

## **Root Causes Analyses of the Oroville Dam Gated Spillway Failures and Other Developments**

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<sup>a</sup> Summary background available at <https://drive.google.com/open?id=0Bz1I1mIutSEnd05fWUNIVXcyWFk>  
Additional background available at - <http://www.mensjournal.com/magazine/bob-bea-the-master-of-disaster-20130225> and  
<http://discovermagazine.com/2013/june/14-master-of-disaster>

<sup>b</sup> Summary background available at <https://drive.google.com/open?id=0Bz1I1mIutSEneTN6YlNKRVdZcGs>

## **Introduction**

We have performed forensic Root Causes Analyses of the Oroville Dam Gated Spillway failures and other associated developments as unfunded (approximately 3,000 pro-bono hours) volunteers of the University of California at Berkeley (UCB) Center for Catastrophic Risk Management (CCRM) Oroville Dam Advisory Group (ODAG). We initiated this work on January 27, 2017.

The results contained in this report have been developed based on the currently available public document and information sources cited at the end of this report, included in the Preliminary Root Causes Analysis of the Failures of the Oroville Dam Gated Spillway report dated April 17, 2017, and in the Legislative Oversight Report: Oroville Dam report dated May 11, 2017.<sup>c,1</sup>

This report documents our analyses of the Root Causes of the initial failure of the Gated Spillway. Appendix A of this report provides summaries of the procedures and processes we used to perform the Root Causes analyses, background on the components that comprise Engineered Systems, and background on the Human and Organizational Factor malfunctions (errors) responsible for failures of Engineered Systems. Appendix B provides details of our analyses of the Physical and Organizational Root Causes of the initial failure of the Gated Spillway.

The opinions expressed in this Report are ours alone. The opinions expressed herein are a fair and accurate summary of our opinions, based upon our experience, education, training, and expertise.

*Robert Bea and Tony Johnson*

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<sup>c</sup> References cited are included in the References Section at the end of this report together with Google Document links to archived copies of the available cited documents.

## **Acknowledgements**

In January 2006, Professor Raymond Seed and the first author of this report co-founded the UCB CCRM.<sup>d</sup> CCRM was formed as a multi-disciplinary, multi-campus research and development center that focused on prevention and mitigation of major failures involving engineered infrastructure systems.

Starting in 2009, CCRM served as the focal point for a Research and Development Project sponsored by the National Science Foundation identified as the RESIN (Resilient and Sustainable Infrastructure Systems) Project.<sup>e</sup> This project developed, validated, and applied advanced System Risk Assessment and Management (SRAM) to the California Delta Infrastructure Systems.<sup>f</sup> During this 6-year duration project, specific infrastructure systems located in the California Delta (e.g. flood protection, emergency evacuation, Sherman Island, Natomas Basin) were studied to determine the risks associated with extreme condition storms based on 2010 and 2100 environmental conditions (including projected global climate changes).<sup>g</sup> Results from the RESIN project provided important starting points for this investigation.

During May 2017, the UCB CCRM Executive Director, Dr. Rune Storesund, initiated formation of the Oroville Dam Advisory Group (ODAG). The UCB CCRM ODAG was formed to provide a public source of information on the developments associated with the failures and potential developing failures of different components in the Oroville Dam System. This work included development of specific short-term and long-term recommendations for ‘going forward.’ Currently, the UCB CCRM ODAG has 15 members that include senior academic faculty, citizens concerned with the Oroville Dam developments, retired California Department of Water Resources (DWR) managers, engineers, and operators, and local business, environmental and government group representatives.<sup>h</sup>

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<sup>d</sup> CCRM background available at <http://ccrm.berkeley.edu/>

<sup>e</sup> CCRM National Science Foundation sponsored RESIN project background available at <http://ccrm.berkeley.edu/resin/>

<sup>f</sup> Detailed descriptions of System Risk Assessment and Management processes, approaches, and analytical formulations available at <https://drive.google.com/open?id=0Bz1I1mlutSEnUEJtbmluSVVCa0U> and <https://drive.google.com/open?id=0Bz1I1mlutSEnTFVkaDUxLTNYZ2M>

<sup>g</sup> Products (documents, reports, videos) developed by the RESIN project are available at <https://drive.google.com/open?id=0Bz1I1mlutSEnOEV1TkFxS2JsZFU>  
[https://drive.google.com/open?id=0B0\\_jjqbhy5meOENOSzRGbTVJNFU](https://drive.google.com/open?id=0B0_jjqbhy5meOENOSzRGbTVJNFU)  
<https://drive.google.com/open?id=0Bz1I1mlutSEnclRwVGNHanVfb1U>  
<https://drive.google.com/open?id=0Bz1I1mlutSEnanczemd2MDBySXC>  
<https://drive.google.com/open?id=0Bz1I1mlutSEneklySnZnOHJkWWW>  
<https://drive.google.com/open?id=0Bz1I1mlutSEnX3gyN2FpWjE3NGc>

<sup>h</sup> Current list of CCRM ODAG members available at <https://drive.google.com/open?id=0Bz1I1mlutSEnWUpfZWkxU0NmOTQ>

Since early February, we have received significant inputs from many retired former California Department of Water Resources (DWR) Division of Engineering engineers, Operations and Maintenance engineers, and former DWR operators and managers. These individuals were and still are highly respected, and experienced in design, construction, operations, and maintenance (O&M) of the California State Water Project (SWP) facilities, and in developing preparations for and responding to SWP emergencies assisted by the California Governor's Office of Emergency Services (Cal OES). These individuals received Director level recognition and awards from the cited State organizations. At this time, with one exception<sup>i</sup>, these people have requested their names not be made public to help preserve their privacy. These people willingly volunteered their knowledge, experience, documentation, and advice as very important resources that have been integrated into this report.

These people have demonstrated consistently their desire to contribute in positive ways to realization of two primary Objectives: 1) attempting to help improve the management, engineering, and operations of DWR, and 2) encourage the State help DWR secure other essential resources needed to develop, maintain, and improve DWR and SWP operations and the results from those operations.

The ultimate Goal of these two Objectives has been to help re-establish and advance DWR and the Division Of Safety of Dams (DSOD) and the associated responsible State and Federal agencies groups (e.g. State Water Contractors) capabilities to provide for the reliable delivery of a vital resource – water, and to contribute to provision of associated Infrastructure Systems,<sup>j</sup> such as those for Flood Protection, that are able to provide essential public infrastructure services having desirable Safety,<sup>k,2</sup> As Low As Reasonably Practicable (ALARP) Risks<sup>l</sup>, and Quality<sup>m</sup> performance characteristics for the citizens of the State of California.

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<sup>i</sup> updated Don Colson report on Emergency Spillway use disastrous decisions available at <https://drive.google.com/open?id=0Bz1I1mlutSEnZGFlnZhoS2tvMkU>

<sup>j</sup> **Systems** - Interconnected, interactive, interdependent Human, Organization, Hardware, Structure, Environment, Guidelines, Standards, Procedures and Processes and Interfaces between the foregoing Components.

<sup>k</sup> **Safety** – Freedom from undue exposure to injury and harm including capabilities to deliver ALARP Risks. For more background: <https://drive.google.com/open?id=0Bz1I1mlutSEnUgwUXZ6WXIYMmc>  
<https://drive.google.com/open?id=0Bz1I1mlutSEnUkpQcXRGQklDbHM>

<sup>l</sup> **ALARP Risks** – Combinations of the Likelihoods and Consequences of major infrastructure System failures – Risks - that are As Low As Reasonably Practicable (ALARP) based on Historic, Current Standards of Practice, and Monetary short-term and long-term present-valued Costs (direct, indirect, current, future) – Benefit (failures prevented and mitigated, decreases in Likelihoods and Costs) analyses and assessments.

<sup>m</sup> **Quality** – combination of public infrastructure system Serviceability (provide important resources and services), Safety, ALARP Risks, Durability (freedom from undesirable, undetected, and un-remediated degradation in System Quality performance characteristics) and Compatibility (freedom significant negative impacts on the environment, public, commerce and industry, and government).

Of particular importance to this phase of our investigation is the report written by two members of the CCRM ODAG that summarizes *The “Watering Down” of the Department of Water Resources Division of Safety of Dams.*<sup>n</sup> This report summarizes DWR and DSOD multi-decade progressive ‘Losses of Core Competencies’ and contains recommendations for DWR – DSOD re-organization, management, operations, maintenance, and engineering resources and oversight.

In addition, we have received important inputs, guidance, and other resources to help develop our understanding of the circumstances and factors that were operative during development of the Oroville Dam Spillway failures from two organizations and groups of concerned citizens who established, operated, maintained, and continue to develop internet Group Communication web sites: 1) Metabunk.org<sup>o</sup> and 2) FreeRepublic.com<sup>p</sup>. These two groups continue to develop important information and insights we have attempted to properly interpret and integrate into this report.

We have compiled a series of discussions previously posted on FreeRepublic.com that have particular importance in this phase of our investigation. This compilation is provided in this report as a single down-loadable reference.<sup>q</sup> The major issues addressed in this series are:

- 1) DWR's decision to Split the Spillway design in 1960's - Politics of Engineering Judgment: How Failure is introduced - #2596
- 2) Cracked Anchor Tendons & Failures, FERC, DWR engineering data conflicts & changing definitions, unknowns of tendons - #3334
- 3) DSOD Inspector "unloads" in report - DWR's indifference to maintenance - DWR using seepage flow as "crude" replacement for lost Piezometers - #3675
- 4) Headworks design flaw - Shear cracking in Pier Columns - Risk to FCO gate structures - differential settlement of bridge lift footing - #3703
- 5) Large Concrete Block formation by DWR in "deep void" filling - erosion forming voids - drain pipe dropping & clogging by concrete/grout entering drain lines - tree roots - #3704
- 6) DSOD Inspector report notes that known defective areas in spillway repairs will be performed only after damage from heavy flows - #3707
- 7) FERC issues a long list of corrections to DWR on Quality Control Inspection Program (QCIP). Demonstrates lack of engineering experience by DWR on QCIP - #3778
- 8) Radial Gate Side Seal Assembly issues - design flaws? - excessive leakage of side seals deemed "normal" by DSOD - susceptible to debris jamming? - divers removing wedged debris to open gates - #3846/3847

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<sup>n</sup> The “Watering Down” of the Department of Water Resources Division of Safety of Dams available at <https://drive.google.com/open?id=0Bz1I1mlutSEnUks4T3ljdlJLcWs>

<sup>o</sup> Metabunk.Org ,accessible at: <https://www.metabunk.org/forums/OrovilleDam/>

<sup>p</sup> Free Republic.Com, accessible at: <http://www.freerepublic.com/focus/search?q=quick&m=all&o=time&s=Oroville+Dam&find=Find> and <http://www.freerepublic.com/focus/news/3524221/posts?q=1&page=1#1>

<sup>q</sup> Compiled Free Republic Oroville Dam spillway failures discussions available at <https://drive.google.com/open?id=0Bz1I1mlutSEnZ1BDXzAwZS12cDA>

- 9) Water Vortex in front of Emergency Spillway noted & photographed by DSOD - withheld this information in public reports - discrepancy Found in FERC Performance Review document - why keep from public? - #3862
- 10) DWR Organizational Ethics - Engineering Incompetence or Engineering Deception - Flawed information - Press Releases, Town Halls, Press interviews, Legislative Testimony - #3903
- 11) New Oroville Spillway 1:50 Model testing - Scalability issues - Forensic Team "stalling"? Politics? - Suggested Forensic Team HOF issues to investigate - #3924
- 12) Former DSOD Chief admits "Maybe we did miss it" (signs to spillway failure) - points to Forensic Team to give an answer - "maybe" verses "Known or Unknown" - #3931
- 13) DWR twisting BOC's comments? Turning them into "conclusions"? Highly Misleading? -Preemptive strike to mute intentional use of "fill material" in building of spillway? - #4012

Of particular importance to this phase of our investigation is a series of ten (10) reports authored by the second author of this report. These reports address four categories of ‘breakdowns’ associated with the Oroville Dam ‘System’:<sup>r</sup>

- 1) Persistent existing ‘Leaks’ and ‘Wet Spots’ on and around the dam (Reports 1 – 4),
- 2) Persistent existing ‘Cracks’ in the Gated Spillway Headworks reinforced concrete supporting structure and broken and cracked gate anchor ‘tendons’ (Reports 6, 7, 10),
- 3) Progressive failures of the Gated Spillway and historic ‘patchwork’ repairs (Reports 5, 8), and
- 4) DWR – DSOD mis-management ‘liabilities’ (Report 9).

## **Summary of Conclusions**

The flaws and defects incorporated into the Oroville Dam Gated Spillway represent accumulated results from the Gated Spillway’s Life-Cycle Phases (1965 to February 2017). The Life-Cycle defects include those developed during Design, Construction, Operations and Maintenance (O&M) Phases. Of particular importance in this Root Causes investigation<sup>s</sup> were the Standards, Guidelines, procedures and processes used by the California Department of Water Resources (DWR) and the associated Division of Safety of Dams (DSOD) during the life-cycle phases of the Gated Spillway.

