7 million customers during times of drought or when alternative supplies are unavailable due to maintenance or emergencies. The design criteria and structural features incorporated in the replacement dam assure continued safety of the communities downstream of the dam and an operational water supply system following a major seismic event. Furthermore, the design of the replacement dam allows for a potential future height increase of up to 140 feet which would provide approximately an additional 389,000 acre-feet of water storage and ensure a reliable water source for generations to come.

For more information on the project, please contact Susan Hou, SFPUC, shou@sfwater.org.

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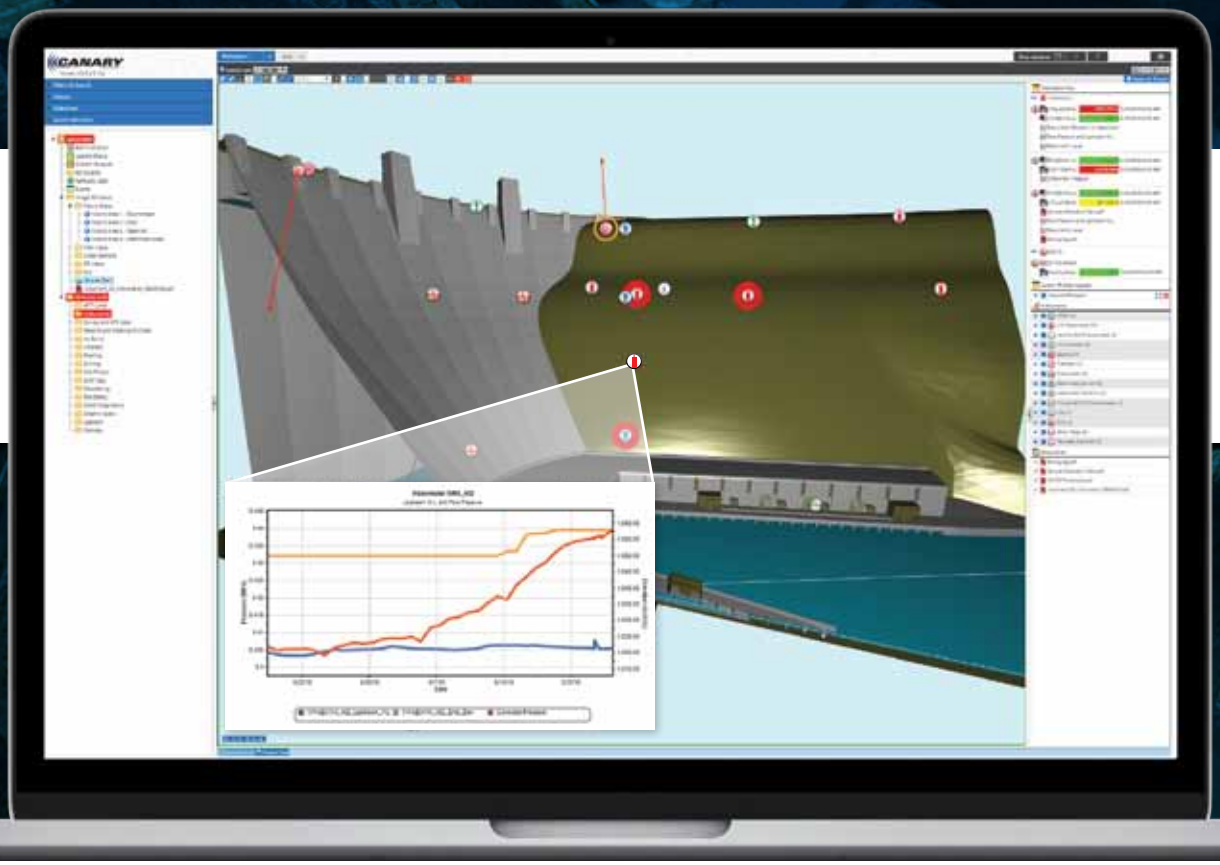

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COMMITTEE CORNER

Foundations

Edwin Friend, Vice Chair (efriend@rjh-consultants.com)

The Foundations Committee has been busy advancing several initiatives during the past year. The foremost was the coordination of the second Legacy Lecture, which took place during the Opening Session of the 2019 USSD Conference and Exhibition. The Legacy Lecture is a forum to recognize and highlight the professionals that have pioneered substantial advances in the field of dam safety and dam engineering. These forums provide an opportunity for esteemed professionals to discuss projects, people, thoughts, and paradigm shifts that led to their advancements. USSD was honored to have Dr. Donald A. Bruce, President of Geosystems, L.P., as the 2019 Legacy Lecturer. Dr. Bruce specializes in geotechnical construction processes, particularly anchoring (his Ph.D. dissertation topic), drilling and grouting. He has more than 42 years of experience in dam anchoring and works on projects throughout North America and four other continents. Brian Greene, Gannett Fleming, provided a stimulating introduction of Dr. Bruce.

Dr. Bruce's lecture covered 40 years of his career and was focused on four technologies that he has extensive experience with:

- Prestressed rock anchors
- Deep mixing methods
- Drilling and grouting
- Positive" cutoff walls

During his lecture, Dr. Bruce also provided his insights on several softer topics including:

- Dam Portfolio Risk Management
- PFMA Process
- Site Safety
- Boards of Consultants
- Mentorship

Ed Friend, Donald Bruce, Brian Greene and Doug Boyer.

The Lecture concluded with a lively question and answer session. Nearly 300 individuals attended the lecture and were rewarded with an outstanding, entertaining, and informational morning. The slides of the presentation were provided to all who attended the 2019 USSD conference and are available at http://ussd2019.conferencespot.org/ (under Download PDFs).

The Foundations Committee is also preparing a white paper, *Guidance for Surface Preparation of Dam Foundations,* with the goal of the paper being published by the spring of 2020, in conjuction with a workshop to present the paper. Other activities being pursued by the committee include a workshop on drilling in dams and a spillway erosion workshop. If you are interested in joining the Foundations Committee and participating in one of our activities, please contact Doug Boyer at Douglas.boyer@ferc.gov or Edwin Friend at efriend@rjh-consultants.com.

Earthquakes

Lelio Mejia, Chair (lmejia@geosyntec.com)

The Committee continues to actively work on its objectives of a) promoting the seismic safety of dams and the development of knowledge on seismic analysis and design of dams; and b) supporting the ICOLD Committee on Seismic Aspects of Dam Design. The committee added three new members in 2018 and its roster now stands at 36. The membership includes representatives of private, government, and academia from the U.S. and Canada.

The Committee has recently worked on four initiatives intended to develop and disseminate knowledge on dam seismic design. One of them was to sponsor workshops on seismic analysis of concrete dams, held during the 2018 and 2019 USSD annual conferences. The other three are in progress, as follows: 1) update of guidelines for the selection of earthquake ground motion parameters of dams (which were last updated by the Committee in 1999), 2) development of guidelines for the seismic design and evaluation of structures appurtenant to dams, and 3) development of guidelines for the seismic deformation analysis of embankment dams. In addition, the Chair attended meetings of the ICOLD Committee on Seismic Aspects of Dam Design in Vienna, Austria (2018) and Ottawa, Canada (2019). The Committee also contributed significantly to the planning of the 2019 USSD Annual Meeting in Chicago, including co-sponsoring, with the Concrete Dams Committee, a workshop on the Seismic Analysis of Concrete Dams.

Future Activities

The Committee is continuing work on its three standing initiatives and is nearing completion of the first one. The Committee will be actively involved in planning the technical program for the 2020 USSD Conference and Exhibition in Denver. Together with representatives of FERC, USGS, and USBR, the Committee is planning a workshop for the 2020 conference on Earthquake Shaking and Ground Failure Hazards for Dams, Including Automated Real-Time Inspection Prioritization. The workshop will discuss new technologies and tools for seismic hazard assessment, earthquake monitoring, and dam post-earthquake inspection.

FEATURE

Richard E Smith, P.G., Dam Safety Program Manager, U.S. Army Corps of Engineers, Seattle, WA (richard.e.smith@usace.army.mil); and Ellen R Engberg, P.G., Operations Project Support, U.S. Army Corps of Engineers, Seattle, Washington

Hard Rock vs. Heavy Metal — an Innovative Sediment Bypass Tunnel Armoring Solution

Introduction

Sediment bypass tunnels (SBTs), though an uncommon feature of dams, pose unique engineering challenges due to the potential for severe invert erosion leading to frequent, costly repairs and dam safety issues. The invert liner of the SBT at Mud Mountain Dam in Washington State (Figure 1) has experienced erosion, requiring frequent, costly repairs since initially put into service in 1942. Strategies to improve the effectiveness of the invert armoring and to reduce lifecycle O&M costs over the intervening decades have been mostly unsuccessful, but a recent, innovative design promises to provide a lower cost, longer service life solution.

Background

Mud Mountain Dam is a 432-foot-tall earth embankment dam (Figure 1) with an uncontrolled chute-style concrete lined spillway, an intake tower, and two gated outlet tunnels (9-foot horseshoe, 23-foot circular). Located in a narrow canyon on the White River on the boundary between King and Pierce Counties, the U.S. Army Corps of Engineers designed, constructed, and operated dam is a run of the river project used for flood storage that does not typically store water longer than the duration of a single flood event. Sediment, originating on the northwestern flanks of Mount Rainer, a 14,410 foot tall, active stratovolcano, passes through the outlet system at an estimated rate of 450,000 tons of materials (20,000 tons of bedload sediment) annually ranging in size from fine glacial flour to boulders (maximum of 20-inches diameter).

Figure 1. Location map and project aerial photo.

The 9-foot SBT has its invert at the river bed elevation of 895 feet (NGVD 29). The 23-foot tunnel has two intakes at invert elevations of 910.5 and 925 feet. The 9-foot tunnel is used as the primary means to pass sediment. The 23-foot tunnel is used to pass flood flows and for downstream juvenile fish migration. The original 1,800-foot-long concrete-lined, SBT had 40-pound steel rails lining the concave shaped invert intended to provide a durable wearing surface for protection against scour (Figure 2). This design required repairs (Figure 3) every two to three years from the beginning of project operations due to impact bedload abrasion of the concrete that subsequently undermined the steel rails.

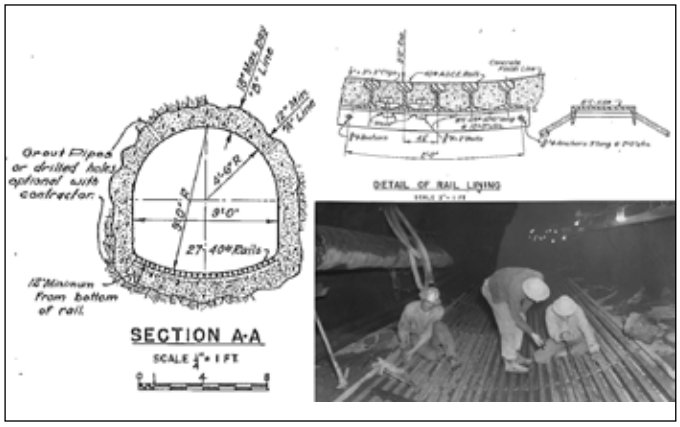

Figure 2. Initial (1940s) project tunnel floor protection design (steel rails embedded in concrete) and installation photo.

Figure 3. Typical invert damage and associated bedload sediment.

In the 1970s, experiments with steel bars of various thicknesses and shape were welded transverse to the tunnel axis on approximately 3.5- and 2.5-foot centers, presumably to alter the sediment abrasion regime. These experiments were unsuccessful, and it wasn't until the 1980s that an opportunity arose to reline the SBT floor. The project's two intake towers were determined to be seismically deficient based on an improved understanding of seismic hazards in the Northwest. As part of the construction of a new, single outlet tower in 1995, the SBT floor was replaced with a flat invert lined with 1-inch thick steel plates.

In August 2006, approximately 11 years after the new steel liner was installed, five holes were discovered during routine inspection. The holes varied in size from six to 18 inches in length, and had completely worn through the 1-inch steel liner, eroding the underlying concrete. The holes were subsequently filled with an abrasion resistant concrete patch material, and the tunnel was placed back in service, but erosion of the steel liner continued to worsen requiring project personnel to dewater the tunnel several times per year to patch holes.

A new experiment with rectangular test sections of alternative liner materials, including two types of plastic and two types of steel was attempted in 2011 through 2013. A suitable anchorage system for the plastic sections could not be devised to prevent them from being torn loose during tunnel use. Of the two types of steel, AR500 abrasion resistant steel performed best and was selected as replacement steel for the existing liner.

By 2015, damage to the liner was extensive (Figure 4) and threatening to wear through the underlying concrete to the more easily eroded bedrock, potentially requiring closure of the tunnel. Although the SBT is not used during major flood management operations, it is unacceptable to have the 9-foot tunnel out of use for repairs for extended periods of time because sediment then must pass through the critical 23-foot tunnel, which does not have adequate invert protection against bedload abrasion.

Figure 4. Damage to 9-foot tunnel liner steel plate and underlying concrete (2017).