The California Code of Regulations and The California Water Code **charge DWR and DSOD with primary responsibilities and accountabilities for specified State Water Supply dams and reservoirs during their lives: “...as to the Safety of design, construction, maintenance, and operation of any dam or reservoir.”<sup>t</sup>**

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<sup>r</sup> Compiled reports 1 – 10 authored by Tony Johnson available at <https://drive.google.com/open?id=0Bz1I1mIutSEnR3U4QVY2TFRWLWc>

<sup>s</sup> See Appendix A pages 1-4 for background on performance of Root Causes Analyses.

<sup>t</sup> A compiled summary of DWR – DOSD responsibilities, accountabilities and practices is available at <https://drive.google.com/open?id=0Bz1I1mIutSEnWTJsM2Q4V0F3MTA>

In the April 17<sup>th</sup> Preliminary Root Causes Analysis report<sup>u</sup> and the May 11<sup>th</sup> Legislative Oversight Testimony report<sup>v</sup>, specific defects and flaws in the Gated Spillway were cited and described that could be identified and corroborated based on the photographic evidence and documentation referenced in those reports' references. A summary of the analyses of the physical causes of the initial failure in the Gated Spillway was provided.

Our Root Causes Analyses investigations have concluded the physical effects of the life-cycle flaws and defects incorporated into the Gated Spillway were **highly interactive and cumulative**. **The interactions resulted in progressive deterioration of the performance abilities of the Gated Spillway and resulted in reduction of its Safety and increases in its Risk of failure. This process continued until the Gated Spillway failed during the early February 2017 Oroville Dam reservoir discharges.**

Our Root Causes Analyses investigations have concluded **that 'inappropriate'<sup>w</sup> standards and guidelines, procedures and processes were used by the Department of Water Resources (DWR) and the associated Division of Safety of Dams (DSOD) to evaluate and manage the Risk<sup>x</sup> of failure characteristics of the Gated Spillway.** These standards and guidelines, procedures and processes failed to adequately and properly address **Aging, Technological Obsolescence, and Increased Risk of failure** characteristics of the Oroville Dam Gated Spillway.

Due to the multi-decade 'Loss of Core Competencies', the management of DWR and DSOD failed to provide adequate Management (planning, organizing, leading, controlling), Engineering, Operations, and Maintenance personnel 'skills, knowledge and performance capabilities' and other important 'resources' required to effectively prevent and mitigate the failures of the Gated Spillway.<sup>m</sup> **The Gated Spillway was 'managed to failure' by DWR and DSOD.**

In addition, the available evidence indicates validation and approval of the long-term continued **use of these 'inappropriate' standards, guidelines, procedures and processes** was provided by the Federal Energy Regulatory Commission (FERC). **The Gated Spillway was 'regulated to failure' by FERC.**

We have received 'redacted' reports released by the DWR Board of Consultants (BOC)<sup>y</sup> and the DWR Forensic Engineering Team (FET),<sup>z</sup> and by the U.S. Army Corps of Engineers (USACE)

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<sup>u</sup> Report available at <https://drive.google.com/open?id=0Bz1I1mIutSEnSUY5WjluQmhPXzg>

<sup>v</sup> Report available at <https://drive.google.com/open?id=0Bz1I1mIutSEnWHozRUSyNf1Y2c>

<sup>w</sup> 'Inappropriate' – intentional deviations from mandated acceptable practice Standards and Guidelines.

<sup>x</sup> **Risk** – Likelihood and Consequences associated with major failures of an Engineered System.

<sup>y</sup> Reports available at <https://drive.google.com/open?id=0Bz1I1mIutSEnOXdGMU1Ob0JGcFE>  
<https://drive.google.com/open?id=0Bz1I1mIutSEnWXB4NVNRVUhsR1U>  
<https://drive.google.com/open?id=0Bz1I1mIutSEnT3ZDcll6NDZkRnM>

<sup>z</sup> Report available at [https://drive.google.com/open?id=0B0\\_jjqbhy5meVEpjR1RIZExBR1E](https://drive.google.com/open?id=0B0_jjqbhy5meVEpjR1RIZExBR1E)



Institute for Water Resources Risk Management Center.<sup>aa</sup> Also, we have received a report written by Bernard Goguel that provides a summary of his analyses of the initial failure in the Gated Spillway.<sup>bb</sup>

Our reviews of the physical causes related to design, construction, operation and maintenance of the Gated Spillway identified in these reports leads us to conclude these findings substantially corroborate those identified in the April 17<sup>th</sup> Preliminary Root Causes investigation report, summarized in the May 11<sup>th</sup> Summary and Recommendations report and in this report. These additional reports have provided important additional details and background on the life-cycle Physical Root Causes of the Gated Spillway failures.

## **Summary of Gated Spillway Defects, Flaws, Development of Initial Failure, and Root Causes**

The following sections summarize the Gated Spillway's physical defects and flaws, initial failure, and Root Causes of this failure identified during this investigation. The evidence (documentation and photographic) to support these identifications are cited in each of the following sub-sections and the References Section of this report:

### **Design<sup>1,3</sup>**

1. Spillway base slabs of insufficient thickness for the design hydraulic conditions: 4 to 6 inches thick at minimum points;
2. Spillway base slabs not joined with 'continuous' steel reinforcement to prevent lateral and vertical separations;
3. Spillway base slabs designed without effective water stop barriers embedded in both sides of joints to prevent water intrusion under the base slabs;
4. Spillway base slabs not designed with two layers of continuous steel reinforcement (top and bottom) to provide sufficient flexural strength required for operating conditions; and
5. Spillway base slabs designed with ineffective 'ground' anchors to prevent significant lateral and vertical movements.

### **Construction<sup>1,4</sup>**

1. Failure to excavate the native soils and incompetent rock overlying the competent rock foundation assumed as a basic condition during the spillway design phase, and fill the voids with concrete, and
2. Failure to prevent spreading gravel used as part of the under-slab drainage systems and 'native' soils to form extensive 'graded blankets' of permeable materials in which water could collect and erode.

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<sup>aa</sup> Report available at <https://drive.google.com/open?id=0Bz111mlutSEnN2V2VnJ2cVhJWVE>

<sup>bb</sup> Report available at <https://drive.google.com/open?id=0Bz111mlutSEncnVEUktrQkNjRms>



## **Operations & Maintenance<sup>1,5</sup>**

3. Repeated ineffective repairs made to cracks and joint displacements to prevent water stagnation and cavitation pressure induced water intrusion under the base slabs with subsequent erosion of the spillway subgrade, and in some cases, to effectively ‘plug’ and severely decrease water flow through the spillway drains; and
4. Allowing large trees and other vigorous vegetation to grow adjacent to the spillway walls whose roots could intrude below the base slabs and into the subgrade drainage pipes resulting in reduced flow and plugging of the drainage pipes.

## **Development of Initial Failure**

Appendix B summarizes a chronological progression of Root Causes analyses to the final genesis of the Initiating Blowout Failure, including the specific Root Causes ‘pre-failure conditions.’ A collection of critical evidential photographs, document clips, and images, from the combing through of thousands of pages of source information and a combined effort of thousands of hours of research and analyses, provides translation of the foregoing summaries to failure - into a ‘walk through’ of the cause and effect chronological progression ending in the final blowout of the spillway on February 7, 2017. The ‘walk through’ chronology also provides insight into the Human and Organizational Factors involved in how conditions continued to progress despite the many signs of distress in the spillway.

By the time of the February 2017 spillway releases from the Oroville reservoir, the Gated Spillway had become heavily undermined and the foundation subgrade eroded by previous flood releases. The spillway releases completed the undermining of the spillway slabs, allowing water cavitation to further damage the slabs and open joints and cracks, and develop stagnation pressures and foundation subgrade seepage pressures to further erode the supporting soils and degraded rock and lift the ‘weak’ slabs (‘hydraulic jacking’) breaking them into pieces.

After the almost catastrophic water release over the un-surfaced Emergency Spillway, the subsequent water releases down the gated spillway propagated the initial spillway breach until the spillway releases ceased.

## **Organizational Root Causes**

Our investigations have concluded the Root Causes of the Gated Spillway failures are founded primarily in Organizational Malfunctions (see Appendix A and Appendix B) due to human and organizational decision making, task performance, knowledge development and utilization as developed and propagated by DWR and DSOD during the Gated Spillway Design, Construction, and Operations & Maintenance activities.<sup>6,7</sup>

The report titled *The “Watering Down” of the Division of Safety of Dams* concludes:<sup>cc</sup>

*“The most significant examples of organizational influence are the recently exposed existence of DSOD inspection reports dating back to 1989. For reasons yet to be fully determined, identified deficiencies were either ignored, treated as low priority, not acted upon or a combination thereof. However, complacency, lack of industry standard level maintenance, and possibly pressure from internal DWR management and external State Water Contractors’ representatives to hold down maintenance costs were key contributors. The lack of concern and focus in the timely addressing of the Dam Headworks concrete spalling and cracking, missing welds, gate trunion cable cracks, and dam abutment “wet spots”, all noted deficiencies listed in reports generated by DSOD, private engineering consultant(s), the Board of Consultants (which reports to the Director), US Army Corps of Engineers, and FRCIT, serve as prime examples of the DWR culture and failures.”*

In 2009, the American Society of Civil Engineers issued a report titled **“Guiding Principles for the Nation’s Critical Infrastructure.”**<sup>11</sup> This identified four guiding principles that form the foundation for **Risk Management** of the Nation’s Critical Infrastructure:

1. Quantify, communicate, and manage Risk,
2. Employ an integrated Systems approach,
3. Exercise sound Leadership, Management, and Stewardship in decision-making processes, and
4. Adapt critical infrastructure in response to dynamic conditions and practice.

This report states: *“these guiding principles are fully interrelated. No one principle is more important than the others and all are required to protect the public’s safety, health, and welfare.”*

A fundamental premise integrated into these four guiding principles is **Risk Management**. ASCE recommended four things needed to effectively integrate risk assessment, risk management, and risk communication strategies into our nation’s critical infrastructure programs:

1. Produce a best-practices guide and develop and publish codes, standards, and manuals for assessing and communicating risk.
2. Develop a public-policy framework that establishes tolerable risk guidelines and allocates costs for managing risks and consequences.
3. Provide professional education and training to members of the design and construction industries on identifying, analyzing, and mitigating risk.
4. Screen all existing critical infrastructure projects to determine if updated risk analyses are warranted. **Require that Risk Analyses be performed for all proposed critical infrastructure projects.**

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<sup>cc</sup> The “Watering Down” of the Department of Water Resources Division of Safety of Dams available at <https://drive.google.com/open?id=0Bz111mlutSEnUks4T3ljdjJLcWs>

In 2016, the Federal Energy Regulatory Commission (FERC) issued **Risk-Informed Decision Making (RDIM) Risk Guidelines for Dams**.<sup>16</sup> These risk-based guidelines were issued 40 years after President Carter's 1977 Memorandum on the Safety of Dams that explicitly addressed "risk based analysis,"<sup>dd</sup> and 7 years after the American Society of Civil Engineers issued the Guiding Principles for the Nation's Critical Infrastructure that also explicitly addressed "**manage risk**." **There is no evidence that FERC or DWR - DOSD utilized this background during the Operations and Maintenance inspections of the Gated Spillway.**<sup>1,5</sup>

**The Oroville Dam Gated Spillway failure – self-destruction was preventable.** Over decades, there were many opportunities for DWR, DSOD, and FERC to recognize and investigate serious issues that could have led to effective remedial measures. Evidence<sup>ee</sup> documented in this Root Causes Analysis Investigation (Appendix B) reveals the significant extent in decades of missed opportunities for DWR, DSOD, and FERC to detect and investigate severe anomalies.<sup>8</sup>

The lack of recognition of the significance of the severe issues revealed in Appendix B, from the beginning of the construction of the spillway to present, reveals the long-term systematic failures of DWR, DSOD, and FERC to identify and rectify critical components of the Oroville Dam Gated Spillway to the required level of the **Operating Standard of Care: thus, "Negligent."**<sup>9</sup> These egregious long-term repeated failures violated the **First Principle of Civil Law: "imposing Risks on people if and only if it is reasonable to assume they have consented to accept those Risks."** Risk control is a central goal of Civil Law<sup>10</sup>

We have concluded DWR and DSOD should have taken the steps to update the design, construction, O&M standards and upgrade the Oroville Dam facilities so as to satisfy its documented Statutory, Regulatory, and Management responsibilities for the Safety and Risk Management of these facilities.<sup>1</sup> A superficial '**Patch and Pray**' approach is not an acceptable Safety and Risk Management Process for important public infrastructure Systems.