USACE subsequently developed a design concept for a replaceable steel liner, but remained open to alternative, but yet undiscovered solutions. A solicitation for a design-build contract was issued in 2016 with performance criteria of an overall 50-year life of the system except for the wear surface, which was required to have a minimum performance life of 15 years before requiring replacement. Additionally, the offerors were encouraged to "…seek innovative, creative, and life-cycle, cost-effective solutions, which meet or exceed these requirements…" The contract was awarded to Garney Companies and their sub-contractor ILF Consulting Engineers (GC/ILF).

Granite Liner Design

The contractor proposed using granite blocks instead of steel as the new tunnel liner. Performance of a SBT in Switzerland (Pfaffensprung SBT) using similar material was used as the basis for the design. USACE approved the granite block concept based on its potential for reduced short- and long-term costs as well as other benefits. A value engineering analysis determined that the granite paver system was approximately $800,000 less expensive than USACE's replaceable steel design concept. The predicted service life of the system before it requires replacement of blocks was 40 years versus the 15 specified in contract solicitation. Worker safety during installation and repair was improved by eliminating the need for welding in the

confined space of the tunnel. Replacing granite blocks can potentially be accomplished by project staff. When combined with low frequency of repairs, this promises significant long-term operations and maintenance cost savings.

The granite block design consisted of the following primary elements:

- Wear surface
- Subbase
- Upstream and downstream transitions
- Analysis of design life
- Instrumentation

Primary Wear Surface

The Hardy Island quarry, located in the Jervis Inlet south of Powell River, British Columbia was chosen as the source for the liner blocks. The salt and pepper gray Hardy Island granite contains few flaws or fractures allowing it to be processed into large, competent blocks. The selected rock was also found to have superior material properties to the model project (Pfaffensprung Urner granite) with average compressive strength of 32,000 psi compared to 26,000 psi, and a density of 168 pcf compared to 165 pcf.

To determine precise dimensions needed for sizing the blocks, the contractor conducted a LiDAR survey of the tunnel. This survey identified several areas where the distance between the side walls of the existing steel liner deviated from the typical 9-foot width cross section. Block dimensions were designed to account for these variations.

The stability of the block design was evaluated utilizing two one-dimensional finite element models to estimate hydraulic pressure: a HEC-RAS model developed for the tunnel was used to estimate the hydraulic conditions in the tunnel, and a mathematical program model to estimate the pressure head in the drainage system subgrade beneath the granite blocks. After determining the pressures, loads were generated at three-foot intervals representing the center of granite blocks within respective rows. Each representative block was evaluated in three failure modes: uplift, sliding, and overturning.

The 10-inch thick granite blocks were specified to be cut and finished at the quarry and delivered to the project site with a dimensional tolerance of plus or minus 1/16-inch. The two primary block sizes were 2-feet 10-inches wide and 2-feet 1.5-inches wide in three and four block row configurations 3-feet long, respectively. The maximum joint spacing for both the longitudinal and transverse joints was ¼ inch. Specialty blocks to accommodate the curved portions of the tunnel were incorporated into the three block rows. The total number of blocks was 2,417 with each block weighing between approximately 900 and 1,200 lbs, depending on size.

The maximum gap between blocks and sidewalls was four inches in the straight section of the tunnel, while in the curved section, a gap of up to six inches was allowed. Gaps were filled with a five inch thick layer of general purpose concrete covered by a five inch layer of high strength, abrasion resistant concrete. For gaps greater than four inches, specially cut granite filler blocks were used to fill at least fifty percent of the gap.

Subbase

The holes in the existing steel liner were repaired by infilling and leveling with either 5,000 psi grout or 7,000 psi concrete. Holes larger than eight inches deep and 12 inches wide also included steel reinforcement of #4 rebar dowels on twelve inch centers embedded six inches into the underlying concrete with epoxy.

Permeable cellular concrete was specified for the subbase bedding material (Figure 5). A minimum permeability of 2.85x10-3 ft/s and a range of wet unit weight of 29 pcf and 35 pcf were required. Wick drains, four inches wide made of composite plastic and geotextile fabric, were provided between the existing steel liner and the permeable concrete and up the sidewalls.

Upstream and Downstream Transitions

The upstream transition from existing steel liner to granite surface is a ramp consisting of four tapered steel beams with an eight-inch flange width stitch welded to the existing ASTM A36 steel gate chamber floor. Atop the tapered steel beams is a one inch thick A36 steel plate covered by a one inch thick abrasion resistant AR500 steel plate secured with plug welds along the beam length. At the upstream connection gate chamber, floor material was removed to provide a flush connection to the wear plate. The voids

Figure 5. Upstream section of liner showing permeable concrete, wick drains, and granite blocks (left) and instrumentation wires (right).

beneath the ramp were fully grouted to prevent ponding, vibration, or other sources of uplift. To provide a smooth transition from the ramp to the granite surface, the top plates extend over the first row of blocks. The blocks were notched down two inches and back four inches from the upstream face prior to placement.

The blocks at the downstream end of the tunnel are secured in place by a steel plate placed flush against the vertical face of the downstream most row of blocks extending the width of the tunnel and from the tunnel invert up to one inch below the top surface of the granite blocks. The steel plate is one-inch thick, with a full penetration weld between the plate and the tunnel side walls. Weep holes in the steel plate allow water to drain from the permeable concrete subbase.

Analysis of Design Life

Abrasion estimation was conducted by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich, Switzerland. Different abrasion models were presented and calibrated based on abrasion measurement data acquired during field tests at the Pfaffensprung SBT, Switzerland. The models were calibrated for sediment load/type and granite properties. These calibrated models were applied to the planned granite blocks for two operating scenarios with different reservoir water levels in order to predict spatially averaged abrasion depths as a function of time and sediment load. The abrasion calculations had to adjust for differences in the invert granite material properties as well. The abrasion depth estimations were determined by calibrating the abrasion formulae for three years of abrasion depth measurements (2012-2014) at Pfaffensprung SBT. Local maximum abrasion depths at Pfaffensprung were two to three times higher than the spatially averaged abrasion depths. A similar behavior was assumed for Hardy Island granite applying three times higher values as local maximum values to yield a lifetime of one half thickness of the blocks (five inches) over 40 years.

Instrumentation

Two continuous loops of wire were placed underneath the cellular concrete to serve as an alert system in the event of block displacement and subsequent erosion of the cellular concrete subbase, in which case the wire would be rapidly severed. If the circuit is broken, the existing on-site instrumentation system (data logger equipped with radio transmitter) is set to send alert messages via e-mail to responsible employees, who can then take appropriate measures including closing the tunnel for inspection.

Construction

Construction of the new tunnel liner began in July of 2017. Components of the project were scheduled to be completed in the following order: patch holes in the damaged steel liner, place screed rails for leveling the permeable concrete, install strip drains, install the monitoring system wire loops, pour and screed the permeable concrete, place granite blocks, fill the gap between the blocks and the sidewall, and install upstream and downstream transition ramps.

The patching of the existing steel liner was completed in November 2017. As the damage was being repaired, test placements of the cellular concrete were made. Revisions were required to the designed mix for the cellular concrete to ensure it had the needed viscosity to be placed on the grade of the tunnel invert and to correct variability of permeability outside the range of design requirements. While working through these changes, the contractor and the government decided to use the delay to flush the forebay sediment buildup through the 9-foot tunnel for approximately one month (January through February, 2018) despite the certainty that the steel liner repairs, screed rails, and test sections of permeable concrete would be scoured away.

Upon resumption of work in February 2018, progress was rapid. The screed rails, instrumentation wires, and wick drains were reinstalled, and the permeable concrete layer poured within two months (Figure 6). Block placement began at the upstream end of the tunnel in early April. Pallets of block were moved into the tunnel and staged throughout, and the individual blocks were set precisely into place using a vacuum-hoist system (Figure 6). The pace of block placement quickly exceeded 50 feet per day, and the last row of blocks was placed by September 2018. A LiDAR survey of the completed system was conducted for future condition comparisons.

Figure 6. Granite block installation (April 2018).

Two observations made during construction resulted in notable changes to the design. The first was that portions of the permeable concrete subbase ponded water indicating that permeability was potentially lower than the design requirements. A hydraulic bypass system consisting of two-inch PVC pipe (Figure 7) was installed to alleviate any hydraulic pressure buildup in suspect regions of the subbase.

The second observation was made by the contractor during the January 2018 tunnel flushing. A previously undocumented hydraulic jump formed at the downstream exit of the 9-foot tunnel under certain sediment elevation

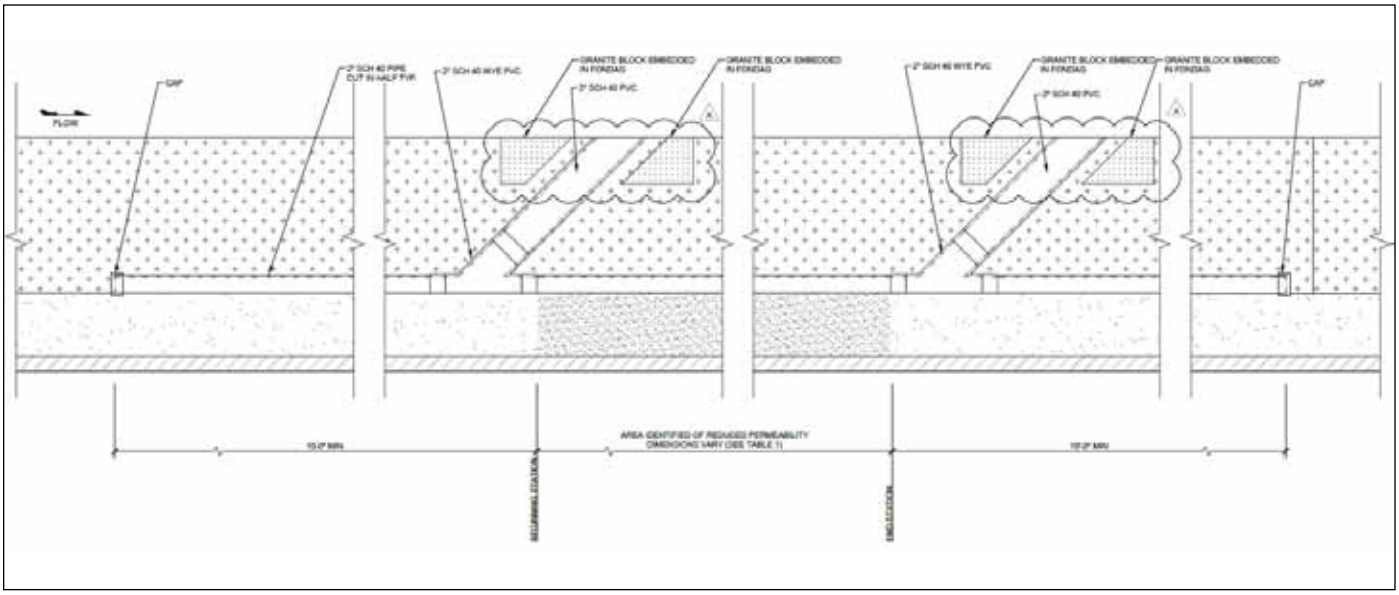

Figure 7. Bypass drains.

and tunnel flow conditions. Hydraulic modeling indicated that uplift pressures on the blocks in this region had the potential to exceed design parameters. Steel jacks (Figure 8) were designed to apply stabilizing lateral force creating additional resistance to uplift to the blocks in the downstream-most 364 feet of tunnel liner.

Figure 8. Block stabilizing jacks.

Performance

The 9-foot tunnel was placed back into service in late November 2018, and approximately 54,000 tons of sediment is estimated to have been flushed through the tunnel up until December 28, 2018, when it was closed briefly for inspection. Aside from minor damage like chipping at the edges of blocks along the transverse joints and a single block with a four inch crack (Figure 9), the liner showed virtually no signs of excessive wear or distress. The abrasion resistant concrete filing the gap between the blocks and sidewalls also exhibited no signs of erosion.

The Corps plans to inspect the tunnel annually beginning in the summer of 2019 but anticipates it will be several years before realistic wear rates and hence the life of the granite liner can be estimated. Annual river sedimentation rates are strongly influenced by rainfall and snowmelt events that vary from year to year. A repeat LiDAR survey will likely be conducted after five years of operation in 2023.

Figure 9. Post tunnel use areas of block wear/damage at transverse joint (left) and the only block with a crack (right).

Summary

Passing a variable grain size bedload poses unique engineering challenges for long term operation of SBTs. Wear and erosion of the invert is inevitable, but the innovative solution of using granite blocks at Mud Mountain Dam has the potential to significantly extend the time between major repairs, and reduce the cost of repairs when they are necessary. The Corps is optimistic that after nearly eighty years of problematic operation, the next few decades may provide relatively maintenance free service.