Previous experiences from formal Root Causes investigations of failures of both U.S. public and private industry infrastructure Systems (e.g. New Orleans hurricane flood protection system during Hurricanes Katrina and Rita<sup>ff</sup>, BP Deepwater Horizon Macondo well blowout<sup>gg</sup>, and the PG&E San Bruno pipeline explosion<sup>hh</sup>) lead to the conclusion **the wrong standards and**

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<sup>dd</sup> 1977 Memorandum available at <https://drive.google.com/open?id=0Bz1I1mIutSEnTGISRzBMNTBsTDA>

<sup>ee</sup> A summary of the written evidence contained in DWR – DOSD and FERC inspection reports is provided in - <https://drive.google.com/open?id=0Bz1I1mIutSEnNG1Vem9IYlFFcjA>

<sup>ff</sup> Katrina Investigation - <https://drive.google.com/open?id=0Bz1I1mIutSEnSlBkVWktZi1uX28>  
<https://drive.google.com/open?id=0Bz1I1mIutSEnNnEwbGRSV3ZxRHM>

<sup>gg</sup> BP Deepwater Horizon Investigation - <https://drive.google.com/open?id=0Bz1I1mIutSEnVVdwnF6czJGTmM>  
<https://drive.google.com/open?id=0Bz1I1mIutSEnM2NrcnpPOEhzY00>  
<https://drive.google.com/open?id=0Bz1I1mIutSEnRjFsUms2TVJRalk>  
<https://drive.google.com/open?id=0Bz1I1mIutSEnbGRRdjlMc3FsSTg>

<sup>hh</sup> PG&E San Bruno Investigation - [https://drive.google.com/open?id=0B0\\_jjqbhy5meWGV5aEtVeFE50UU](https://drive.google.com/open?id=0B0_jjqbhy5meWGV5aEtVeFE50UU)  
<https://drive.google.com/open?id=0Bz1I1mIutSEnTTEwcEpLRjFPWHM>

**guidelines were being used (applied) to re-qualify these other critical infrastructure systems for continued service.** Like the Oroville Dam Gated Spillway, these critical infrastructure systems had embedded defects and flaws introduced during Design, Construction, and Operating & Maintenance that were combined with Aging, Technological Obsolescence, and increased Risk effects.

Similarly, these infrastructure systems purportedly were designed, constructed, operated, and maintained according to the “Standards and Guidelines of the time.” **In all cases, the evidence indicates there were multiple intentional deviations from these Standards and Guidelines during their entire life-cycles.** All of these infrastructure Systems were regulated by Local, State, and Federal agencies. These major failures also represented ‘Regulated Failures.’

Further, our previous experiences from formal Root Causes investigations indicate the majority of Standards and Guidelines currently being used were originally intended for design, not re-qualification or re-assessment of existing aged infrastructure Systems that have experienced Aging, Technological Obsolescence, and increased Risk effects. Our reviews indicate in many cases ‘inappropriate’ standards and guidelines were being used to re-qualify these infrastructure systems for continued service. **The currently available information indicates this continued long-term use of ‘out-of-date’ and ‘inappropriate’<sup>ii</sup> Standards, Guidelines, processes and procedures is one of the primary Root Causes of the failures of the Orville Dam Gated Spillway.**

## **Other Developments**

### **Gated Spillway Headworks**

We have reviewed documentation and written testimony that provides plentiful evidence (e.g., DWR – DOSD - FERC annual inspection reports 2008-16) there are important existing defects and damage in critically important parts of this Gated Spillway subsystem. The reported defects and damage include failed (2) and cracked (28) spillway gate anchor tendons (Figure 1), cracked reinforced concrete gate supporting structures (Figure 2), and severe gate binding.

We have not found evidence these important Gated Spillway subsystem components have been included in the current or future DWR – DOSD – FERC Gated Spillway repair and rehabilitation planning. If the structural support and anchorages are inadequate to support the gate loadings, catastrophic failure of the gates could occur with catastrophic effects. Given the extreme importance of the Spillway Headworks, DWR – DOSD and FERC should be required to take effective actions to properly remediate these important structural components. Advanced Quality Assurance and Quality Control (QA/QC) equipment and methods should be used to assure that the desired initial and long-term Safety and Reliability characteristics of this important structure are achieved and maintained.

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<sup>ii</sup> ‘Inappropriate’ - intentional deviations from mandated ‘acceptable practice’ standards and guidelines.





Figure 1: Broken (2) and cracked (28) spillway gate control anchor tendons.

Near 14 foot Crack has shifted a seam close to 4 inches in offset in a 5 foot thick, solid concrete Pier. This crack is growing. Inspectors monitor the crack growth with red paint. Crack is just above array of anchor tendons for Radial Gate 8 Trunnion Anchor. Further cracking may threaten tendons.

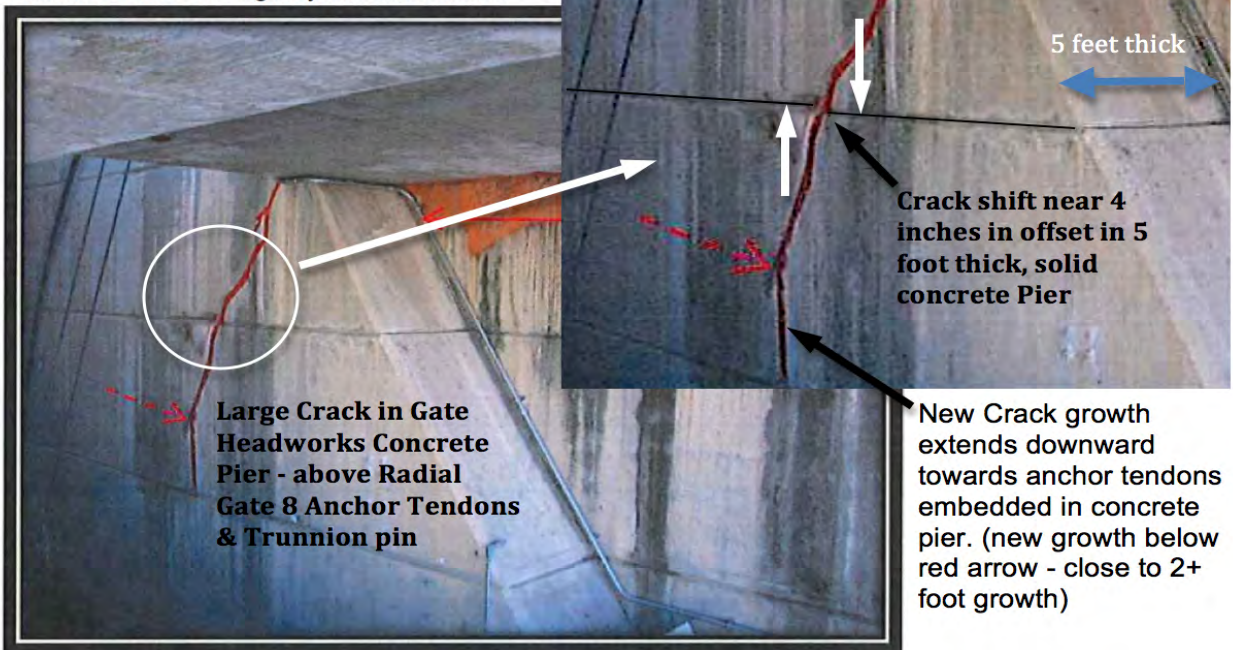


Figure 2: Gate Headworks cracked reinforced concrete pier support structure.

Three reports written by the second author of this report review and analyze the available documentation on these concerns. These reports are summarized below and identified as Reports 6, 7, and 10:<sup>9</sup>

**Report 6: Large 14 Foot Crack in Headworks? Cracking Radial Gate Steel Tendons? Threat to Spillway yet no Repairs in 2017? A threatening 14 foot long crack growing in a massive 5 foot thick concrete pier at Radial Trunnion Gate 8 in Oroville's Spillway Headworks? DWR Board investigating how many of the internal cracking of the 50 year old aging "end of life" 384 steel anchor tendons may fail before they deem the Headworks operationally unsafe?** Two steel tendons have already failed, test data reveals 28 more with crack indicators in the steel, some near the "critical failure size". Yet DWR doesn't know with certainty how many more are at risk of failure? Are there any plans to fix these major spillway Gate Headworks issues with emergency repairs for 2017? Why hasn't DWR revealed this information to the public?

**Report 7: Headworks Cracking Risking 3 Highest Level FERC Category 1 Probable Failure Modes? New Design Flaws Discovered?** The Federal Energy Regulatory Commission (FERC) requires Potential Failure Mode (PFM) assessments at dams in a process to proactively identify modes of "potential" failure as a method to ensure appropriate safe operating performance margins. PFM's are an integral part of the FERC Dam Safety and Surveillance Monitoring Reporting process (DSSM's). High Reliability Systems, such as a dam and a spillway structure, require a constant assessment of conditions where FERC and the dam owners cooperate in this proactive DSSM's based exercise. Thus any findings requiring actions, whether further assessment or structural remedies, provide safeguarding the level of failure probabilities to "As Low As Reasonably Practicable" (ALARP). Civil law is based on this principle when entering into "controlling risk as effectively as possible"

**Report 10: Will Oroville Spillway Gates Fail in Heavy Flows? Design Flaws & Fixes Risk Gate Binding?** In 2007, during an official Federal Energy Regulatory Commission (FERC) Inspection, Radial Gate 4 jammed after only lifting 6 feet of its 33 foot travel. From the perspective that all components of the Spillway Radial Gates are considered a High-Reliability System, what ensued in the subsequent Engineering Failure Analysis Report findings could only be read as an engineering nightmare. Quoting the Report: "During Federal Energy Regulatory Commission required operational testing Spillway Gate No. 4 would only open to approximately 7 feet at which time the motor would trip offline from overload." "Initial inspection found heavy galling marks on the right side wall plates as well as protruding bolts on the seal assembly directly adjacent to the wall plates. A bronze plate was also found between the wall and seal. This plate was later determined to be from a retrofit done in 1974." "The seal assemblies were removed and disassembled. A large amount of mud and debris was found behind the seal. The seal inflation piping was completely filled with mud and debris also. One bronze guide shoe was damaged beyond repair." "Two main items were attributed to the gate binding: 1. Lack of maintenance caused the system to degrade and become clogged with mud and debris. 2. Due to irregularities in the seal assemblies - it appears they were not properly



adjusted for the proper clearance over the entire length of the seal."

## Oroville Dam Persistent 'Wet Spots'

We have reviewed DWR – DOSD – FERC Oroville Dam inspection reports covering the period 2008 – 2016. These reports contain a series of photographs that show the continued development of 'Leaks' and 'Wet Spots near the dam abutments (Figures 3, 4, 5).

DWR - DSOD, and FERC should be required to focus high quality field investigations and detailed analyses of the results from these investigations to determine and confirm if important seepage is taking place in and around the Oroville Dam. If such threats are confirmed, then proven effective remediation measures should be implemented and validated to assure that the dam is 'Safe' and 'Reliable' for current and future use.



**Figure 3: Does the water 'seepage' in the Oroville Dam endanger its Safety and Reliability?**



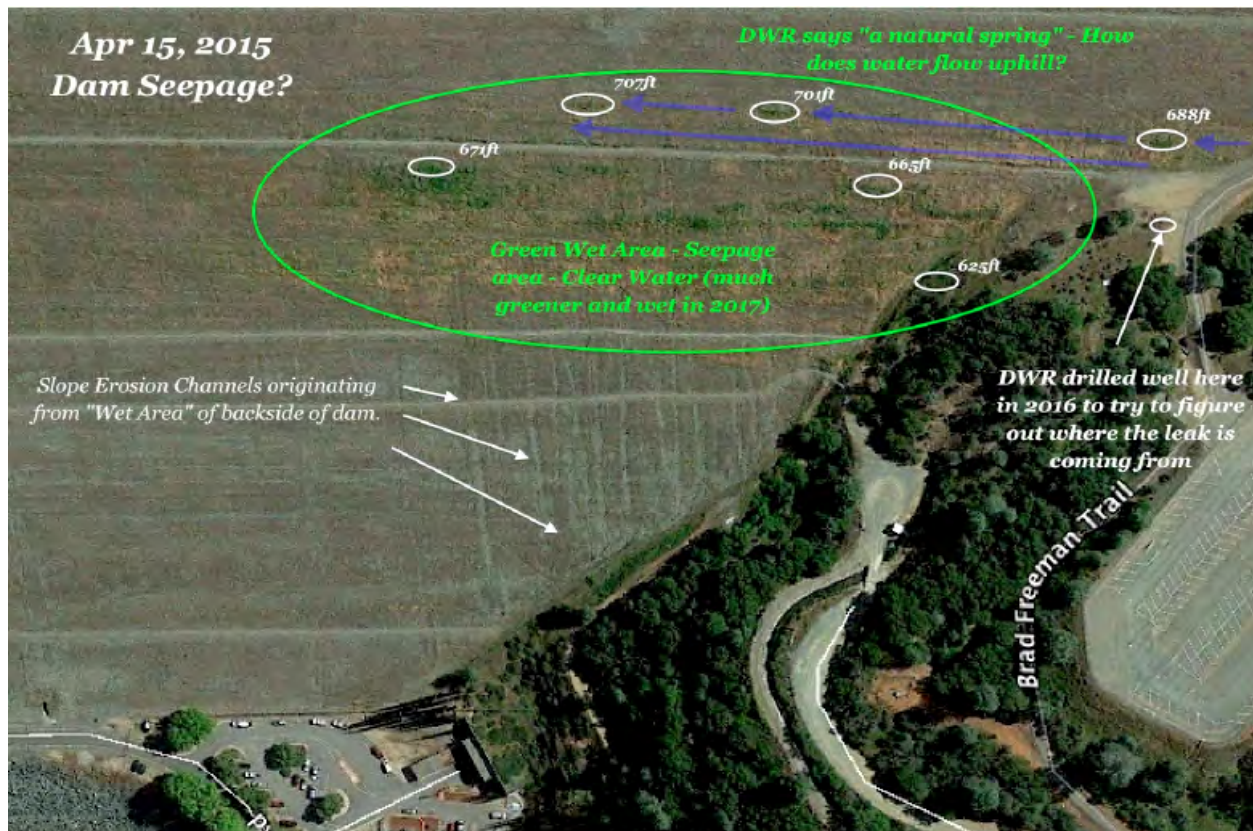


Figure 4: 2015 image of vegetation following an upward elevation slope away from the left abutment. Erosion channels, greenage locations, non-greenage above and below and up the embankment, uphill water flow, contradicts against a left abutment spring. Image courtesy of Google Earth.

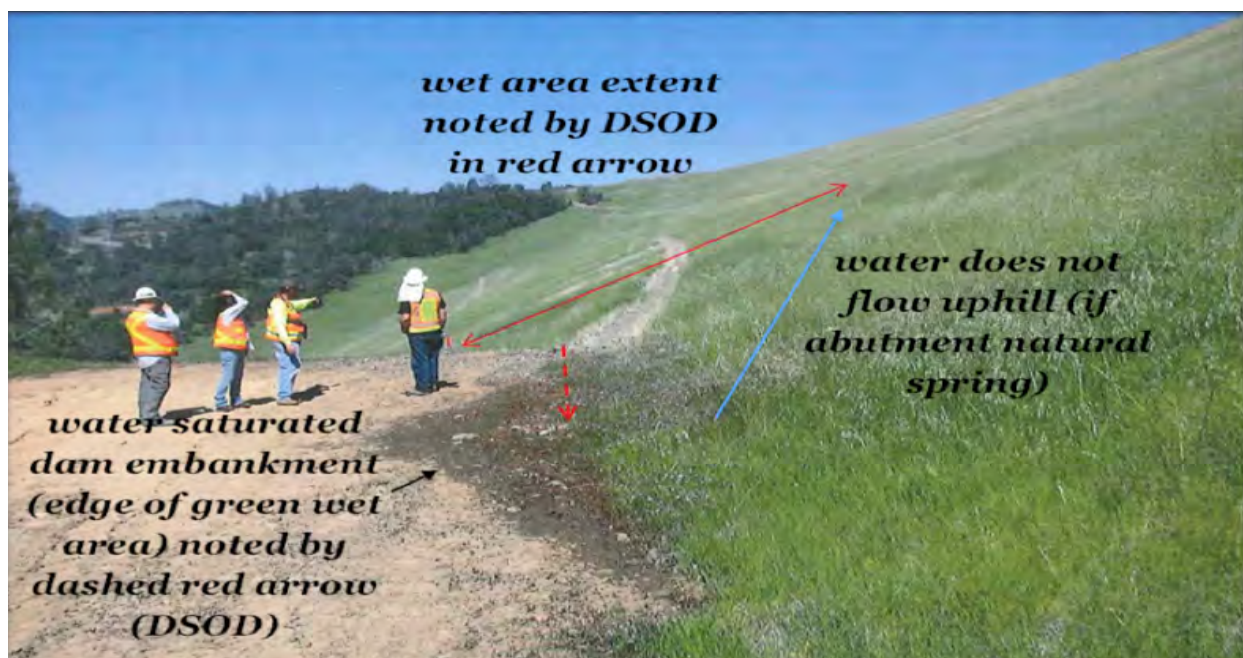


Figure 5: Water does not flow uphill if the dam abutment ‘wet spot’ is a “natural spring.”

Four reports written by the second author of this report review and analyze the available documentation on these concerns. These reports are summarized below and identified as Reports 1, 2, 3, and 4:

**Report 1: Oroville Dam Leaking? 50yr Proof of "through the dam" leakage? Will the dam breach?** Oroville Dam may be facing a breach danger from a serious and a dangerous form of a slow motion failure mode of the left abutment of the dam. Recently, authorities to the dam have responded to the public stating "its a natural spring", or "the green spot is from rain". Yet, outside of a public forum, DWR asked the Federal Energy Regulatory Commission (FERC) to move a test drill well near the leakage to try to get answers in 2016. If it's known to be a harmless "natural spring" or from "rain" why drill? Why hasn't DWR publicly announced that they have a "test well" near the leakage area, which they noted to FERC, quote "data collected may be beneficial in understanding seepage"? However, DWR's recent town hall meeting's answers, by DWR engineers and representatives, do not stand up to honest engineering scrutiny. The public deserves an honest technical risk assessment of this known dam failure mode threat.

**Report 2: Oroville Dam Breach? DWR Investigating Leaking - Hasn't Revealed This to the Public** - Oroville Dam may be exhibiting a dangerous failure mode from an effect known as "Differential Settlement". This phenomenon occurs by sections of the dam "compacting" at a different rate. Thus, internal forces are applied to the center of the dam that has known to cause loss of the integrity of the core, cracking of the core, clogging of the internal drainage system, and longitudinal cracking along the interface between embankment zone fill materials. Historic failures of "Differential Settlement" at dams has found a critical component that risks the danger from the dam having an abutment with a "sharp abutment" slope change. A first sign of this alarming problem would be unexplained seepage, wet spots, or greening areas on the back side of the dam (to which Oroville Dam is exhibiting).

**Report 3: Oroville Dam History Images, Reveals Clues to Dam Leakage? What Should be Done? Mysteries to the clues of Oroville Dam's leakage revealed in historical dam images?** Does DWR/DSOD already know that there is a leak through the dam from inspection reports, yet they are keeping this from the public? Why push the narrative of "rain falls...then grass grows" when the public should be made fully aware of a potentially serious precursory dam failure mode? What should be done to guarantee that this leak is not at an accelerated threshold risk threat if there is greater "unseen" leakage?

**Report 4: Oroville Dam Leak? With All Internal Dam Water Sensors Broken? No Breach Warning?** An earthquake induced leak or if an internal erosion defect develops, deep within the earthen fill zones at Oroville dam, DWR would have no warning, nor the ability to do an immediate slope stability assessment, as the numerous dam's internal Piezometers are non-functional or dead. FERC has been asking DWR to fix this issue for years, as it's a major Dam Safety Issue. Why hasn't DWR responded? Why does the tallest earthen dam in the U.S.A. have zero working Piezometers to detect any threat to a potential internal instability to warn citizens of a pending breach?

# **Remediation of Organizational Root Causes**

## **Recommendation #1**

DWR – DOSD have demonstrated important needs for significant additional resources – primarily human and organizational resources – to help them get the proposed spillway repairs and rehabilitation efforts completed so those parts of the Oroville Dam system can meet current applicable **System Risk Assessment and Management based standards and guidelines** for development of **High-Reliability Organizations<sup>jj</sup>** having **High-Reliability Management** able to deliver **High-Reliability Systems with As Low As Reasonably Practicable Risks<sup>11</sup>**.

This development would go above and beyond the current standards and guidelines currently cited by DWR, DSOD, and the DWR Board of Consultants. The Oroville Dam is an extremely important part of the State Water Project and of California’s public infrastructure systems. **Going forward, the Best Available and Safest Technology (BAST) should be required and properly used.<sup>12</sup>**

In addition to the results from this Root Causes Investigation, this recommendation is based on experiences and results from a six-year duration research and development project sponsored by the NSF and conducted by the Center for Catastrophic Risk Management (CCRM) at the University of California Berkeley. This project was identified by NSF as the RESIN systems project.<sup>kk</sup>

This project had two fundamental goals: 1) further develop and validate advanced analytical processes and procedures that could provide realistic quantitative evaluations of Risks associated with operations of complex engineered infrastructure systems—SRAM processes, and 2) apply these advanced validated SRAM analytical processes and procedures to the infrastructure systems in the California Sacramento – San Joaquin Delta.<sup>9</sup>

The advanced SRAM analytical procedures and processes were developed and validated with applications to past infrastructure failures.<sup>9</sup> Then, these validated SRAM analytical procedures and processes were applied to several specific infrastructure systems that had particular importance to continued operations in the California Delta.<sup>9</sup> These specific structure locations were identified with a Geographic Infrastructure System (GIS) developed specifically for the RESIN project in accordance with the guidelines provided by the Department of Homeland Security and the Federal Emergency Management Agency (FEMA).

The locations were identified as choke points – locations where failures would trigger failures of the other infrastructure systems that were in the same locations; these multiple infrastructure systems were interconnected, interdependent, and highly interactive. Two environmental conditions were specified: 1) potential flooding events during 2010, and 2) potential flooding events during 2100 (including potential effects from global climate changes, and continued use

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<sup>jj</sup> See Appendix A pages 13 – 17 for background on characteristics High Reliability Organizations.

<sup>kk</sup> University of California CCRM NSF RESIN research and development project - <http://ccrm.berkeley.edu/resin/>



of the 2100 inspection, maintenance, and repair Operations and Maintenance processes and procedures).

The two locations chosen for the application of the advanced analytical formulations and processes were: 1) Sherman Island and 2) Natomis Basin. Representatives from local, state, and federal government agencies that had responsibilities for the infrastructure systems were involved in these developments (e.g., DWR, California Emergency Management Agency, U.S. Army Corps of Engineers, Sherman Island Reclamation Board, U.S. Coast Guard, University of California Davis, University of Colorado, Mills College). During this project, the RESIN research project team involved 35 faculty members, 73 undergraduate and graduate students in courses and research projects developed for this project, six post-doctoral researchers, and many other vital support personnel.

Results from the applications were documented extensively in public reports and reports to NSF, and published in reports, presentations, graduate and undergraduate courses, and refereed conference and journal publications. During 2009 – 2010, results from these applications were presented to public and government representatives concerned with the infrastructure systems located at Sherman Island and the Natomis Basin.

These applications of the advanced SRAM processes and procedures to the infrastructure systems at the two locations had one consistent result:<sup>13</sup> **The risk of major infrastructure systems failures were not “tolerable” or “As Low As Reasonably Practicable” (ALARP) based on U.S. and international Risk Tolerability guidelines.**

The recent experiences with other U.S. infrastructure systems have served to corroborate results from these NSF RESIN Infrastructure SRAM studies (New Orleans hurricane flood protection system during Hurricanes Katrina and Rita, BP Deepwater Horizon Macondo well blowout, and the PG&E San Bruno pipeline explosion). **The infrastructure System Risk Assessment and Management challenges at the Oroville dam involve much more than the Oroville Dam infrastructure system challenge. These infrastructure SRAM challenges also are State<sup>14</sup> and U.S. National challenges.<sup>11,15</sup>**

## **Recommendation #2**

DWR’s Management, Division of Engineering, and Division of Operations and Maintenance (O&M) standards, guidelines, procedures, and processes should be founded on the **proven best available SRAM** technology. This technology includes, **but “goes beyond”**, that currently documented in the U.S. Army Corps of Engineer’s *Dam Safety* guidelines,<sup>16</sup> <sup>11</sup>in the Federal Energy Regulatory Commission (FERC) *Risk Guidelines for Dam Safety*,<sup>17</sup> in the Federal

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<sup>11</sup> More background provided at <http://www.iwr.usace.army.mil/Missions/Flood-Risk-Management/Flood-Risk-Management-Program/About-the-Program/Policy-and-Guidance/> and <http://www.iwr.usace.army.mil/Missions/Flood-Risk-Management/Flood-Risk-Management-Program/About-the-Program/Policy-and-Guidance/Federal-Flood-Risk-Management-Standard/>

Emergency Management Agency (FEMA) *Federal Guidelines for Dam Safety*,<sup>18</sup> and in the Bureau of Land Management (BLM) *Dam Safety Public Protection Guidelines*.<sup>19,mm</sup>

The most important “goes beyond” elements concern those associated with **Human and Organizational Factor Uncertainties (Appendix A)**.<sup>2, 6, 10</sup> Multi-decade International use of System Risk Assessment and Management processes has clearly shown these elements must be included in valid and validated procedures and processes required to develop “realistic” assessments of the likelihoods and consequences (Risks) of major failures and for development and implementation of effective risk management barriers – standards, guidelines, procedures, and processes – used during the life-cycle of important public and private infrastructure systems.