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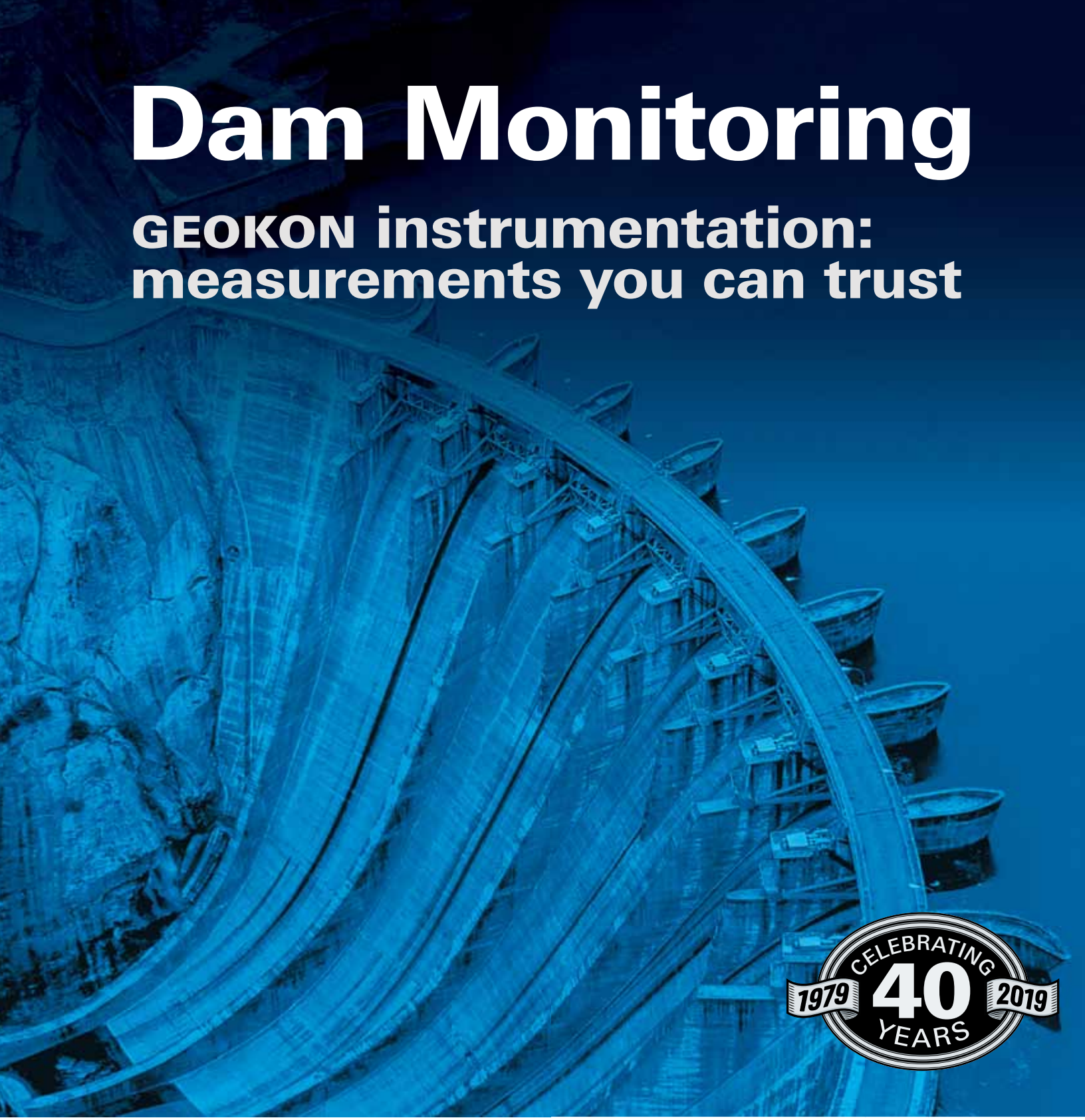

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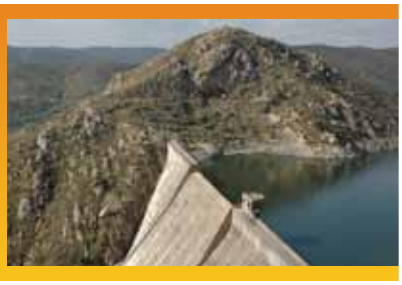

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USSD Chicago Highlights

The 39th USSD Annual Conference and Exhibition was a big success. The local host was the Federal Energy Regulatory Commission, and Commissioner Cheryl LaFleur gave a plenary session presentation.

Technical Program

The Conference Technical Program began with the second in a series of Legacy Lectures. Donald Bruce, President of Geosystems, L.P., was the featured lecturer. Plenary sessions on Tuesday and Wednesday included several invited presentations that focused on engineering in the Second City and dam history and future trends. During five concurrent technical sessions, more than 100 presentations addressed the conference theme, *Second City, Second Chances: Stories of Rehabilitation, Modification and Revitalization*, and other topics corresponding to USSD technical committees. The conference proceedings can be downloaded at http://ussd2019.conferencespot.org.

Exhibition

More than 80 organizations showcased their products and services. New to the exhibit hall this year was a Best in Show award. An anonymous panel of judges rated each booth on creativity, overall appeal, and staff engagement with attendees. Congratulations to Geosyntec Consultants for their winning exhibit.

Conference App and USSD Game

There was a lot of activity on the new conference app, including the USSD game. Participants completed tasks aimed at increasing exhibitor traffic. Competition was fierce, but at the end of the day, the winners were Soma Baladrandra, 1st place; Mark Fountain, 2nd place; and Zara Plasencia, 3rd place.

5K FUNds Run/Walk

Fifty hearty runners braved the blustery weather conditions to support the USSD Scholarship Program. Others opted to become 'virtual' runners. Congratulations to David Lehto, Tim Dolen, and Scott Raschke for placing in the top three. Thanks to more than 40 Partners in Education who made donations, and race fees from runners, the event raised $17,800 for the USSD scholarship program.

Thank you to Elena Sossenkina, 5k Chair; Greg Paxson for assisting on fundraising efforts with Elena; and Debra Hempel, Richard LeBlanc, John Hynes, Ali Tabrizi, Paul Kokoszka, Marilyn Sabido, and Steve Spicer.

USSD Gives Back

In what has become an annual tradition at each USSD annual conference, donations were collected from attendees to help support a local STEM organization. A check for $1, 940 was presented to the Young Women's Leadership Charter School. They also received 55 Taste of Chicago gift cards valued at $550 to be used as student incentives.

Awards and Recognitions

Lifetime Achievement

Dave Kleiner with award nominator Rachael Bisnett.

The 2019 Lifetime Achievement Award was presented to David Kleiner, recognizing his 56 years of experience in hydropower, dams and water resources projects. As a principal geotechnical engineer and project manager with Harza and MHW, he has provided knowledge and solutions for more than 75 large hydropower and dam projects in over 25 countries. In his current capacity as a consultant for Stantec, he serves as a senior reviewer and geotechnical subject matter expert for large and complex dam and hydropower projects throughout the world. Kleiner is currently a member of the Board of Engineering Experts for Hydro Quebec for the Romaine River Hydro Projects. He is a graduate of Northwestern University with a Master of Science in Civil Engineering, and is licensed in five states. His 35 publications establishes him as a thought leader throughout the industry. He has been an active member of USSD and ICOLD for many years, and served as Vice President for USSD.

Exceptional Young Professional of the Year

The inaugural award went to Rachael Bisnett, Stantec. She serves as a project technical lead and project manager on domestic and international projects at Stantec. Most recently she has been the lead geotechnical engineer and overall technical lead for the design and construction of the Red Rock Hydroelectric Project near Pella, Iowa. She is the chair of the USSD Committee on Embankment Dams and

served as Chair of the Planning Committee for the USSD 2019 Conference and Exhibition in Chicago. She also led the effort to develop a new website for USSD in 2016.

Public Safety and Security for Dams Recognition

Frank Calcagno is a senior security advisor/engineering geologist for Gannett Fleming. He has 36 years of federal dam safety and security experience with the Federal Energy Regulatory Commission and the Bureau of Reclamation. The recognition is sponsored by Worthington Products, who donated $2,500 to the USSD Scholarship Program.

Excellence in the Constructed Project

The announcement of the recipient of the **Excellence in the Constructed Project Award** is eagerly anticipated each year. This year the award went to the Calaveras Dam Replacement Project, Alameda County, California, owned by the San Francisco Public Utilities Commission. Also recognized were Design Consultant AECOM; Construction Management Consultant Black & Veatch; and Contractor Dragados USA, Flatiron West Inc. and Sukut Construction (Joint Venture). For more information about the project, see the article beginning on page 8.

Susan Hou, San Francisco PUC, and Manuel Morejon, Dragados USA hold the Excellence in the Constructed Project Award. They are joined by individuals representing the owner, consultants and contractor.

Outstanding Papers

The **Outstanding Paper Award** was presented to Lelio Mejia, Geosyntec Consultants, and Ethan Dawson, AECOM for *Evaluation of Earthquake-Induced Cracking of Embankment Dams*. The paper is featured beginning on page 31.

Nicholas Paull, University of California, Davis, received the **Outstanding Young Professional Paper Award** for *Seismic Deformation of Different Size Embankments on a Spatially Variable Liquefable Deposit*. Ross W. Boulanger and Jason T. Dejong were co-authors. Anurag Singhal, HDR, was given the **Outstanding Poster Presentation Award** for *Effects of Gate-Wall Interaction on Spillway Tainter Gates*. Kevin Gerst and Kenwarjit S. Dosanjh were co-authors.

President's Award

Dean Durkee, Immediate Past President

It was my great pleasure and honor to present the 2019 President's award to Dr. Debora Miller. Dr. Miller has been a member of USSD since she was awarded the first USSD Scholarship in 1992, when she was a graduate student at Colorado State University. It is notable that during that time, She was working on the first comprehensive book on expansive soils, which was published shortly after she completed her MS Degree in geotechnical engineering. In addition, Dr. Miller worked part time throughout her graduate studies for ESA Consultants, where she was involved in and often led the design and construction for a number of new dam and dam rehabilitation projects.

Since that time shwhas remained committed to the dam engineering profession and USSD. Serving on the Embankment Dams Committee throughout her career, Dr. Miller has been involved in the publication of white papers and the development of several workshops relating to embankment dams. In 2001, she was the first woman elected to the USSD Board of Directors, serving two terms for a total of six years. Since the end of her term on the Board, she has continued to make lasting contributions to the industry and USSD and has set the example for what it means to be a professional in the dam engineering industry.

Dr. Miller has had many positive impacts on my career, including introducing me to geotechnical engineering as my first lab instructor, encouraging me to join USSD, and convincing Gannett Fleming to hire me while she was leading the firm's efforts to expand operations in the mountain west. This, combined with her contributions to the industry and USSD, made this a very easy choice.

Scholarships

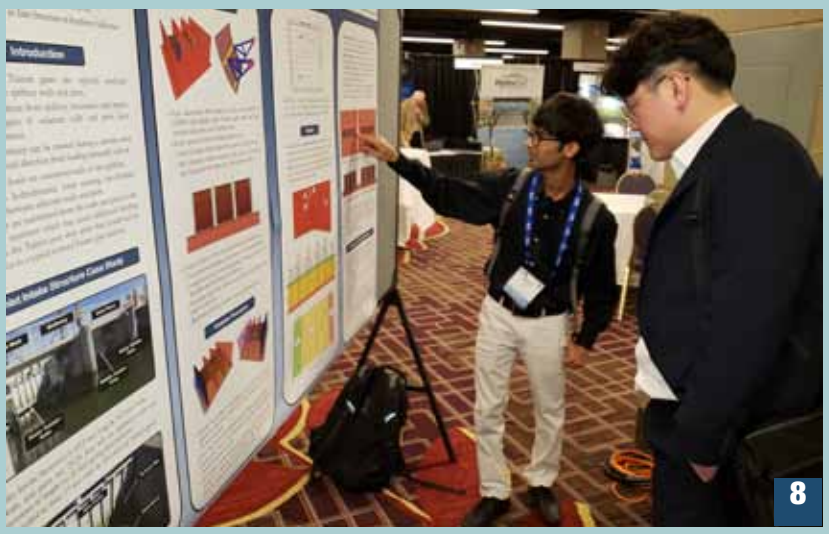
Four scholarships were presented during the conference:

Jack Cadigan, Louisiana State University – $5,600, *Design Trends and Guidance for Substratum Pressure Relief Wells for Dams and Levees Using Computational Methods*.
Amy Getchell, Purdue University – $4,800, *Alternative Use of Synthetic Nanoclay for Permeation Grouting in Dam and Levee Engineering.*
Michael Kiernan, Auburn University – $4,800, *Improving Methods to Evaluate the Effect of Strain-Softening Clays on the Stability of Dams*.
Tyler Oathes, University of California, Davis – $4,800, *Implementing the Effect of Strain-Rate on Strain-Softening Clays into Nonlinear Dynamic Analyses*.

2019 ANNUAL CONFERENCE AND EXHIBITION

Chicago, Ilinois

1 Dean Durkee thanks Alex Grenoble for his service on the USSD Board of Directors. **2** Phoebe Percell, outgoing chair of the Communication subcommittee. **3** Emily Schwartz and Brandan Vavrek present Rachael Bisnett with the Exceptional Young Professional of the Year Award. **4** Pierre Choquet, RST Instruments. **5** Sharon Krock, Schnabel Engineering. **6** Kevin Schneider, Barnard Construction; and Neil Hancock, Moretrench.



7 MWRD officials brief field tour participants at McCook Reservoir. **8** Anurag Singhal explains his poster to an attendee. **9** Dean Durkee congratulates outgoing board member Eric Halpin. **10** Mario Ciccone and Evan Sockaci, Brayman Construction. **11** Awards Committee Chair Tina McMartin with Lelio Mejia, winner of the Outstanding Paper Award. **12** Kieran Keefe and Tim Newton, Canary Systems. **13** Jim Lindell, outgoing board member.