Analyses of these “Human and Organizational Factor” Uncertainties (Extrinsic, Types 3 and 4 Uncertainties) are combined with those included in many traditional engineering analyses: natural (Aleatory) variability and analytical model (Epistemic) uncertainties (Intrinsic, Types 1 and 2 Uncertainties). Detailed investigation of a wide variety of failures associated with engineered infrastructure Systems has demonstrated that the majority of the Root Causes of these failures are associated with Human and Organizational Factors – Extrinsic Uncertainties. All four categories of Uncertainties must be included to develop realistic full-scope Risk Analyses, thus avoiding the “E3” error of “working the wrong problems precisely.”<sup>2,13</sup>

**Other countries have continued, and are continuing, to implement advanced System Risk Assessment and Management standards and guidelines to help manage, engineer, construct, operate and maintain their important infrastructure systems.** Examples include those developed and implemented by the U.K. Health and Safety Executive in their Safety Case Regime developments, and by the governments of Australia and New Zealand in their Risk Management Guidelines.<sup>20,21</sup> The International Standards Organization (ISO) have developed and published a large number of very useful standards based on System Risk Assessment and Management that have been incorporated into those of the U.K. Health and Safety Executive, and those of Australia and New Zealand.<sup>22</sup> In addition, similar standards and guidelines have been developed and implemented in Norway and the Netherlands.<sup>23</sup> **These Standards and Guidelines – ‘Safety Case Regimes’ – address both Intrinsic (Types 1 and 2) and Extrinsic (Types 3 and 4) Uncertainties.**

In the U.S., the commercial Nuclear Power Generation and Transmission organizations and owner-operators (e.g., the PG&E Diablo Canyon nuclear power plant) and the U.S. Nuclear Regulatory Commission (NRC) for many years have applied this proven advanced technology.<sup>nn</sup> Similarly, the commercial public air transportation organizations (e.g. United Airlines, Boeing Aircraft Company) and the U.S. Federal Aviation Administration (FAA) have applied this technology in development of their standards, guidelines, procedures and processes. These organizations have developed an admirable record for safety and reliability. The U.S. Chemical

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<sup>mm</sup> For additional references consult National Dam Safety Program at <http://damsafety.org/resourcecenter/national-dam-safety-program-guidelines-flyers-and-other-tools>

<sup>nn</sup> Nuclear Regulatory Commission SRAM Probabilistic Risk Analyses (PRAs) – <http://www.nrc.gov/about-nrc/regulatory/risk-informed/pr.html>

Safety Board (CSB) and Center for Chemical Process Safety have advanced a similar set of standards and guidelines for implementation of safety case regimes for high hazard chemical processing facilities.<sup>oo</sup>

Experience during the past several decades has shown that System Risk Assessment and Management technology, if properly implemented, can be very useful to help develop and maintain **Safe** (risks are ALARP) and **Reliable** (high likelihoods of delivering acceptable performance) systems. **This experience has also shown that if not properly implemented, System Risk Assessment and Management technology can be very counterproductive.** Some of this experience has shown that improper implementation can help cause major infrastructure system failures.<sup>2, 8</sup> **The single most important resource required for proper implementation are people who have formal training and experience in Risk Management – System Risk Assessment and Management processes and procedures.**

Experience and results from analyses of 10-year duration formal efforts by seven organizations to effectively apply SRAM technology has shown that “**Five Cs**” are required to be able to develop and maintain safe and reliable systems.<sup>24</sup> **All Five Cs are required all of the time to be able to realize success with implementation of this technology.**

The **Five Cs** are:

- 1) **Cognizance** – the involved organizations must develop an acute awareness of the hazards and threats that confront their systems. Worry and concern is constant. Awareness is crucial. Diligence to maintain systems with ALARP Risks that are ‘Safe’ is even more critical.
- 2) **Commitment** – the management and operating personnel must develop a sustained ‘top down and bottom up’ commitment from those involved that the necessary resources (human, organizational, monetary, knowledge, experience, physical, environmental) will be provided to enable effective application of ALARP risk management ‘barriers’ (integrated proactive, reactive, and interactive processes) to enable development and maintenance of systems that have ALARP risks. The commitment must be to develop high reliability organizations with high reliability management that will consistently deliver systems having ALARP risks.
- 3) **Culture** – The beliefs, values, feelings, and resource allocation and utilization processes of the organization must be one devoted to “Getting it right, doing it right and knowing what is right,” consistently delivering Systems that have ALARP risks, and understanding that these efforts require constant vigilance, diligence and continuous improvements.
- 4) **Capabilities** – The human, organizational, and other parts of the systems (combinations of human operators, responsible organizations, hardware, structures, environments, standards and guidelines, and the interfaces between these interconnected, interactive, interdependent **components**) must be highly developed and “excellent” so the proven

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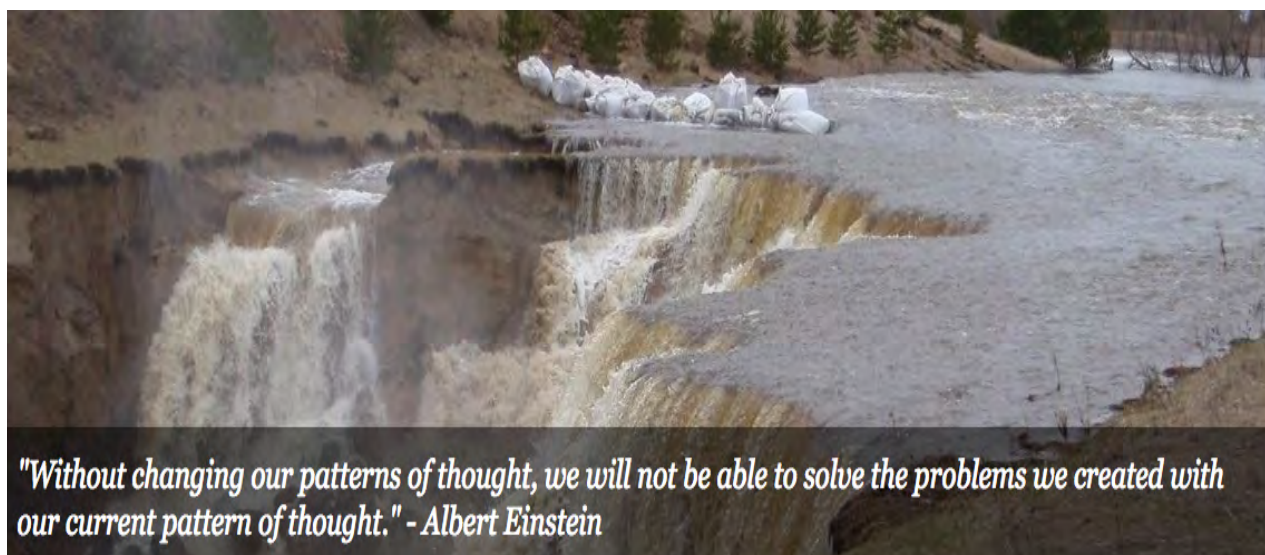
<sup>oo</sup> <https://www.aiche.org/ccps/topics/elements-process-safety/commitment-process-safety/process-safety-culture>

principles of SRAM technology can be properly and effectively developed and implemented. These efforts are focused on continuous improvements to enable realization of the different kinds of benefits from application of SRAM technology.

- 5) **Counting** – This is a very important ‘C.’ Counting means development of valid and validated *quantified metrics* (with numbers) that can be used by managers, engineers, and operations and maintenance personnel to help them determine system risks (likelihoods and consequences) throughout the life-cycle of a system. These valid and validated metrics serve the same purposes as an automobile speedometer; to give the driver/s dependable ways to determine the safe speed, given the road, traffic, weather, and surrounding community conditions; the safe speed (ALARP risk) depends on the local conditions. Risks that are ALARP are based on quantitative monetary cost-benefit evaluations that include proper recognition of both short-term and long-term monetary costs (direct, indirect, onsite, offsite, property, productivity, quality of human life, and environmental impacts), standards-of-practice evaluations, historic precedents, and national and international standards and guidelines for determination of ALARP risks.<sup>25</sup> What is effectively measured can be more effectively managed.

## Summary

Results from this investigation of the Root Causes of the failures of the Gated Spillway, Emergency Spillway, and Other Developments (Spillway Headworks, Dam Abutments ‘Wet Spots’) have been consistent with those from a large number of previous forensic investigations of failures and disasters associated with engineered infrastructure systems: **it is the *Human and Organizational Factors* that are the primary challenge to being able to develop Safe and Reliable engineered infrastructure systems.**<sup>26</sup> This is the reason for emphasizing in this report **the need to develop high-reliability organizations with high-reliability management that can and will deliver High Reliability Systems that have As Low As Reasonably Practicable Risks and are Safe, Durable, Serviceable, and Compatible (Appendix A).**



<http://damfailures.org/>



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# APPENDIX A

## **Background Summary: Root Causes Analyses, Engineered Systems, Human & Organizational Factors, and Taxonomies for Root Causes Analyses<sup>1</sup>**

### **Root Causes Analyses**

The Center for Chemical Process Safety (CCPS) has developed guidelines for investigating incidents and performing safety audits associated with near-misses and failures of engineered systems (1992, 1993, 1994)<sup>2</sup>. These guidelines indicate that the attitudes and beliefs of the involved organizations are critical in developing successful systems, particularly doing away with ‘blame and shame’ cultures and practices (Turner, 1991; Rasmussen, 1980). It is further observed that many if not most accident and failure investigation systems focus on ‘technical causes’ including equipment and hardware. Human – system failures are treated in a cursory manner and often from a safety engineering perspective that has a focus on outcomes of errors (e.g. inattention, lack of motivation) and statistical data (e.g. lost-time accidents).

Guidelines have been developed for incident reporting systems, near-miss reporting systems, and Root Cause Analysis investigation, assessment, and documentation processes for failures of engineered systems (Center for Chemical Process Safety, 1992, 1993, 1994; Bea, 2009).

The primary objective of incident reporting systems is to identify recurring trends from the large numbers of incidents with relatively minor outcomes. The primary objective of near-miss systems is to learn lessons (good and bad) from operational experiences. Near-misses have the potential for providing more information about the causes of serious accidents than accident information systems. Near-misses potentially include information on how the human operators have successfully returned their systems to safe-states. These lessons and insights should be reinforced to better equip operators to maintain the quality of their systems in the face of unpredictable and unimaginable unraveling of their systems.

Root Cause Analysis is generally interpreted to apply to systems that are concerned with detailed investigations of failures of engineered systems with major consequences (Figs. A.1–2). The authors have a fundamental objection to the term ‘Root Cause’ Analysis because of the implication there is a single cause at the root of the accident. This is rarely the case. Identification of a single Root Cause is an attempt to simplify what is generally a very complex set of interactions and factors, and in this attempt, the lessons that could be learned from the accident are lost.

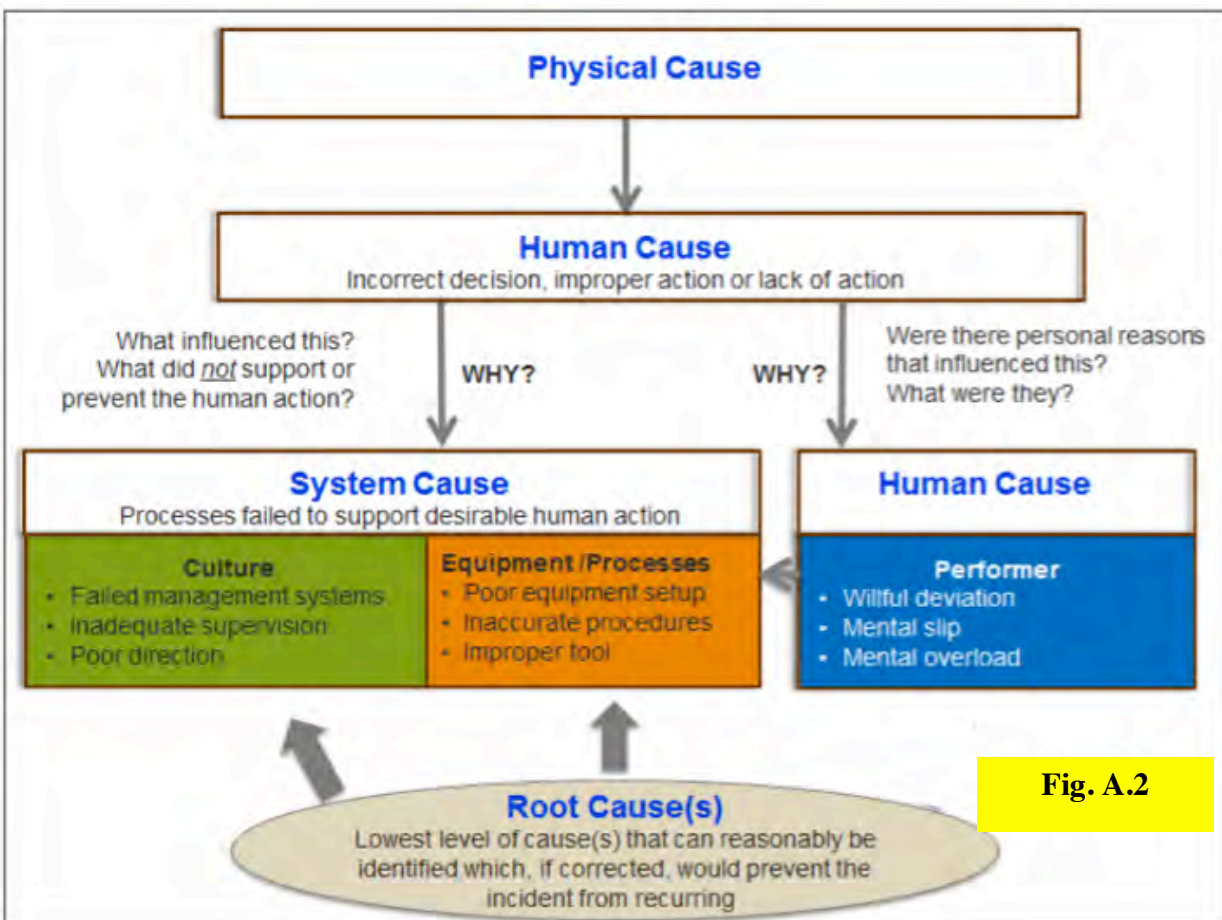
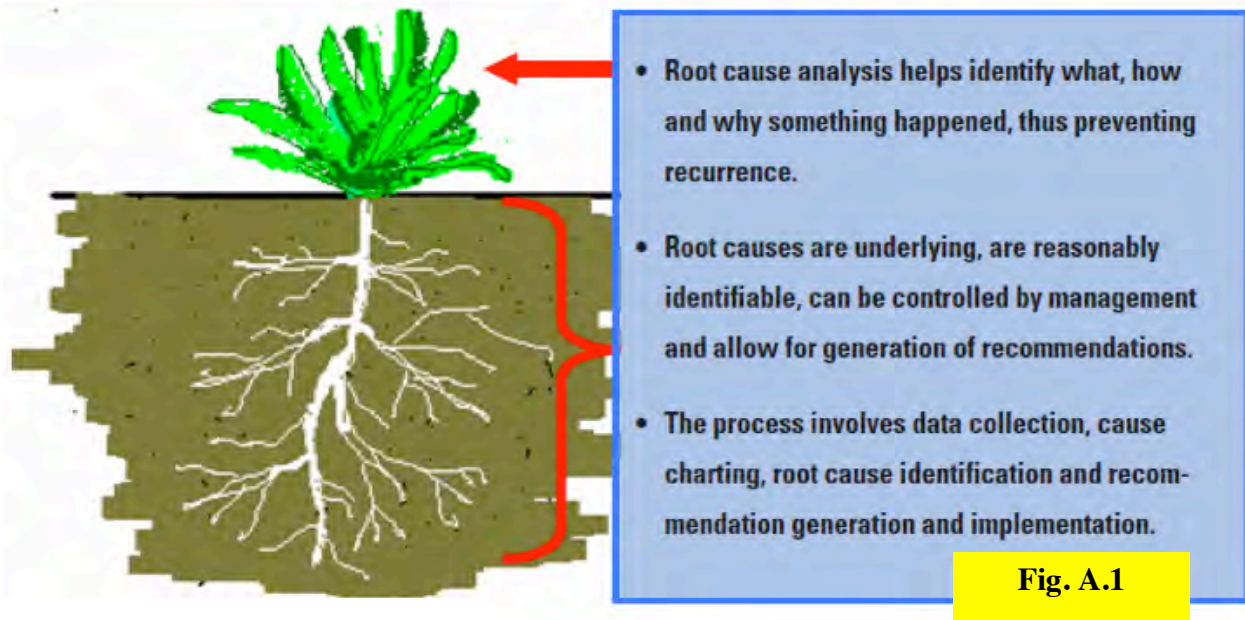
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# Root Cause Analysis



Important elements in a Root Cause analysis includes an investigation procedure based on a model of accident causation. A systematic framework is needed so that the right issues are addressed during the investigation. There are high priority requirements for comprehensiveness and consistency. The comprehensiveness needs to be based on a systems approach that includes error tendencies, error inducing environments, multiple causations, latent factors and causes, and organizational influences. The focus should be on a model of the system factors so that error reduction measures and strategies can be identified. The requirement for consistency is particularly important if the results from multiple accident analyses are to be useful for evaluating trends in underlying causes over time.

Systems that have been used extensively in development of Root Cause analysis systems include the Tree of Causes (Leplat, 1982), MORT (Management Oversight & Risk Tree) (Johnson, 1980), STEP (Sequentially Timed Events Plotting) (Hendrick and Benner, 1987), and the HPIP - Human Performance Investigation Process (Paradies, et al, 1992).

The principle of the Tree of Causes method is that an accident results from changes or variations in normal processes. These variations must be identified, listed, and organized into a inductive analysis diagram (starting with the accident and working backward to define the causes and interactions) to define their interrelationships. This method was further developed by Leplat and Rasmussen (1984) in a Variation Diagram approach. This development was based on application of the Rasmussen 'stepladder' model of human error at each branch of the inductive analysis diagram. This stepladder model involved an alert on the part of a system operator, observation of what might be abnormal, identification of the state, evaluation of the implications, definition of goals for returning the system to a safe state planning how to accomplish the plan, formulating and executing the actions, and then developing feedback on the effects of the action/s. This involved skill, rule, and knowledge based activities, shortcuts, and information feedback loops (Rasmussen, 1986).

MORT was developed to provide a disciplined method for defining and evaluating the causes and contributing factors of major accidents in nuclear power plants. The approach utilizes a logic diagram which represents an idealized safety system based on a fault tree method. The diagram defines specific control factors and general management factors. MORT does not provide a process to guide the investigation or the representation of the accident sequence. The MORT process addresses oversights and omissions, assumed risks, control factors, and management system factors.

STEP is an investigation process that structures data collection, representation and analysis. Actors (individuals, equipment, etc. involved in the accident), actions, and events are identified and portrayed in an event sequence diagram. This diagram involves listing the agents down a vertical axis and establishing a time line on the horizontal axis showing how the agent's actions interact to cause the accident. A necessary and sufficient test is applied to pairs of events and checks for completeness and sequencing are made. The analyst proceeds through the diagram to identify the sets of events that were critical in the accident sequence. These critical events are used to develop a causal analysis based on Root Cause Coding (Armstrong, 1989).

The Root Cause Coding consists of six levels that address equipment failures, quality failures, management systems failure, and human error. The STEP decision tree identifies the critical

actions and events. Starting at the top level of the tree, the analyst has to determine whether the critical event involved equipment, operations, or technical difficulties. Based on the identification, the analyst identifies more specific issues relating to function, equipment, major root causes, near root causes, and finally root causes.

HPIP combines many of the techniques described above. HPIP involves seven stages in the investigation of an accident (Paradies, et al, 1992): 1) failed System investigation, 2) event sequence development, 3) analysis of barriers and human performance difficulties, 4) analysis of root causes, 5) analysis of programmatic causes, 6) evaluation of corrective actions and identification of violations, and 7) development of a report. The plant investigation involves collecting physical and documentary evidence and interviewing key participants. The event sequence is developed in a manner similar to that described in the Tree of Causes and STEP. A task analysis method is used to identify the critical actions necessary for the performance of a task and a Change Analysis is performed to define the roles of changes in the accident causation. The Change Analysis (Ferry, 1988) considers planned versus unplanned changes, actual versus potential changes, time changes, technological changes, personnel changes, sociological changes, organizational changes, and operational changes.

It is not often that one can truly understand the Root Causes of accidents (Center for Chemical Process Safety, 1992). If one does not understand the true Root Causes, how can one expect to put the right measures in place to prevent future accidents? Further, if the causes of accidents represent an almost never to be repeated collusion of complex actions and events, then how can one expect to use this approach to prevent future accidents?

Further, the usual reaction to accidents has been to attempt to put in place hardware and equipment that will prevent the next accident. Attempts to use equipment and hardware to fix what are basic Human and Organizational Factor related problems generally have not proven to be effective (Center for Chemical Process Safety, 1994).

## **Engineered Systems**

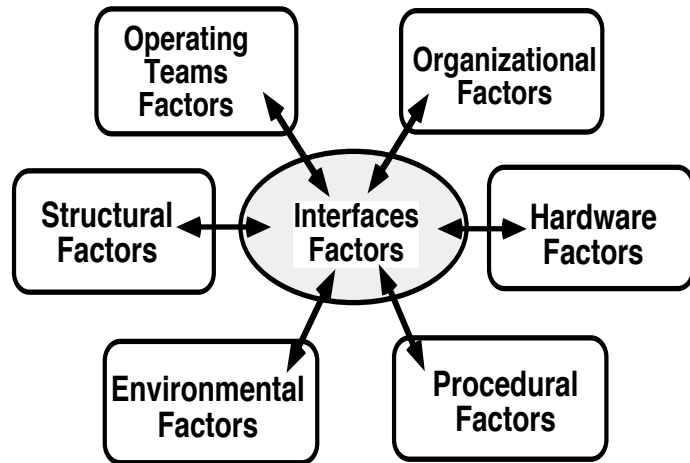
Any activity that involves people is subject to flaws and defects (Reason, 1990)<sup>3</sup>. These flaws and defects (malfunctions) are generally identified as errors. Human and Organizational Errors (malfunctions) represent the hazards (threats to Quality of Systems) associated with Human and Organizational Factors. Human and Organizational Errors are ‘results, not causes’ (Woods, 1990, 1994).

Human and Organizational Factors that occur during the life-cycle of an Engineered System can be related first to the individuals who design, construct, operate, maintain, and decommission the system. These are the ‘front-line’ System Operators – Operating Teams. The actions and inactions of these operators are influenced to a very significant degree by five other components that comprise Engineered Systems (Fig. A.3):

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<sup>3</sup> References listed at the end of Appendix A.

- The Organizations they work for and with,
- The Procedures (formal, informal, software) they use to perform their activities,
- The Structures and Hardware (equipment) involved in these activities,
- The Environments (external, internal, social) in which the Operator activities are performed, and
- The Interfaces between the foregoing components.



**Fig A.3: Influences on the Quality, Safety, Reliability and Risks associated with engineered Systems**

These components are highly inter-related, interactive, and interdependent.

A System is a set of two or more elements (components) whose behavior has an important effect on the behavior of the system, and are interdependent, inter-related and interactive. In this report, the term 'Engineered System' is used: a system is a collection of elements (components) which interact with each other to function as a whole. These assemblies are brought into being through the processes that include concept development, design, construction / manufacturing, operations, maintenance, and decommissioning. Management of the engineering processes is also included.

Synthesis is the key to understanding engineered systems and includes identifying and describing a system of which the elements to be understood are a part, explaining and understanding the properties and functioning of the system and explaining and understanding the behaviors of the elements in terms of their roles in the functioning of the system

This is an advanced approach to make better sense out of engineered systems and help equip managers, operators, engineers, regulators and society to cope with such systems more effectively. This systems 'sense making' consists of placement of items into frameworks, comprehending, constructing meaning, anticipating, interacting in pursuit of understanding, patterning, and redressing surprise. The goal of this 'sense making' process is to help better understand the Quality and Safety associated with Engineered Systems to lessen their potentials for 'revenge' effects (unintended consequences) and to increase their potentials for important improvements in the quality of life.

## **Human and Organizational Factors**

There are many different ways to classify and characterize Human and Organizational Factors (HOF). Popular classifications include mode (errors of omission and commission) and task performance (rule based, skill based, and knowledge based) (Rasmussen, 1982; 1983). The method developed in this Appendix is based on a study of more than 600 well documented cases of major accidents involving marine systems (Moore 1993; 1994; Moore and Bea, 1993a; 1993b;

1993c; Bea, 1994a; Gates, 1989; Wagenaar and Groeneweg, 1987; Gates, 1989; Bea, et al, 1997; Lancaster, 1996; U. S. Coast Guard, 1995; Nagendran, 1994; Perrow, 1984; Pate-Cornell, 1990; Pate-Cornell and Bea 1989; 1992). The taxonomy (classification system) developed as a result of this work is one that addresses the primary way (mode) in which HOF malfunctions or flaws develop. Most importantly, this taxonomy is focused on definition of malfunction developments that can be remedied.

In order to effectively combat the risk of HOF malfunctions, it is important to analyze these malfunctions to determine answers to the how's and why's of their occurrence. Analyses such as these have been in progress for quite some time in the psychology and cognitive science communities (Rasmussen, Leplat, 1987; Reason, 1990). As will be discussed later, such engineering - technological fields as the aviation and nuclear power industries have taken the theoretical aspects of this knowledge and put them to practical use. From these primary sources, one can build an analytical model for HOF malfunctions (errors) that not only accounts for differences in behavior between individuals, but also addresses the extensive list of performance shaping factors which affect the base behavioral characteristics (Williams, 1988; Gertman and Blackman, 1994; Center for Chemical Process Safety, 1994; Boniface, 1996; Boniface and Bea, 1996a; 1996b; Woodson, Tillman, and Tillman, 1981).