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ICOLD UPDATE

ICOLD 87th Annual Meeting

Sharon Powers, USSD Executive Director

USSD was well represented with over 100 attendees at the recent ICOLD Annual Meeting in Ottawa. Approximately 1,000 dam and levee professionals from 58 countries took part in committee meetings, workshops, and technical sessions. There were also 152 young professionals attending. When not participating in technical sessions, the exhibit hall bustled with activity as conference-goers visited vendors to learn about the latest products and services. Thanks to the Canadian Dam Association (CDA), we also experienced the hospitality of Ottawa with a cultural event at the Canada Museum of History.

During the meeting of INCA (ICOLD National Committees of the Americas) Regional Club, of which USSD is a member, USSD President Denise Bunte-Bisnett provided an information-packed presentation on notable dam incidents and innovations in dam design and construction in the U.S.

Bunte-Bisnett represented the U.S. National Committee at the General Assembly, the annual business meeting of ICOLD. Several presentations, including one from the India National Committee, were made; India will be the site of the 88th ICOLD Annual Meeting in 2020. Four questions for the 27th Congress, to be held in Marseille, France in 2021, were selected out of eight questions considered:

Denise Bunte-Bisnett awaits the start of the General Assembly.

Q104 – Concrete Dams Design Innovation and Performance

Q105 – Incidents and Accidents Concerning Dams

Q106 – Surveillance, Instrumentation, Monitoring and Data Acquisition

Q107 – Dams and Climate Change

Other significant decisions were voted on during the meeting including:

- Sweden named the site of the 2023 ICOLD Conference
- Enrique Cifres (Spain) and Devendra Sharma (India) elected as ICOLD Vice-Presidents
- Uganda approved as the 101st member country of ICOLD
- USSD members appointed to ICOLD Committees:
  - Phoebe Percell (USACE): Computational Aspects of Analysis and Design of Dams
  - Amanda Sutter (USACE): Dam Surveillance

In preparation for the General Assembly, input was solicited on a number of agenda items from the USSD Board of Directors as well as Technical Committee Chairs.

ICOLD President Mike Rogers presented his initiatives that included improvements in the Technical Committee processes. A World Declaration of Dam Safety was presented for vote; however, due to a number of National Committee Chairs not having received it beforehand, the item was tabled until next year's meeting.

Mike Rogers during the General Assembly.

As a USSD member, you also hold membership in ICOLD as part of the U.S. National Committee. This important benefit includes access to ICOLD Bulletins and other information on their website, as well as ICOLD meeting registration discounts. Please contact USSD at info@ussdams.org to receive the national committee code to set up your ICOLD membership.

Marty Teal enjoys the field tour.

Marty Teal (third from left), Chair of the Sedimentation of Reservoirs Committee, with committee members.

Sharon Powers, Amanda Sutter, Denise Bunte-Bisnett and Stuart Harris.

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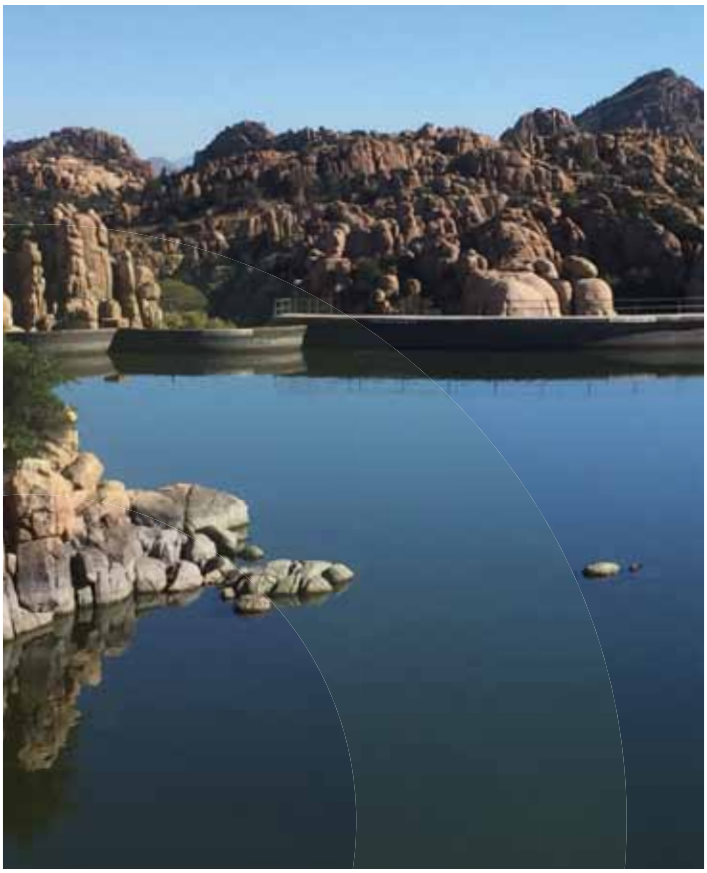

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FEATURE

Lelio Mejia, PhD, PE, GE, Geosyntec Consultants, Oakland, California (lmejia@geosyntec.com); and Ethan Dawson, PhD, AECOM, Los Angeles, California

2019 USSD Outstanding Paper

Evaluation of Earthquake-Induced Cracking of Embankment Dams

Note: This shortened version was provided by the author. To download the full paper, go to www.ussd2019.conferencespot.org.

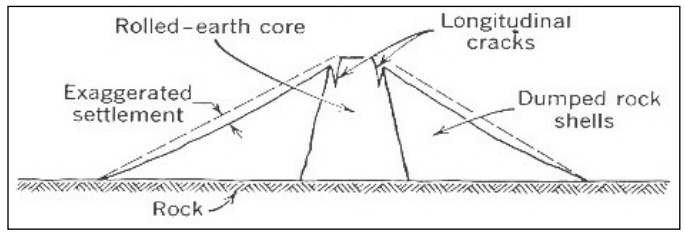
Introduction

One of the most hazardous consequences of earthquakes on embankment dams is cracks induced by strong earthquake shaking. Foundation fault rupture during an earthquake can also lead to cracking of an embankment dam. Co-seismic foundation rupture, however, is a much less frequent occurrence in dams than strong shaking.

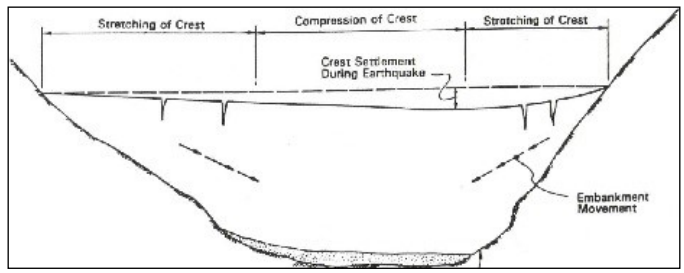
Cracks are caused by tensile stresses that exceed the tensile strength of soils. Because of their temporary nature, transient tensile stresses that might be induced during earthquake shaking are unlikely to leave open cracks in soils after the shaking ceases. In embankment dams, open cracks (from here on simply referred to as cracks) observed after an earthquake are most often associated with tensile stresses and strains resulting from earthquake-induced permanent deformation of the embankment.

Dam embankment cracks can form in various orientations and shapes. Because of the sustained stress field imposed by gravity, cracks will often be roughly vertical. However, depending on soil tensile strength and on geometric constraints and stiffness discontinuities that may lead to soil arching, cracks can take non-vertical orientations.

Earthquake-induced deformations often correspond to transverse spreading, bulging, and/or settlement of embankment dams (e.g., see Swaisgood, 2014). Transverse spreading of embankment dams often leads to tensile stresses normal to the dam axis near the crest, whereas dam settlement can lead to tensile stresses parallel to the axis (particularly at the crest near steep rock abutments and above irregularities in the longitudinal foundation profile).



(a) Longitudinal cracking.



(b) Transverse cracking.

Figure 1. Example mechanisms of earthquake-induced cracking of embankment dams.

Thus, earthquake-induced cracks in embankment dams typically develop near the crest, in directions approximately parallel to the dam axis (longitudinal cracks) or transverse to it (transverse cracks). However, cracks are also often observed on the embankment upstream and downstream faces (e.g., see Fong and Bennett, 1995). Figure 1 illustrates some of the mechanisms of cracking often observed in embankment dams after earthquakes (Sherard et al., 1963).

Cracking due to static deformation and hydraulic fracturing is known to be pervasive at depth within dam embankments, as discussed in the landmark paper by Sherard (1973). As pointed out by Sherard, seismically-induced cracking is frequently similar in pattern and location to cracking commonly caused by differential settlement under gravity

loading.

Whether at depth or near the crest, cracks can lead to increased seepage or leakage and internal soil erosion, which if allowed to progress uncontrolled, can lead to piping failure of embankment dams. Cracks located and oriented in such ways that allow concentrated flows through an embankment dam, even under moderate hydraulic gradients, are particularly dangerous. Transverse cracks that extend below the reservoir level and are long enough or interconnect to cut through the embankment impervious zone and allow flows to exit unfiltered into coarse pervious zones or at the downstream slope, may readily initiate internal erosion and lead to failure (Mejia, 2013). Longitudinal cracks are also hazardous, as they can interconnect transverse cracks and provide pathways for leakage through a dam.

Clearly, assessment of the potential for earthquake-induced cracking is critically important to the seismic safety evaluation of embankment dams. Reliable evaluation of the likely location and geometric characteristics of potential cracks is essential for a rigorous evaluation of potential failure modes related to cracking of an embankment dam.

Considerable effort has been made by the dam engineering profession over the last few decades to study the nature and effects of earthquake-induced cracking of embankment dams and to develop defensive design measures to minimize its occurrence and mitigate its potential consequences. Extensive work has been devoted to developing methods to evaluate the location, extent, and depth of cracking in dams (e.g. Pells and Fell, 2002). However, few references are available in the literature (e.g. USBR, 2015) that provide an overview of available methods for the evaluation of earthquake-induced cracking of embankment dams.

The purpose of this paper is to provide a summary of previous studies, a brief discussion of the mechanics of cracking in soils, and an overview of available methods for evaluating the location, orientation, and depth of earthquake-induced cracking in embankment dams. The paper also presents an approach to the evaluation of potential embankment dam cracking using three-dimensional (3D) nonlinear dynamic analysis procedures. The use of such procedures is illustrated by the response analysis of Lenihan Dam for the M 6.9, 1989 Loma Prieta Earthquake.

Cracking in embankment dams may also result from desiccation of the dam materials or from hydraulic fracturing, in the absence of general embankment deformation. However, discussion of these two latter causes of cracking is beyond the scope of this paper. So is cracking of non-earth water barriers in embankment dams, including impervious upstream facings.

Overview of Previous Studies

Because of the similarities between various aspects of embankment dam cracking under seismic and static loads, general research on cracking under static conditions is relevant to the evaluation of seismically-induced cracking. Previous research related to the evaluation of cracking of embankment dams under gravity loads includes several underpinning studies dating back to the seminal work of Leonards and Narain (1963) and of Covarrubias (1969), who studied tensile strains at failure in compacted clays and cracking of earth and rockfill dams. Research on the use of finite element analysis procedures to calculate stresses in dams under static conditions, which are necessary to evaluate potential cracking, included insightful studies by Lefebvre et al. (1973), Lefebvre and Duncan (1974) and Chirapuntu and Duncan (1975).

Notable compilations of field observations of embankment dam cracking during earthquakes have been published by Fong and Bennett (1995) and by Pells and Fell (2002). Fong and Bennett reported on transverse cracking observed at 19 dams after the 1989 M 6.9 Loma Prieta, the 1992 M 7.4 Landers, and the 1994 M 6.4 Northridge earthquakes. Pells and Fell significantly expanded the Fong and Bennett database to include longitudinal cracking and other types of earthquake damage. In forward evaluations of dam safety, those compilations often offer useful benchmarks for assessing potential crack characteristics in an embankment dam, such as crack depths and widths, based on estimates of seismically-induced dam deformations. An example of the use of such compilations for assessing embankment cracking under strong earthquake shaking was presented by Mejia and Dawson (2015).

Recent research has been carried out by Professors Robin Fell and Chongmin Song and other researchers from the University of New South Wales in Australia and has focused on numerical evaluation of the characteristics of cracking under static loading (Fell et al., 2015).

Field Observations and Case Histories

Previous observations of dam cracking during earthquakes have been very useful in developing an understanding of the potential characteristics of cracks and of the conditions under which seismically-induced cracking may occur in embankment dams. Cracks are often observed in dams after earthquakes and post-earthquake reconnaissance reports commonly document observations of earthquake-induced cracking of embankment dams (Fong and Bennett, 1995; Pells and Fell, 2002).

By far, the 12 May 2008 M 8.0 Wenchuan Earthquake in

(a) Longitudinal cracking of Xinyoufang Dam.

(a) Longitudinal cracking of Xinyoufang Dam.

Figure 2. Examples of severe damage in embankment dams during the 2008 M 8.0 Wenchuan Earthquake (from Jing et al., 2011).