This discussion will start with a description of HOF malfunctions: *a deviation from acceptable or desirable practice on the part of an individual (human malfunctions) or group of individuals (organizational malfunctions) that can result in unanticipated and/or undesirable results* (Stamler, 1993). These HOF malfunctions (commonly termed 'human errors') can take active (errors of commission) or inactive (errors of omission) forms (Reason, 1990). **HOF malfunctions are a result, not the cause** (Woods, 1990; 1994).

The key questions in understanding (and therefore combating) HOF malfunctions are the how's and why's of HOF malfunctions. How do these errors occur? Why do errors occur in some situations and not others? Why has the introduction of automation not alleviated the risks of HOF malfunctions? To address these and other questions, one must better understand both human nature and the workings of the human mind, which requires some knowledge of psychology and cognitive science (Follett, 1924; Mandler, 1984; McCormick and Sanders, 1982; Allport, 1985; Winograd and Flores, 1986; Meister and Rabideau, 1965; Katz and Kahn, 1966; Meister, 1971; Miller, 1978; Leplat and Rasmussen, 1984; Rasmussen, Leplat, 1987; Hawkins, 1987; Kantowitz and Sorking, 1983; Rasmussen, 1980; 1982; 1983; 1986; 1995; 1996; Reason, 1990a; 1990b, 1991, 1997; Norman, 1992; Sanders and McCormick, 1993; Groeneweg, 1994; Kirwan, 1994; Bogner, 1994; Cook and Woods, 1994; Dorner, 1996).

## **Operator performance**

This discussion is based primarily on the concepts developed and applied by Reason (1990a). From these principles, a Root Causes Analysis system is developed that will allow for a simple yet powerful collection and analysis of data. It is important to note that the mechanisms and theories put forth by Reason are not the only possible explanation. The literature has a wide variety of theories to explain why and how humans make errors (e.g. Center for Chemical Process Safety, 1994; Kirwan, 1994; Fleishman, et al 1990).

The advantages of Reason's model as applied here lies in its simple yet powerful description of human and organizational performance. It combines the cognitive aspects of the knowledge

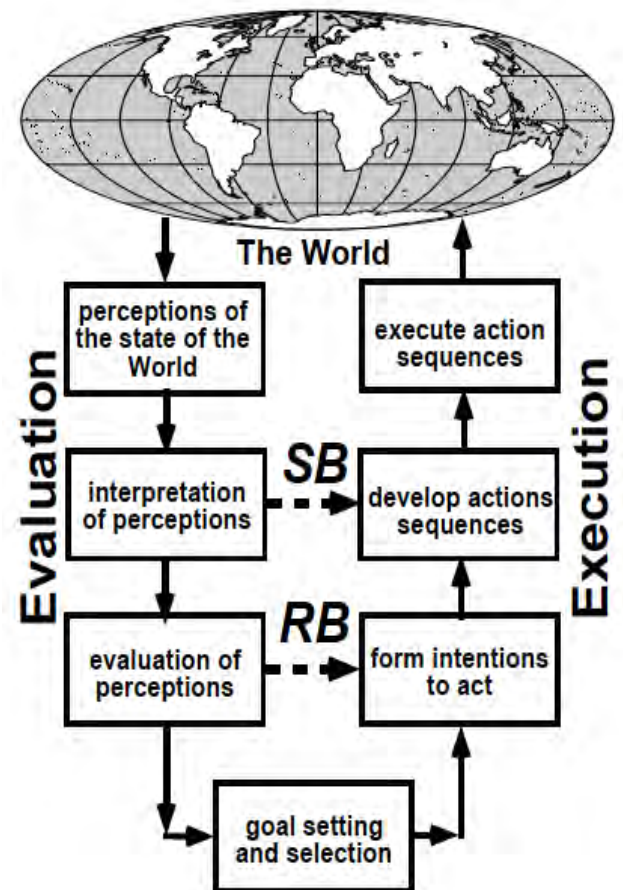
based modeling system with a much needed description of the non-cognitive aspects of the task-network modeling. Although more detailed and intricate models may seem more accurate, the high levels of human variability minimize their advantage over the more simple methods chosen. Furthermore, the analysis of reliability in the engineering/technology vocations typically seek only order of magnitude estimations of errors, rather than exact descriptions.

In order to answer the above questions, we started with an analysis of how humans act and perform the myriad of tasks and sub-tasks that make up everyday life. There are three main phases of actions: 1) evaluation, 2) goal-setting, and 3) execution (Reason, 1990a). These three phases can then be subdivided into the seven stages of action as shown (Fig. A-4). Within such a framework, all actions can be categorized, and the problems associated with human and organizational errors studied.

As described by Rasmussen (1982, 1983), all human tasks can be classified by three performance levels; skill-based (SB), rule-based (RB), and knowledge-based (KB). In order to differentiate between these levels and understand their meaning and importance, a review of the cognitive science literature in this area was required, which resulted in an understanding of the shaping factors that play such an important role in the occurrence of errors and accidents. A description of these performance levels therefore precedes a detailed discussion of the three performance levels. The three task levels; knowledge-based, rule-based, and skill-based, are described below, in order of decreasing cognitive demand.

Knowledge-based performance is the most cognitively demanding level. At this stage there are no pre-planned actions which can be called upon, due to the novelty of the situation. Instead, stored knowledge and sensory inputs are analyzed to determine and develop a requisite plan of action. This places the limited cognitive capacity under an obvious strain, thus requiring the full attention of the individual. Examples of such performance include goal setting, planning, problem solving, and response to unusual situations or emergencies. Errors at this level originate from resource limitations (attention, cognition, and/or time), and incomplete or incorrect knowledge.

Rule-based performance is the next cognitive level. This class involves responding to familiar problems to which stored, standardized rules can be applied. This stage



**Fig. A.4: Seven Stages of Action with 'shortcuts' based on Skill-Based (SB) and Rule-Based Performance Levels; Knowledge- Based (KB) Performance is based on use of all seven stages of action**



lends itself to lower cognition levels in that the only demand on these resources is in the selection of the rule that applies to the particular set of calling conditions. The four criteria for rule selection are: 1) be recallable, 2) be applicable to context, 3) have expected utility, and 4) be executable.

Errors in rule-based performance stem from the improper application of a rule, be it from incorrect selection or incorrect procedural recall.

The least cognitively demanding level is skill-based performance. At this level, calling conditions have been called so often that knowledge retrieval and action are virtually automatic. Indeed, actions at this level are so automatic (and therefore efficient), that, should the subject exert conscious attention at the wrong stage, discomfort is felt and the likelihood of error is increased. Examples of skill-based behavior include driving, eating, and walking under normal conditions.

With this description of human cognition, the task breakdown summarized in Fig. A.4 can be modified to account for the shortcuts used in rule-based (*RB*) and skill-based (*SB*) behavior (Dougherty and Collins, 1996). Repetition (practice) of various tasks, including knowledge retrieval, will increase their familiarity and therefore allow for the development of standardized rules to deal with them. As repetition increases, these rule-based behaviors require less and less attention, finally becoming the automatic skill-based form. As a rule, the mind will always attempt to use the lowest level possible, in order to conserve attention resources. In fact, the shift to rule-based and knowledge-based behavior will only occur upon detection of a problem. Furthermore, only knowledge-based performance requires plan/goal formulation, which provides a further conservation of attentive resources.

As defined by Reason (1990a), error forms are recurrent types of fallibility that appear in all levels of cognitive activity. These error forms are tied to the mechanics of the cognitive process described previously, namely similarity and frequency biases. The incorrect selections (knowledge and/or actions) are thus a result of under specification of either stored knowledge and/or calling conditions (the under specification of knowledge can also be seen as an over specification of the calling conditions, depending on the context.). Being tied to these basic cognitive mechanisms, they pervade all categories of the thought processes and are more general in nature than the error types, which are described next (Table A-1).

Error types differ from error forms in that they are tied to the individual levels and stages of cognition, while the latter are global in nature. There are three stages involved in carrying out a task: Planning, Storage and Execution (Table A.1) with the corresponding error types of mistakes, lapses, and slips (Reason, 1990a). These three primary error types relate to the potential ways a given action can go wrong and can be allied with the three performance levels as shown in Table A.2. Table A.2 is especially important in that it introduces the second of the two reasons why mishaps occur - violations (Dougherty, 1995). These forms will be discussed in detail later. For now, they can be viewed as being variations from the accepted performance specifications of the social setting.

**Table A-1: Cognitive stages and Primary error types**

<b>Cognitive Stage</b>	<b>Primary Error Type</b>
Planning	Mistakes
Storage	Lapses
Execution	Slips



**Table A.2: Performance levels and mishap classes**

<b>Performance Level</b>	<b>Error Type</b>	<b>Violation Type</b>
Skill-based level	Slips and lapses	Erroneous or Unintended
Rule-based level	Rule-based mistakes	Routine
Knowledge-based level	Knowledge-based mistakes	Exceptional

When an action is in error due to a faulty plan, it is identified as a mistake. Here, the plan is remembered and executed correctly, but the desired outcome does not occur due to faulty goal selection and/or poor planning.

Lapses are defined as those errors which result from a failure in the storage of the action plan. This breakdown can either occur in the encoding of the plan as it is cached in a buffer store or in the subsequent retrieval when the action is called upon or scheduled. These errors are fairly well hidden, and tend to be identified only by the person who experiences them.

Slips are errors in the plan execution phase. The plan is sound and is remembered correctly. Due to variety of cognitive causes, however, things do not go as planned. There are many causes of slips, ranging from inattention, to distraction, to substitution of one (incorrect) familiar action for another.

Discussions of how cognitive actions deviate from acceptable parameters, however, would be incomplete without consideration of violations. These deviations differ from errors as follows. Errors are defined as the inadvertent ‘straying’ of actions from the action sequence to the intended outcome. Violations, on the other hand, are defined as ‘deliberate- but not necessarily reprehensible- deviations from those practices deemed necessary to maintain in the safe operation of a potentially hazardous system’. As discussed by Reason (1980), this delineation of errors versus violations can perhaps best be demonstrated by the cognitive source of errors versus the social psychological sources found in violations.

Violations can be broken down into four categories: erroneous/unintended actions, routine violations, exceptional infractions, and sabotage. This categorization is important because different types of measures and means should be used to reduce their incidence and effects.

The three primary violation types are related to the three performance levels (Table A.2). Here, the differentiation lies not with the actual performance, but rather with the intentionality (and thus cognitive load) of the action. Erroneous or unintended violations are therefore those violations for which there were no prior intention to commit. Routine violations, on the other hand, are habitual infractions which, while at least initially intentional, have become so ingrained into the normal practice that they are usually accepted as part of the normal rule-based behavior (Dougherty, 1995). These violations arise from two main factors; the tendency to take the path of least resistance, and the existence of an environment that was largely indifferent. Finally, exceptional violations are those which are individually chosen at the time of the violation. These result from the existence of such flaws as design and/or organizational ‘double-binds’, where the decision-maker is put in a position where he/she views the violation as being the optimal

decision. These violations complete the ways that the evaluation and goal-setting phases can go wrong.

In virtually all tasks, individuals go through some form of self-monitoring to assess the adequacy of actions. These checks can range from spot-checks during problem solving, to the continuous feedback and correction. In self-monitoring, the individual compares his perceptions of performance with the milestones and goals set in the planning stage. If discrepancies and/or shortcomings are noted, another decision-making process must ensue, and new goals chosen, new plans/actions used, or acceptance of flawed performance made. This decision-making process and subsequent actions are themselves subject to errors. While these subsequent error rates do vary depending upon the particular situation and performance shaping factors, it has been shown that the higher the cognitive level at which they operate (i.e.- knowledge-based versus skill-based), the more likely they are to be erroneous themselves.

Given the two types of checks that can be made for a given action/process, it has been shown that a subject is far more likely to look for errors in plan execution than in goal setting or plan formulation and storage. Not only is it often difficult to assess the adequacy of a goal or plan prior to task completion, but it is almost unheard of for a subject to call into question the basic goals and assumptions used, as these tend to be based upon the experience and personality of the person involved. In most circumstances, the goal as set and the formulated plan are accepted as being correct without question, and checks are made for all subsequent stages.

Reason (1990a) has broken down self-monitoring into three types: the standard check, direct error hypotheses formulation, and error suspicion. The standard check (SC) is a general progress check that is cyclic in nature and does not depend on the previous work. Here, the subject commences a check based upon the time elapsed and/or number of operations since the last check. Direct error hypotheses (DEH), on the other hand, are triggered by the detection of a perceived error, although not necessarily immediately after presumed error commission. This usually arises from signals provided by the subjects external surroundings. Error suspicion (ES) differs from DEH in that there is no specific error to trigger the process. Instead, a feeling that something is wrong is encountered.