China affected a greater number of dams than any other earthquake in recent history. As reported by Jing et al. (2011), the Wenchuan Earthquake shook over 35,600 dams and damaged over 2,660 dams, of which 69 were severely damaged. Figure 2 shows examples of the types of observed damage in embankment dams during the earthquake.

Previous observations indicate that the interface between concrete walls (or other types of rigid walls) and embankment fills are particularly vulnerable to cracking during earthquakes. Such vulnerability was exemplified by the cracking observed near the spillway structure at Austrian Dam during the 1989 M 7 Loma Prieta earthquake in California. Figure 3 illustrates the locations where cracks were observed at the dam after the earthquake and the extent of cracking seen near the spillway walls (Babbitt, 2014).

(a) Locations of observed cracking at the dam.

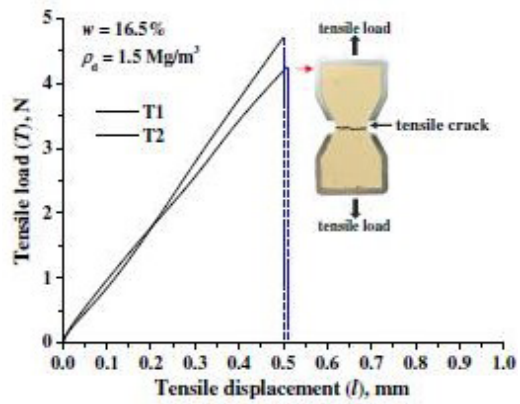
(b) Cracks near spillway walls.

Figure 3. Cracking observed at Austrian Dam after the 1989 M 7 Loma Prieta Earthquake.

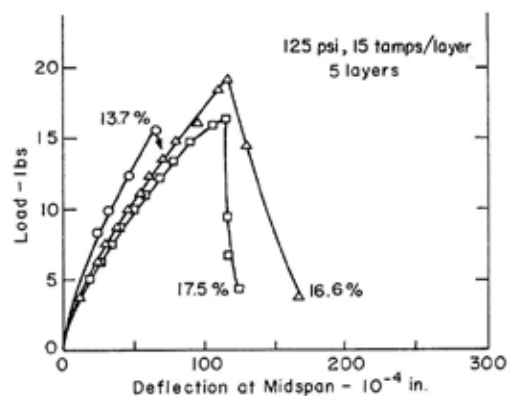
Concrete or masonry walls founded on rock may be considered to offer a rigid interface with a dam fill, which can crack readily if the fill tends to pull away from the wall. Thus, under those or similar conditions, such as at the contact between a dam embankment and a steep rock abutment, it is necessary to provide protection against cracking and internal erosion of the embankment.

Considerations from Mechanics of Cracking

In concept, a soil will crack when subjected to tensile stress that exceeds the tensile strength of the soil. Soils generally exhibit brittle behavior during tensile failure, such that they are unable to sustain tensile stress once the tensile strength is exceeded. Figure 4 shows the results of strain-controlled direct-pull tests by Tang et al. (2015) and of load-controlled beam bending tests by Chirapuntu and Duncan (1975). It may be seen that once the peak tensile load was reached, the soil specimens quickly lost their ability to carry load.



(a) Strain-controlled direct-pull tests (Tang et al., 2015).



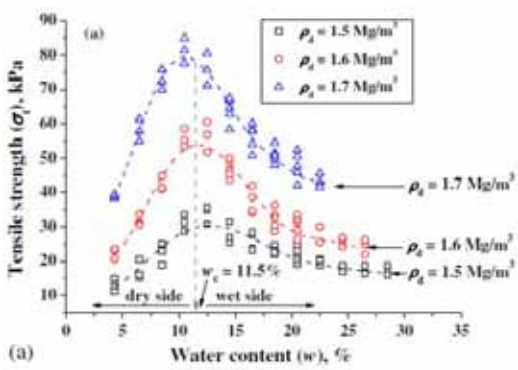
(b) Load-controlled beam tests (Chirapuntu and Duncan, 1975).

Figure 4. Typical load-displacement relationships from tensile strength tests in clayey soil.

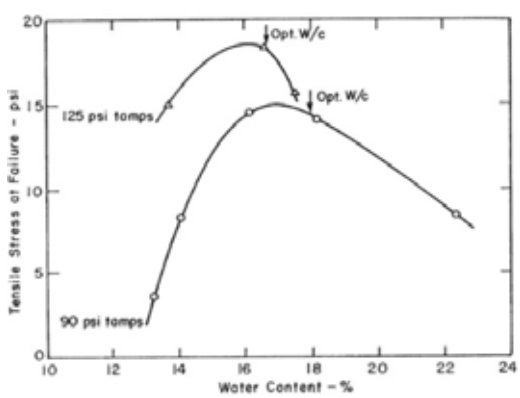
Crack propagation is controlled by the principles of fracture mechanics. Once a crack initiates, stress concentrations (singularities) at the ends of the crack dictate propagation of the crack. In soils, cracking will propagate until the driving stress or strain conditions change, or the capacity of the soil to support an open crack is exceeded. In the field, as

cracks propagate within an embankment zone, the driving stress can change spatially (and temporally), or the ability of the soil to support an open crack may be exceeded, thus determining the extent and depth of cracking. As they propagate, cracks change the state of stress, relieving tensile stresses in nearby areas.

The tensile strength of compacted clayey soil in the laboratory has been shown to be a function of soil type (including gradation and plasticity), specimen size, loading type and rate, and density and water content at the time of fracture. Figure 5 shows the variation in tensile strength with density (or compaction effort) and water content of compacted clayey soils of medium plasticity (CL) from direct-pull tests by Tang et al. (2015) and beam bending tests by Chirapuntu and Duncan (1975). For a given density, the soil tensile strength varies significantly with placement water content and reaches a maximum value at a water content of a few percent dry of optimum.



(a) Direct-pull tests – Silty Clay (Tang et al., 2015).



(b) Beam tests – Sandy Clay (Chirapuntu and Duncan, 1975).

Figure 5. Variation in tensile strength with density and water content for compacted clayey soils .

Considerations for Assessing Field Behavior

Because all soils have flaws and crack initiation and propagation is controlled by such flaws, the tensile strength of soils is highly dependent on specimen size. Durelli and Parks (1962) found the following relationship between the tensile strength of brittle materials (σ_t) and the volume of that part of the specimen subjected to at least 95% of the maximum tensile stress (V95):

$$\sigma_t = C(V95)^n$$

where C and n are constants. The results of ring and Brazilian tests by Harison et al., (1994) correspond to a value of n ≈ -0.2 for a silty clay soil (CL). Such type of information may be used to infer the tensile strength of intact soil in the field. It suggests that the tensile strength of intact clayey embankment material at the scale of small cracks often observed in the field may be 1/10 to 1/30 of the tensile strength measured in laboratory tests. It follows that the tensile strength of most embankment dam materials in the field is typically very low.

Crack widths are determined by the magnitude and spatial extent of tensile strains and are roughly correlated to the depth of cracking. The depth of cracking below the ground surface is limited by the cohesion component (or apparent cohesion) of shear strength, which determines the ability of a soil to support an open crack. The maximum depth of cracking below the surface, $(D_{crack})_{max}$, in a soil is given approximately by the following expression:

$$(D_{crack})_{max} = 2c \operatorname{Tan}(45° + \varphi/2) / \gamma$$

where c = cohesion, φ = friction angle, and γ = unit weight of the soil, applicable to the pertinent load condition. It follows that coarse cohesionless soils, such as gravels, are unable to support open cracks and thus, cannot crack. As shown in Figure 6, medium sands in a moist condition, can support open cracks temporarily to considerable depths. However, once they become saturated, the materials lose their 'apparent cohesion' and collapse, closing any cracks (Mejia, 2013).

(a) Trench excavation in moist sand.

(b) Trench collapse after flooding.

Figure 6. Trench tests in moist medium sand before and after saturation.

Procedures for Evaluation of Earthquake-Induced Cracking

Various approaches have been used in practice to evaluate potential cracking for seismic safety evaluation and risk assessment of embankment dams. These procedures may be generally classified into two broad categories: a) indirect evaluation through uncoupled analyses of embankment seismic deformations and crack development, and b) direct evaluation through numerical analysis.

Because seismic deformations of embankment dams often exacerbate static deformations, seismically-induced cracking is frequently similar in pattern and location to cracking under gravity loading. Thus, any evaluation of earthquake-induced cracking of an embankment dam should be preceded by a thorough examination of its performance (observed or anticipated) during construction and long-term loading. Observed or anticipated differential settlement under static loads is often a good indicator of potential differential settlement under seismic loads. In addition, static differential settlement may reveal zones of weakness or discontinuities in the embankment and foundation that may promote cracking.

Indirect Procedures

In these procedures, the evaluation of cracking is generally done in two steps. Seismic deformations of the embankment dam are calculated first using one or more of currently available techniques. Using the calculated embankment deformations as input, the potential for cracking is then evaluated using simplified methods or numerical analyses.

Methods to evaluate embankment dam seismic deformations can range from empirical correlations (e.g., Swaisgood, 2014), to the Newmark sliding-block method of analysis, to numerical analysis using non-linear finite element methods. Procedures to assess potential cracking range from empirical use of case history databases to numerical analyses of stresses and strains for the expected embankment dam deformations.

Case history databases that may be used to empirically assess potential earthquake-induced cracking include those published by Fong and Bennett (1995) and Pells and Fell (2002). Notwithstanding uncertainties inherent to calculated embankment dam seismic deformations, the main issue with the empirical use of case history databases is the large uncertainty associated with the resulting cracking estimates. Such uncertainty is due to: a) the limited number of cases in the databases, and b) the few parameters used to represent the many factors that affect cracking in any one case. The large uncertainty in the resulting cracking estimates may be inferred from Figure 7, which illustrates data for normalized dam crest settlement and crack depth compiled in the Fong-and-Bennett and Pells-and-Fell databases.

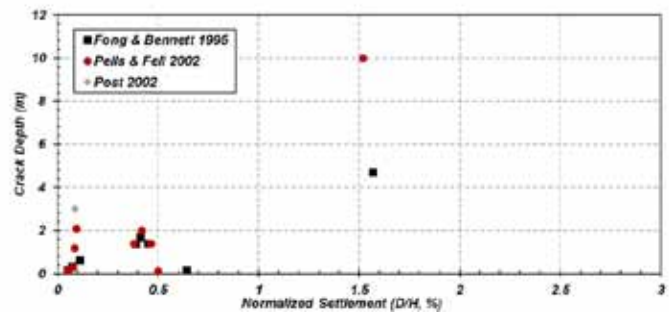


Figure 7. Normalized crest settlement and crack depth data in published databases.

Basic assessments of potential transverse cracking have occasionally been made in practice based on simplified kinematic analysis of the longitudinal strains associated with differences between calculated deformations for various transverse sections of a dam. Conceptually, numerical plane-strain analyses of stresses and strains in the longitudinal section of a dam can also be used to evaluate potential transverse cracking due to seismic deformations calculated at transverse sections of the dam. The main issues with this numerical approach, however, lie in the lack of analytical rigor and inaccuracies associated with imposing on the longitudinal section of a dam the deformations calculated for its transverse sections. Therefore, these types of numerical analyses are not common in practice.

Direct Procedures

In these procedures, the extent of cracking is estimated directly from numerical dynamic response analysis of a dam. Two-dimensional analyses of transverse sections of a dam may be used to examine the potential for longitudinal cracking. However, 3D dynamic response analyses are necessary to examine the potential for transverse cracking. The use of 3D numerical analyses to examine the potential for cracking due to foundation fault rupture on embankment dams has been discussed by Mejia and Dawson (2012).

Three-dimensional dynamic response analyses have seldom been used to evaluate potential cracking of embankment dams because of their complexity. Key considerations in performing these types of analyses include: a) the significant effort involved in generating a representative analysis mesh, b) the need to appropriately model boundary conditions that account for the unbounded nature of a dam system, c) the selection of input motions that properly represent the complex wave field generated by an earthquake and are consistent with the choice of system boundaries for analysis, and d) the use and characterization of material constitutive models that adequately simulate 3D stress-strain behavior under shear, compression, and tension loading.

If precise modeling of crack location and geometry is not required for analysis of a dam, it is usually satisfactory to

use a strength-of-materials approach. This approach is acceptable for approximate evaluation of cracking location, orientation, extent, and depth, provided suitable nonlinear constitutive models with an appropriate tensile strength are used in the analysis. Typically, a zero or small tension cutoff is appropriate for analysis, considering that the field tensile strength of most embankment dam materials is expected to be very low.

In the strength-of-materials approach, the location, extent, orientation, and depth of cracks are given by the calculated extension strains and zones where the minor principal stress reaches the tension cutoff. For special dam applications, simulation of crack propagation with analysis methods for continuous media may be achieved by using 'crack band' models (Bazant, 1982), or other strain-softening-localization models, or by using interface elements.

Proposed Approach for Evaluation of Earthquake-induced Cracking

A practical approach to the evaluation of earthquake-induced cracking of existing embankment dams consists of the following steps. These steps should be implemented as necessary, depending on the importance and characteristics of a dam project:

1. Examine the observed or anticipated performance of the dam under construction and long-term loading conditions, including history and location of previous settlement and known cracking, if any.

2. Estimate seismic settlements of the dam using simplified methods of deformation analysis, such as: empirical correlations, analytically-based correlations, or sliding-block analyses.

3. For the estimated seismic settlements, assess the potential for cracking empirically using available case-history databases.

4. Using 2D models of selected transverse sections of the dam and a strength-of-materials approach, evaluate seismic deformations and the potential characteristics of longitudinal cracking at the selected dam sections.

5. For the seismic deformations estimated from the 2D analyses, assess the potential for transverse cracking using simple kinematic considerations and case-history databases.

6. Using 3D models and a strength-of-materials approach, evaluate seismic deformations and the potential characteristics of longitudinal and transverse cracking in the dam.

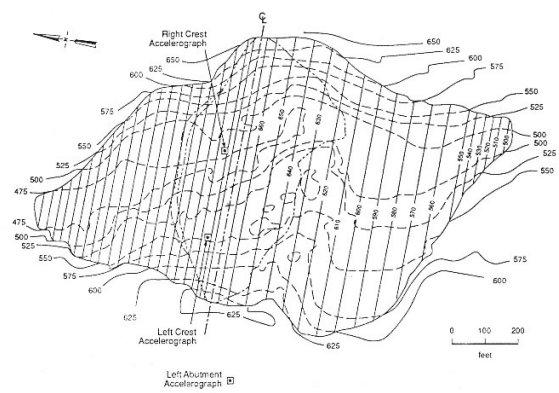
For new dams, the approach would consist of the same steps, but be based on the anticipated characteristics of the dam and its foundation. For large and important dams, the potential for settlement during construction and long-term loading conditions would typically be estimated using finite element analysis procedures.

Analysis of Lenihan Dam for the 1989 Loma Prieta Earthquake

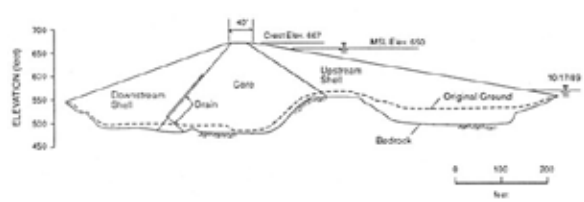
The procedures for 3D analysis of earthquake-induced cracking of embankment dams, using a strength-of-materials approach, are illustrated by the seismic response analysis of Lenihan Dam for the 1989 Loma Prieta earthquake. The response of the dam during the earthquake was previously analyzed by Makdisi et al. (1991) using 2D equivalent-linear analysis methods, and by Mejia et al. (1992) using 2D nonlinear dynamic analyses procedures. The dam response to the earthquake was also recently analyzed by Hadidi et al. (2014) using similar methods. However, none of these previous studies used 3D analysis models or included explicit evaluation of potential cracking of the dam during the earthquake.

Dam Description

Lenihan Dam is located in the Santa Cruz mountains of California about 13 miles northwest of the epicenter of the M 6.9 1989 Loma Prieta earthquake. The dam is a 207-foot-high zoned earthfill with upstream and downstream slopes of 5:1 and 3:1, respectively. The crest of the dam is 40 feet wide and about 810 feet long. A plan view and the maximum cross section of the dam are shown in Figure 8.



(a) Plan view.



(b) Maximum section.

Figure 8. Plan view and maximum cross section of Lenihan Dam.

The dam is founded on Franciscan sandstone and shale bedrock. The downstream shell consists of clayey sandy gravel with about 15 to 40% fines of low to medium plasticity. The materials in the upstream shell and the upper 80 feet of the core are generally similar and consist of clayey sands with about 15 to 35% gravel and 20 to 50% fines of medium plasticity. The materials in the core below 80 feet from the crest are distinct from those above and consist of a clay of medium to high plasticity. Additional information on the characteristics and engineering properties of the embankment and foundation materials is presented by Mejia et al. (1992) and Hadidi et al. (2014).

Recorded Response and Observed Cracking

Three accelerographs, located as shown in Figure 8(a), recorded the ground motions at the site during the Loma Prieta earthquake and other earthquakes. The ground motions recorded at these instruments during the Loma Prieta earthquake are described in previous studies (e.g. Makdisi et al., 1991). The instrument at the left abutment recorded peak ground accelerations of 0.44 g and of 0.41 g in the upstream-downstream and cross-canyon directions, respectively. The maximum crest settlement measured after the earthquake was about 10 inches. The pattern of earthquake-induced cracking at the dam was digitized by Hadidi et al. (2014) and is shown in Figure 9.

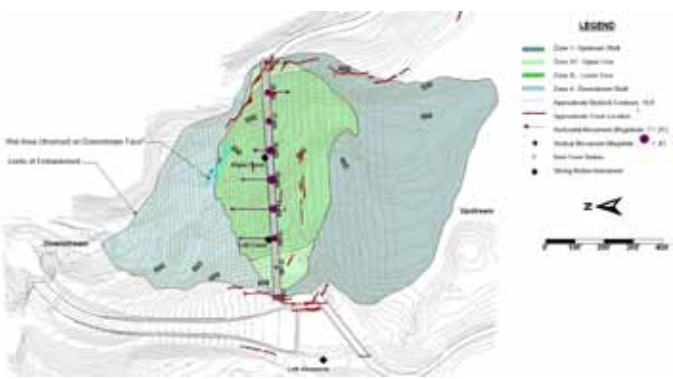


Figure 9. Locations of surface cracks after the 1989 Loma Prieta Earthquake.

Three-Dimensional Dynamic Analysis

The 3D dynamic analyses of the dam were performed using the computer program FLAC3D (Itasca, 2013). Constitutive soil models based on a rigorous mechanics framework for dynamic elasto-plastic behavior of soils in 3D were used. Only the analyses using the linear-elastic-perfectly-plastic Mohr-Coulomb model, built into the FLAC3D code, are presented here.

Figure 10 shows the 3D numerical mesh used in the

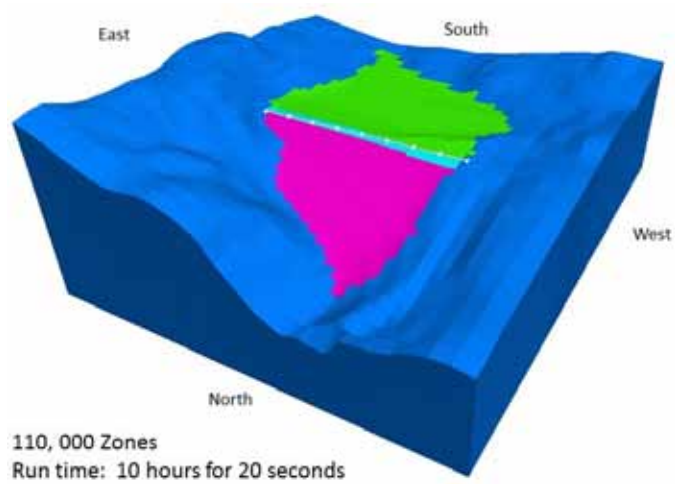


Figure 10. Three-dimensional model for dynamic analysis of Lenihan Dam.

analyses. The model includes the dam embankment and a significant extent of the bedrock foundation and abutments, to allow for proper simulation of dynamic interaction between the dam and the supporting rock domain. Free-field boundaries are included at the base and sides of the model. The earthquake motions recorded at the left abutment were used to develop the input tractions applied at the base of the model.

The Mohr-Coulomb model was used to simulate the stress-strain behavior of the embankment materials. The foundation rock was assumed to be elastic. The key parameters of the Mohr-Coulomb model are the elastic constants of the materials, which control material behavior before yield, and the shear strength, which defines the limits of elastic behavior and the stress state and plastic strains at yield. The analyses were performed assuming a zero-tension cutoff for the embankment materials. This cutoff properly represents the expected low field tensile strength of the embankment materials and ensures that the extent of cracking is adequately captured by the analysis.

The analyses were used to calculate the earthquake ground motions at the locations of the crest accelerographs, the embankment displacements at the locations of the crest survey monuments, and the distribution of tensile stresses and strains in the dam after the earthquake. Figure 11 shows the distribution of maximum horizontal tensile strains at the embankment surface after the earthquake.

Near the ground surface, horizontal tensile strain reflects tensile stress because the static horizontal stresses under gravity loading are small. Thus, near the surface, significant tensile strains are directly associated with cracking. As shown in Figure 11, the distribution of tensile strains closely resembles the distribution of surface cracking observed at the dam after the earthquake, which was mainly transverse

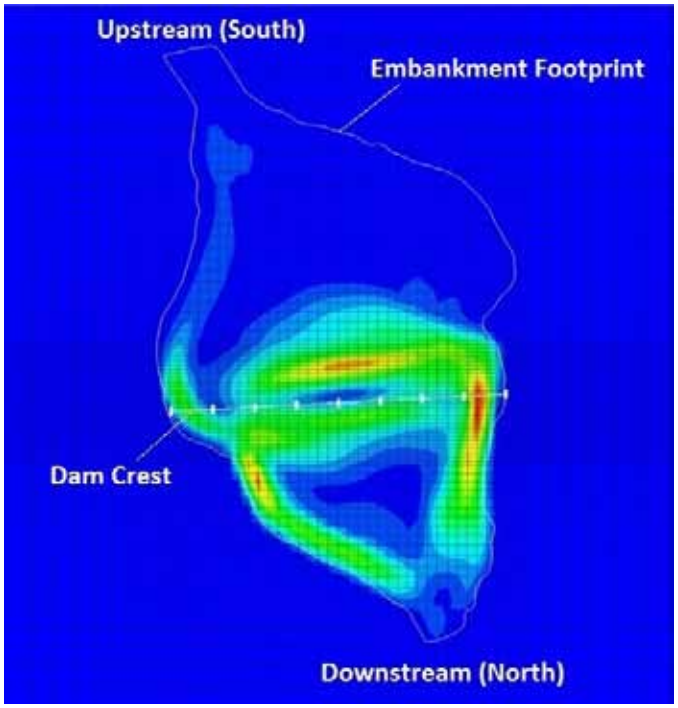


Figure 11. Plan view of maximum surface horizontal tensile strains after the earthquake.

cracking at the abutments and along the groins and longitudinal cracking high on the dam upstream face (Figure 9). Thus, it may be concluded that this type of analysis can be useful in evaluating the potential for and the locations of earthquake-induced cracking in embankment dams.

Concluding Remarks

Transverse cracking at the crest commonly represents a potential failure mode for embankment dams because it can lead to leakage from the reservoir, internal erosion and piping, and dam breaching. An overview of previous studies, key aspects of the mechanics of cracking in soils, and currently available methods to assess the potential for earthquake-induced cracking of embankment dams has been presented.

In addition, a practical, phased approach to the evaluation of potential embankment dam cracking has been proposed. The approach consists of a series of steps to be implemented in order of increasing complexity and effort, as necessary depending on the importance and characteristics of a dam. The process begins with an examination of dam performance under construction and long-term loading and, for important dam projects, culminates with the use of 3D nonlinear analyses of dynamic response using a strength-of-materials approach to estimate potential cracking.

The use of 3D nonlinear dynamic analysis procedures to evaluate potential cracking is illustrated by analysis of the response of Lenihan Dam during the M 6.9, 1989 Loma Prieta Earthquake. It is shown that this type of analysis, if properly implemented, can be useful for evaluating the potential for earthquake-induced cracking in embankment dams, and can indicate the likely locations and extent of potential cracks.

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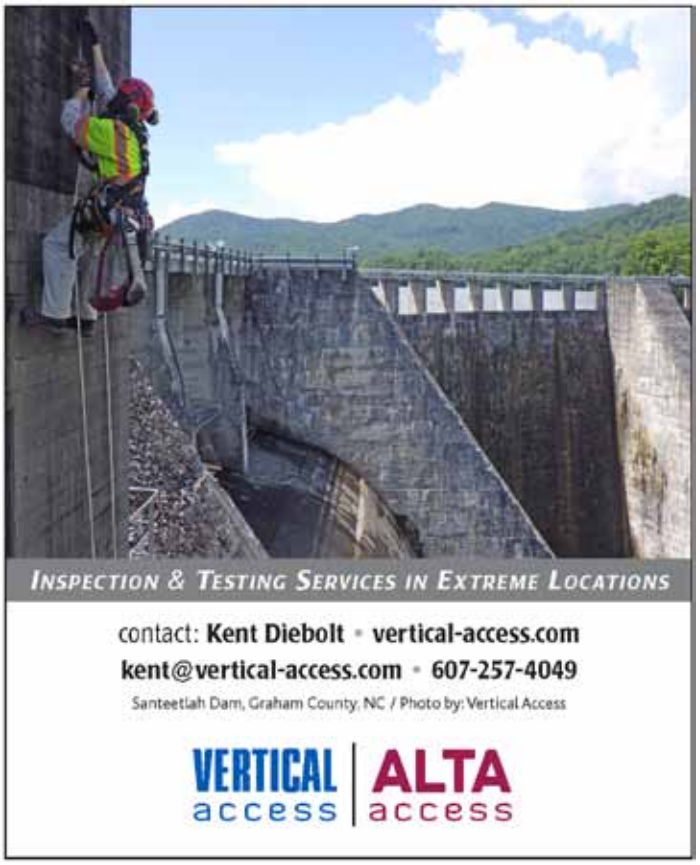

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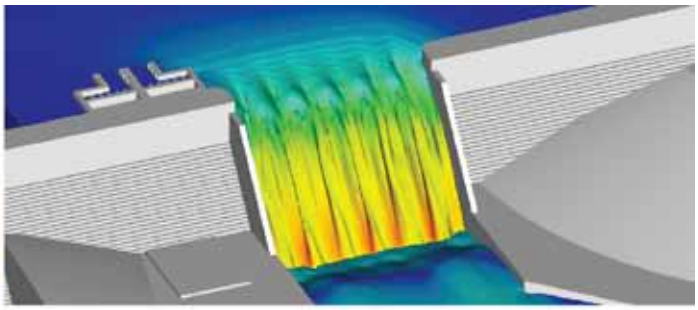

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Probabilistic Dam Breach Analysis — The Future of Dam Safety is Here!

Chris Goodell, Principal Consultant for H&H (chris.goodell@kleinschmidtgroup.com); and Glen DeWillie, Vice President, Kleinschmidt Associates, Portland, Oregon

According to the U.S. Army Corp of Engineers' National Inventory of Dams, more than 15,000 dams are rated as "high hazard" and over one third of the more than 90,000 dams in the inventory are listed as not having an emergency action plan. In seven states , more than half of the high hazard dams are operating without an emergency action plan. Government and private dam owners are confronted with the rising costs of repairing and maintaining this important infrastructure, while balancing the need for keeping public safety at the forefront within their limited budgets.

The question facing our nation is not if we should quickly invest more in dam safety, but instead how to get the most value out of each dollar invested in our dam safety programs. Emergency planning should be a foundational component for dam owners who have an obligation to protect the public and minimize their potential exposure to risks associated with dams. Emergency planning also represents a significantly lower cost item when compared to infrastructure repair, representing an area where owners can reduce risk while meaningfully communicating with and engaging the public.

An immediate area of focus within emergency planning is associated with predicting downstream flooding associated with a dam failure. Our nation's adopted methods for characterizing risks associated with dam breaching and the related downstream flooding are perhaps outdated, and most could argue, overly conservative in assessing downstream hazards related to inundation. Present methods are deterministic, reflecting a single inundated area for which an inhabited structure is either "in" or "out" of the inundated area. There is no communication of risk-no quantification of uncertainty. While such methods create a worst-case breach scenario, they are perhaps misleading, or certainly less informative than using a range of partial dam failure releases that could result in a much wider range of inundation scenarios and flood related outcomes for downstream populations and critical infrastructure.

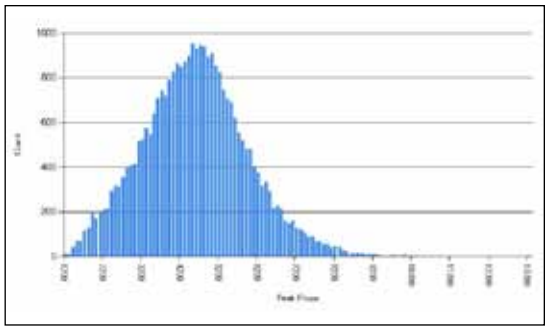

Figure 1. Distribution of dam breach peak outflow rates.

To address this uncertainty of flooding outcomes and improve decision making capabilities at the emergency planning level, Kleinschmidt has developed techniques to perform probabilistic evaluations of dam breach consequences to compliment the traditional deterministic approach. These techniques are built into the McBreach software application. This unique dam breach software allows the user to specify statistical distributions for the dam breach parameters, making way for the software to randomly sample dam breach parameter sets. Coupled with the USACE modeling software HEC-RAS, McBreach launches a Monte Carlo simulation consisting of many thousands of dam breach simulations to produce a distribution of possible dam breach peak outflow rates (Figure 1). Exceedance probabilities can then be assigned to the full range of possible dam breach peak outflow rates. The resultant output files are then mapped to visualize downstream impacts over a range of outcomes and the respective probabilities of occurrence for those outcomes, instead of a single deterministic outcome.

A key design element built into the software is the ability to randomly sample breach characteristics into several thousand (or more) breach parameter sets; each set being applied to a single dam breach simulation (or realization) in HEC-RAS. More realizations provide a more robust statistical output that demonstrates convergence of statistical moments of the computed peak discharges. But the tradeoff involved is simulation runtime. Varying the sample size provides the user with control over fidelity of output as a function of computing power available. Knowing this tradeoff is important, as statistical convergence normally occurs in the range of five to ten-thousand simulations, as shown in Figure 2. With the advent of efficiency techniques like model truncation, we have cost-effectively reduced the Monte Carlo simulation from weeks or longer, to an overnight exercise. Cloud computing can further reduce simulation times to as little as 30 minutes for up to 10,000 simulations.

So why is this new dam breach modeling practice important to

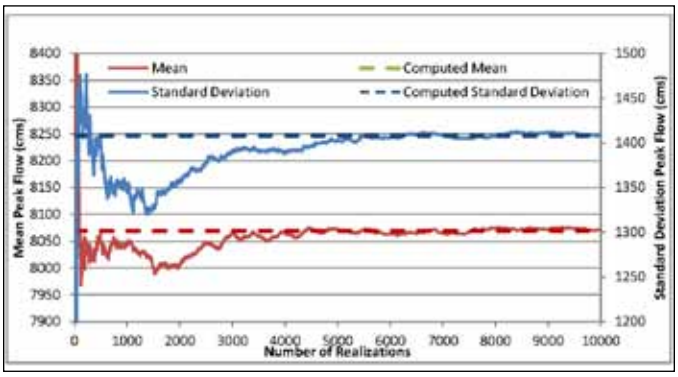

Figure 2. Number of realizations to achieve statistical convergence.

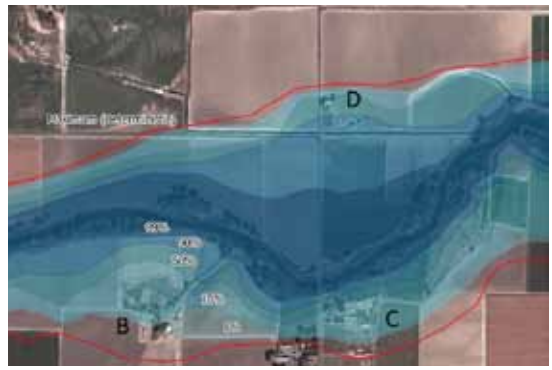

Figure 3. Exceedance Probability Inundation Map.

emergency planners? Picture a mapped overlay of shaded zones of inundation (shown in Figure 3) with stated probabilities reflecting the likelihood of flooding occurrence at a given point on the ground. As one example, high probability inundation areas (those with the highest chance of flooding) could be prioritized for evacuation and specific evacuation routes could be created that allow for organized traffic egress. With limited traffic management resources and an informed citizenry aware of staged evacuation planning, this critical thinking and risk informed decision making in advance of an event could save lives. Armed with this information, decision makers can identify the risks associated with key infrastructure. Key bridges, road intersections, can all be visualized in the context of likelihood of inundation from the breach event, coupled with the local flooding that could exacerbate the situation.

Inundation maps are a required component of emergency action plans. Having a detailed, risk-informed map arms decision makers with better information in advance of an actual emergency, transforming the state of the practice of deterministic outcomes, to those based on probabilities over a range of flooding scenarios. Getting McBreach into the hands of experienced modeling professionals will advance both the level of preparedness and decision-making capability of dam safety owners across the US, and will provide more context and understanding to the estimated consequences of a dam breach event. More information on this tool and its unique capabilities can be found at https://www.kleinschmidtgroup.com/mcbreach/.

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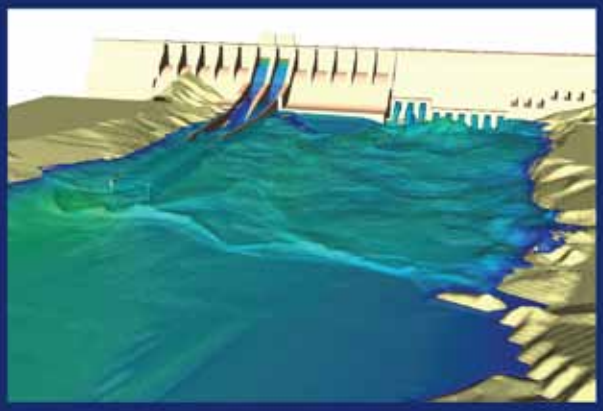

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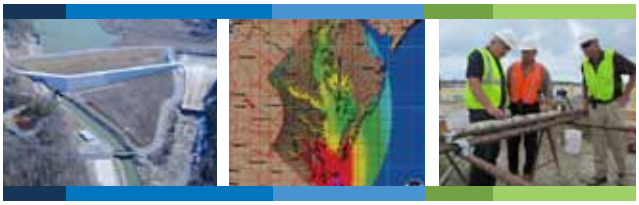

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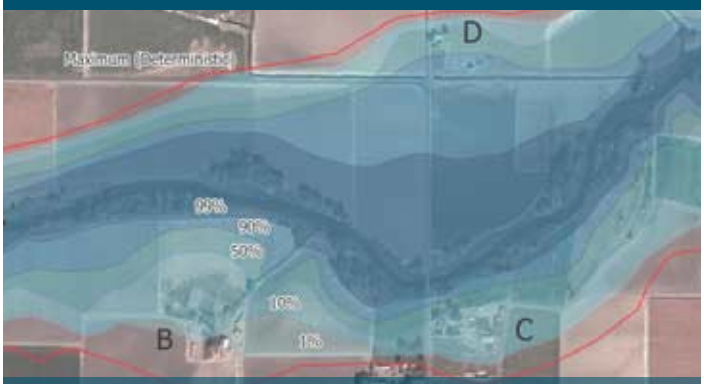

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GEI
Oakland, CA

Membership

Board of Directors Update

The USSD Board of Directors has approved the following committee appointments:

Dam Safety — Chair, **Robert Pike;** Vice Chair, **Jacob Davis**
Environment and Sustainability — Chair, **John Osterle**; Vice Chair, **Brandan Vavrek**
Young Professionals — Chair, **Emily Schwartz**

During its April 7 meeting in Chicago, the Board elected **Denise Bunte-Bisnett**, Santee Cooper, as President; **Stuart Harris**, Tennessee Valley Authority, as Vice President; and **Del Shannon**, Barnard Construction Company, as Secretary-Treasurer.

USSD's Executive Committee recently attended *Exceptional Boards: Strengthening the Governance Team*, put on by ASAE in Carlsbad, California. The two-day workshop, attended by Denise Bunte-Bisnett, Stuart Harris, Del Shannon, and Executive Director Sharon Powers, delved into best practices and legalities for associations and its boards, as well as developing strong working relationships between staff and volunteer leaders.

News of Members

Nathan Bolles is now with Stantec in Fort Collins, Colorado.

Gannett Fleming, Inc. acquired **SAGE Engineers Inc.** on April 1, marking the firm's fourth acquisition in seven months and the second in California. Sage Engineers will operate as a business group of Gannett Fleming.

Global Diving & Salvage, Inc. announced their acquisition by Moran Environmental Recovery, LLC. Global will continue to operate under its current brand, as a wholly-owned subsidiary of MER.

Tim Newton is now with **Arcadis** in Chattanooga, Tennessee.

Ali Tabrizi is now with **Stantec** in Sacramento, California.

WEST Consultants, Inc. announced the opening of a new office in Dallas. Ramesh Chintala will lead Texas area operations.

WSP USA has announced that Karen Block has been promoted to business development director of the firm's national water and environment business. The firm also announced its intent to become carbon neutral across its U.S. operations, including all offices and employee business travel, in 2019.

Board Election

In recent balloting, USSD Members elected Dina Hunt, Paul Meeks and Elena Sossenkina to three-year terms on the USSD Board of Directors.

Dina Hunt is a Seismic Hazard Engineer with Gannett Fleming's Dams & Hydraulics group. She has 15 years of experience with a focus on developing seismic design criteria for large dams. She focuses on site specific seismic hazard evaluations using both probabilistic and deterministic approaches, as well as developing design time histories. Her current expertise includes conducting advanced seismic hazard analyses, in depth knowledge of seismic codes, design guides, and seismology research.

Paul Meeks is the President and CEO of Worthington Products, Inc. He has been actively involved in the dams industry since 1989 where his first exposure to large dams took place at B.C. Hydro's G.M. Schrum generating station in northern British Columbia. Following that start, he has worked with dam owners, engineers and consultants on projects in more than 62 countries.

Elena Sossenkina is the National Levees Practice Leader, for HDR. She has 20 years of experience in dam safety engineering, including design, construction, surveillance and monitoring, risk assessment and emergency action planning. She has extensive dam design and construction experience and specializes in dam and levee safety risk management, with a strong background in quantitative risk analysis.

In Memorium

Don U. Deere passed away on January 14, 2018, in Gainesville at the age of 95. An expert on tunneling, and dam design and construction, he co-founded Deere and Merritt in 1972, an international consulting firm in geology and rock mechanics.

Donald Stager, 88, of Woodside, California, passed away on March 6, 2019. He joined Guy F. Atkinson Company in 1952, overseeing construction of dams. He worked in Pakistan as general superintendent of excavation for the Mangla Dam project from 1962–1967. In 1982, he joined Dillingham Construction, eventually becoming president and CEO.

Membership

Life Members

George L. Barber
Steven L. Barfuss
Zoren Batchko
Ralph R. W. Beene
Wilson V. Binger, Jr.
John A. Bishoff
David S. Bowles
Tobia L. Brewer
Rodney Bridle
Denise Bunte-Bisnett
Edwin H. Campbell
John J. Cassidy
Sanjay S. Chauhan
Ying-Kit Choi
Anil K. Chopra
John P. Christensen
Ashok K. Chugh
William B. Connell
Stephen D. Cross
Woodrow W. Crouch
Kim de Rubertis
Franklin G. DeFazio
Jerry S. Dodd
Karl J. Dreher
William H. Duke
Lance Duncan
Blaine Dwyer
Donald R. East
Joseph L. Ehasz
E. Harvey Elwin
Kathleen Evans
R. Craig Findlay
Steven A. Fry
Duane L. Georgeson
Yusof Ghanaat
James R. Graham
Christopher C. Grieb
Patrick M. Griffin
Sammie D. Guy
James V. Hamel
Gregory G. Hammer
Michael Jonathan Harris
Mark R. Haynes
Alfred J. Hendron, Jr.
Daniel J. Hertel
H. John Hovland
Carlos Alberto Jaramillo
Palmi Johannesson
Michael C. Johnson
Robert W. Johnson
Pierre Julien
Charles E. Karpowicz, Jr.
Byron C. Karzas
Woogu Kim
Terence M. King
David E. Kleiner
Hasan T. Kocahan
Richard W. Kramer
Paul Krumm
Haibo Liang
Frederick Lux III
Arthur C. Martin
B. Philip Martin
Errol L. McAlexander
Christopher L. Meehan
Andrew H. Merritt
Donald L. Millikan
Mahmoudreza Mivehchi
Paulo J. M. Monteiro
Warren J. Paul
Michael J. Pauletto
J. Bruce Pickens
Robert Pyke
Jin Tien Quin
Vikram V. Rajadhyaksha
Alan T. Richardson
Bennie N. Rinehart
J. David Rogers
Michael F. Rogers
Kelly R. Schaeffer
Ernest K. Schrader
E. Douglas Schwantes, Jr.
Paul H. Schwartz
Chander K. Sehgal
Suprabhat Sengupta
Francisco Silva
John D. Smart
Jay N. Stateler
Kenneth Aaron Steele
Larry D. Stephens
Amanda Sutter
Gilbert R. Tallard
Glenn S. Tarbox
Robert E. Tepel
Lloyd O. Timblin, Jr.
Daniel Martin Toft
Daniel A. Vellone
J. Lawrence Von Thun
Michael Wainaina
Arthur H. Walz, Jr.
John E. Welton
Roman P. Wengler
John W. Williams
Richard Lyman Wiltshire
Christina Winckler
C. H. Yeh
Darell Dean Zimbelman
John A. Zygaj

Sustaining Members

AECOM
ASI Construction LLC
Barnard Construction Company, Inc.
Black & Veatch Corporation
Campbell Scientific
Emagineered Solutions, Inc.
Federal Energy Regulatory Commission
Flow Science
Freese and Nichols, Inc. *
Gannett Fleming, Inc. *
GEI Consultants, Inc. *
Geocomp
Geosyntec Consultants
Golder Associates Inc.
GZA GeoEnvironmental, Inc. *
Hatch Associates Consultants, Inc. *
HDR
Keller Foundations, LLC
Kleinfelder, Inc.
Kleinschmidt Group
OBG, Part of Ramboll
Phillips and Jordan, Incorporated
RIZZO International, Inc.
RJH Consultants, Inc.
Schnabel Engineering, Inc.
Stantec
U.S. Army Corps of Engineers *
U.S. Bureau of Reclamation*
Worthington Products, Inc.
WSP

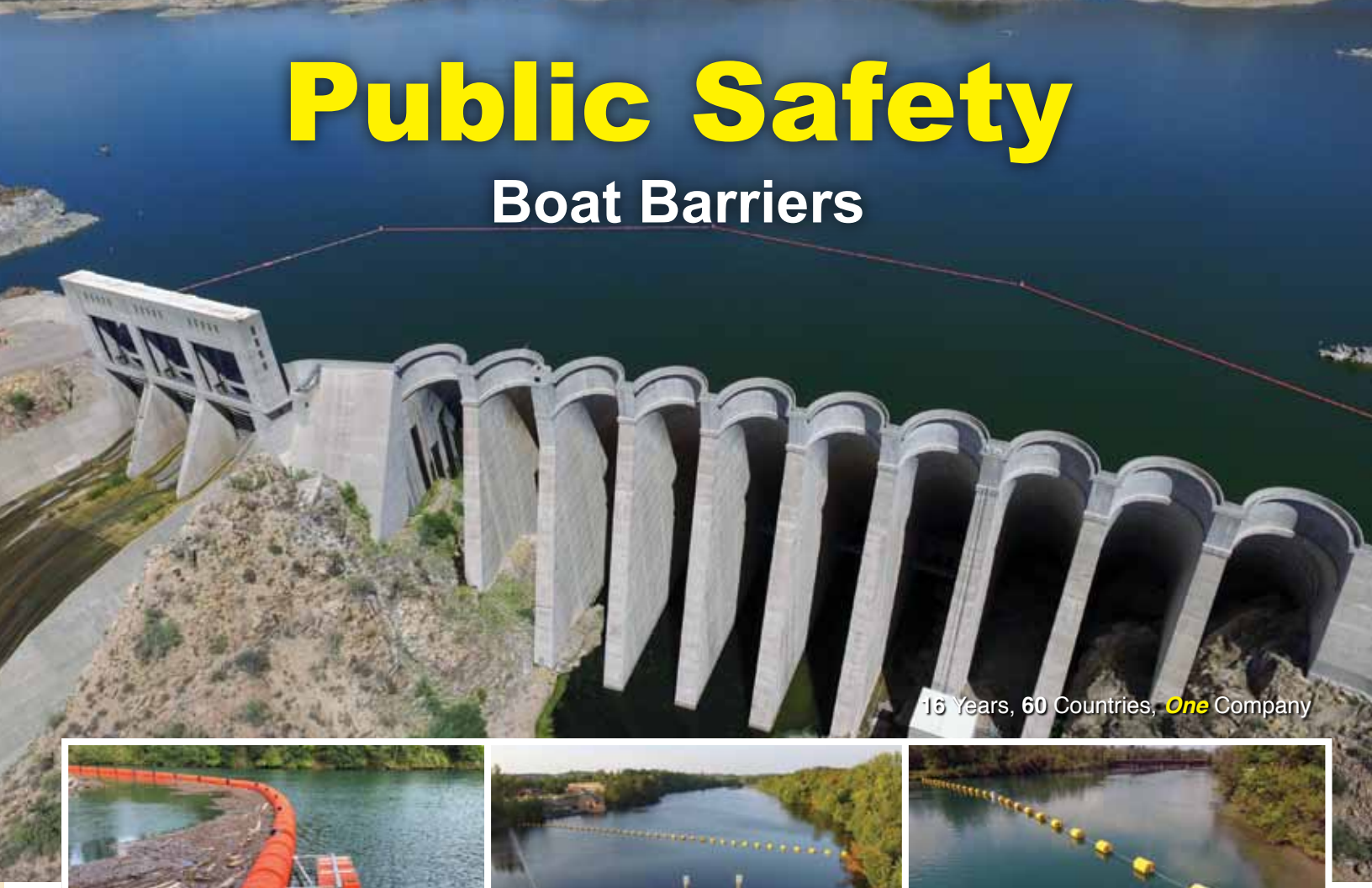
**designates Charter Sustaining Member*

Organizational Members

Advanced Construction Techniques Inc.
Alaska Department of Natural Resources
Arcadis
ASI Group Ltd.
ASI Marine, L.P.
Ballard Marine Construction
BAUER Equipment America
Bechtel Global Corporation
California Department of Water Resources
Canary Systems, Inc.
Cascade Drilling, L.P.
CDM Smith
Colorado River Water Conservation District
Condon-Johnson & Associates Inc.
Crowder Construction Company
D'Appolonia Engineering
DLZ National, Inc.
Durham Geo-Slope Indicator
East Bay Municipal Utility District
GENTERRA Consultants, Inc.
GeoEngineers, Inc.
Geokon, Inc.
Geo-Solutions Inc.
Global Diving & Salvage, Inc.
Griffin Dewatering Southwest, LLC
J.F. Brennan Company, Inc.
Knight Construction & Supply
Knight Piesold and Co.
Malcolm International
Mead & Hunt, Inc.
Measurand
Medatech Engineering Services Ltd.
Metropolitan Water District of Southern California
Mississippi Department of Environmental Quality
Nicholson Construction Company
Olson Engineering
OneRain Incorporated
Pacific Gas and Electric
Rembco Geotechnical Contractors, Inc.
RST Instruments Ltd.
Santee Cooper
Shannon & Wilson, Inc.
SNC Lavalin
Sukut Construction, LLC
Tennessee Valley Authority
Traylor SRG LLC
WEST Consultants, Inc.
Wood
Xcel Energy Corporation

Public Safety

Boat Barriers



Worthington is the right partner to solve your waterway barrier challenges. Worthington has been the trusted choice of dam professionals for more than 18 years and in over 62 countries.

Let us put our global installation expertise, common sense engineering, and understanding of debris, fish, public safety and security issues at dams to work for you.

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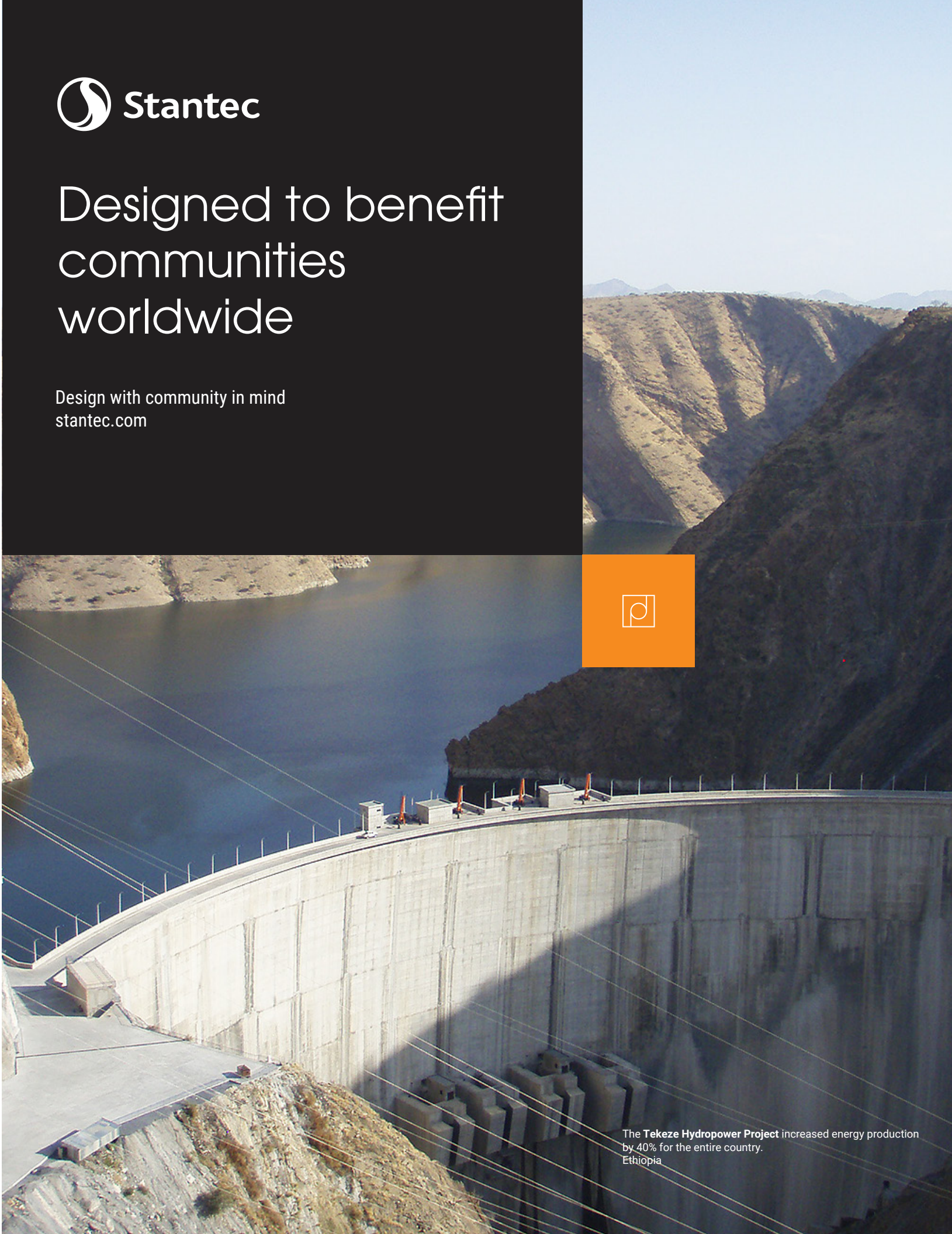

The **Tekeze Hydropower Project** increased energy production by 40% for the entire country.
Ethiopia