Among these three self-monitoring mechanisms, direct error hypotheses are most common, followed by error suspicion and then standard checking. Furthermore, it was found that slips were more likely to be detected than mistakes, and that the predominant detection mode for slips were direct error hypothesis episodes (Reason, 1990). Knowledge-based mistakes tended to be picked up by error suspicion conditions, while rule-based mistakes were found to be mostly the result of direct error hypothesis or error suspicion episodes. Finally, the effectiveness of error suspicion detection was found to decrease rapidly after error commission.

In the second checking form, environmental error warning, the subject's external surroundings provide the indications of an error condition. Errors can be indicated by either an alarm signaling an out of parameter condition, and/or an interlock blocking further progress. These conditions can be either natural or man-made, both of which can take numerous forms. Error cues include such manifestations as physical blocking (e.g.- screen over a fan housing), geometrical constraints (e.g.- oil filter for engine will only fit in the correct direction), and checks on order (e.g.- failure to provide salt water cooling to engine will prevent starting).

With judicious use of both natural and man-made error cues, the technical system designer/manager can greatly reduce the risk of human and organizational error. With such a

system, both the probability of failure and the costs associated with these errors (through casualty control provided by automatic shutdowns, etc.) can be minimized. However, these alarms should not be so numerous as to overwhelm and/or distract the operator with redundant or unimportant information. They should also present a complete set of data in a clear, unambiguous manner, so as to avoid causing confusion and/or mis-identification of the error(s). This information should be given in a hierarchical format, so as to allow the operator to access more detailed material if required or desired.

The final checking form, external monitoring, is one often used in design and engineering tasks, although frequently ineffectively. If performed properly, however, these checks provide a powerful tool for detecting and correcting errors. Characteristics of quality external checking systems include; independence between checker and task performers, and use of expert checkers (it takes one to catch one). Perhaps the most important property of a proficient external monitoring system is the ability to identify errors in the goal selection and planning stages. Qualified, experienced, *independent* checkers are far more likely to identify errors in the objectives and performance strategies than any other checking form.

Dorner (1989) has developed some important concepts regarding ‘the logic of failure.’ Dorner contends that people have extreme difficulties in dealing with complex systems because of their many inter-acting and inter-dependent variables and their intransparency. Dorner’s extensive experimental observations of people’s failures with complex systems are summarized in Table A.3.

**Table A.3: Failures to deal successfully with complex systems**

<ul style="list-style-type: none"> <li>• slowness of thinking</li> <li>• slowness of knowledge storing</li> <li>• act without prior analysis</li> <li>• do not anticipate side effects</li> <li>• assume absence of negative effects</li> <li>• blind to changes</li> <li>• prone to cyclical actions</li> <li>• cognitive vagabonding</li> <li>• shift responsibilities</li> <li>• low capacities to tolerate uncertainties</li> </ul>	<ul style="list-style-type: none"> <li>• over-steering dynamic systems</li> <li>• time pressures</li> <li>• violations</li> <li>• memory limitations</li> <li>• reductive analysis (single causes)</li> <li>• contradictory goals</li> <li>• wrong models</li> <li>• active treated as passive</li> <li>• extrapolations based on present conditions</li> <li>• incapacity to deal with nonlinear time configurations</li> </ul>
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Key observations that came from these experiments were:

- “reality models can be right or wrong, complete or incomplete. Most are wrong and incomplete.”
- “contradictory goals are the rule, not the exception.”
- “most approach the continuing need for problem solving in complex systems with a repair service behavior; fix it once for all. But, the problems keep occurring.”
- “people are far more able to recognize and deal with arrangements in space than in time.”

- “we can not interpret numbers based on their size; to understand what they mean, we must understand the process that produced them.”

Dorner’s experimental observations lead to development of a five step process to deal with complex systems:

- Formulate goals,
- Formulate models and gather information,
- Predict and extrapolate effects,
- Plan actions, decisions, and executions, and
- Review effects of actions and revise strategy.

Dorner’s advice in dealing with complex systems is to know how the goal variables depend on the other variables in the system, to know how individual components fit into the hierarchy of the system, and to know how component parts of a system can be broken into elements.

Senders and Moray (1990) review of the taxonomies of human error suggest three primary types of human error taxonomies:

- Phenomenological – taxonomies which classify errors in a behaviorally descriptive way,
- Cognitive – taxonomies which reflect assumptions about underlying cognitive processes, and
- Deep-Rooted-Tendency – taxonomies which emphasize human higher-order biases and propensities

Senders and Moray (1990) distinguish two categories of human error: 1) endogenous, and 2) exogenous. Endogenous errors are those developed by an individual. Exogenous errors are those that arise outside of the individual or within the ‘environment.’

Swain and Guttman (1983) advanced a behavioral taxonomy that includes: errors of omission, errors of commission, sequence errors, and timing errors. Fitts and Jones (1961) developed a taxonomy based on their analysis of some 460 aircraft incidents that included six major categories: substitution errors, adjustment errors, forgetting errors, reversal errors, unintentional activation, inability to reach.

Meister (1971) suggests that errors be classified according to causes including: systems induced errors, design induced errors, and operator induced errors. A primary contribution of this taxonomy is classifying errors in terms of the major stages of a system development including design, production, and operations.

Rasmussen (1987) observes that human errors are events in the causal path that leads to system malfunctions (TableA.4). This observation is mirrored by Woods (1990): errors are results, not causes. Rasmussen contends that human errors cannot be defined in isolation from the systems in which they occur and that they must always be referenced with respect to human intentions and expectations. Rasmussen proposed the multifaceted taxonomy for description and analysis of events involving human malfunctions (instead of errors) summarized in Table A.4.

**Table A.4: Rasmussen's taxonomy for analysis of events involving human malfunctions**

<b>Performance Factors</b>	<b>Situation Factors</b>	<b>Personnel Task Factors</b>
<ul style="list-style-type: none"> <li>• subjective goals and intentions</li> <li>• mental load and resources</li> <li>• affective factors</li> <li>• causes</li> <li>• external events</li> <li>• excessive demands</li> <li>• incapacitation</li> <li>• intrinsic variability</li> </ul>	<ul style="list-style-type: none"> <li>• task characteristics</li> <li>• physical environment</li> <li>• work time characteristics</li> <li>• Mechanisms</li> <li>• discrimination</li> <li>• information processing</li> <li>• recall</li> <li>• inference</li> </ul>	<ul style="list-style-type: none"> <li>• equipment design</li> <li>• procedure design</li> <li>• fabrication</li> <li>• installation</li> <li>• inspection</li> <li>• operation</li> <li>• test and calibration</li> <li>• maintenance, repair</li> <li>• logistics</li> <li>• administration</li> <li>• management</li> </ul>
<b>External Malfunctions</b>	<b>Internal Malfunctions</b>	
<ul style="list-style-type: none"> <li>• task not performed</li> <li>• commission of erroneous act</li> <li>• commission of extraneous act</li> <li>• accidental timing of faults</li> </ul>	<ul style="list-style-type: none"> <li>• detection</li> <li>• identification</li> <li>• decision</li> <li>• action</li> </ul>	

## Organizational performance

Studies of HRO (Higher Reliability Organizations) (Roberts, 1989-1994; Roberts, et al, 1989-1995; Weick, 1979-1995b; Weick, et al, 1993-1999; Wenk, 1988; 1986; 1998) has shed some light on the factors that contribute to errors made by organizations and risk mitigation in HRO. HRO are those organizations that have operated nearly error free over long periods of time. A variety of HRO ranging from the U. S. Navy nuclear aircraft carriers to the Federal Aviation Administration Air Traffic Control System have been studied.

The HRO research has been directed to define what these organizations do to reduce the probabilities of serious errors (Roberts, 1989; Roberts and Rousseau, 1989). Reduction in error occurrence is accomplished by the following:

- Command by exception or negation,
- Redundancy,
- Procedures and rules,
- Training,
- Appropriate rewards and punishment
- Ability of management to "see the big picture".

Command by exception (management by exception) refers to management activity in which authority is pushed to the lower levels of the organization by managers who constantly monitor the behavior of their subordinates. Decision making responsibility is allowed to migrate to the persons with the most expertise to make the decision when unfamiliar situations arise (employee empowerment).

Redundancy involves people, procedures, and hardware. It involves numerous individuals who serve as redundant decision makers. There are multiple hardware components that will permit the system to function when one of the components fails.



Procedures that are correct, accurate, complete, well organized, well documented, and are not excessively complex are an important part of HRO. Adherence to the rules is emphasized as a way to prevent errors, unless the rules themselves contribute to error.

HRO develop constant and high quality programs of training. Training in the conduct of normal and abnormal activities is mandatory to avoid errors. Establishment of appropriate rewards and punishment that are consistent with the organizational goals is critical.

Lastly, Roberts and Roberts, et al. define HRO organizational structure as one that allows key decision makers to understand the big picture. These decision makers with the big picture perceive the important developing situations, properly integrate them, and then develop high reliability responses.

In recent organizational research reported by Roberts and Libuser (1993), they analyzed five prominent failures including the Chernobyl nuclear power plant, the grounding of the Exxon Valdez, the Bhopal chemical plant gas leak, the mis-grinding of the Hubble Telescope mirror, and the explosion of the space shuttle Challenger. These failures were evaluated in the context of five hypotheses that defined "risk mitigating and non-risk mitigating" organizations. The failures provided support for the following five hypotheses.

Risk mitigating organizations will have **extensive process auditing procedures**. Process auditing is an established system for ongoing checks designed to spot expected as well as unexpected safety problems. Safety drills would be included in this category as would be equipment testing. Follow ups on problems revealed in prior audits are a critical part of this function.

Risk mitigating organizations will have **reward systems that encourage risk mitigating behavior** on the part of the organization, its members, and constituents. The reward system is the payoff that an individual or organization gets for behaving one way or another. It is concerned with reducing risky behavior.

Risk mitigating organizations will have **quality standards that meet or exceed the referent standard** of quality in the industry.

Risk mitigating organizations **will correctly assess the risk associated with the given problem or situation**. Two elements of risk perception are involved. One is whether or not there was any knowledge that risk existed at all. The second is if there was knowledge that risk existed, the extent to which it was acknowledged appropriately or minimized.

Risk mitigating organizations will have a **strong command and control system** consisting of five elements: **a) migrating decision making, b) redundancy, c) rules and procedures, d) training, and e) senior management has the big picture.**

Weick, Sutcliffe, and Obstfeld (1998) have extended these concepts to characterize *how* organizations can organize for high reliability. Their extensive review of the literature and studies of HRO indicate that organizing in effective HRO's is characterized by:

**Preoccupation with failure** – any and all failures are regarded as insights on the health of a system, thorough analyses of near-failures, generalize (not localize) failures, encourage self-reporting of errors, and understand the liabilities of successes.

**Reluctance to simplify interpretations** – regard simplifications as potentially dangerous because they limit both the precautions people take and the number of undesired consequences they envision, respect what they do not know, match external complexities with internal complexities (requisite variety), diverse checks and balances, encourage a divergence in analytical perspectives among members of an organization (it is the divergence, not the commonalities, that hold the key to detecting anomalies).

**Sensitivity to operations** – construct and maintain a cognitive map that allows them to integrate diverse inputs into a single picture of the overall situation and status (situational awareness, ‘having the bubble’), people act thoughtfully and with heed, redundancy involving cross checks, doubts that precautions are sufficient, and wariness about claimed levels of competence, exhibit extraordinary sensitivity to the incipient overloading of any one of its members, sensemaking.

**Commitment to resilience** – capacity to cope with unanticipated dangers after they have become manifest, continuous management of fluctuations, prepare for inevitable surprises by expanding the general knowledge, technical facility, and command over resources, formal support for improvisation (capability to recombine actions in repertoire into novel successful combinations), and simultaneously believe and doubt their past experience.

**Under-specification of structures** – avoid the adoption of orderly procedures to reduce error that often spreads them around, avoid higher level errors that tend to pick up and combine with lower level errors that make them harder to comprehend and more interactively complex, gain flexibility by enacting moments of organized anarchy, loosen specification of who is the important decision maker in order to allow decision making to migrate along with problems (migrating decision making), move in the direction of a garbage can structure in which problems, solutions, decision makers, and choice opportunities are independent streams flowing through a system that become linked by their arrival and departure times and by any structural constraints that affect which problems, solutions and decision makers have access to which opportunities.

The other side of this coin are LRO (Lower Reliability Organizations). Weick, Sutcliffe, and Obstfeld observe that these non-HRO’s are characterized by a focus on success rather than failure, and efficiency rather than reliability. In non-HRO the cognitive infrastructure is underdeveloped (Wagenaar, et al, 1990), failures are localized rather than generalized, and highly specified structures and processes are put in place that develop inertial blind spots that allow failures to cumulate and produce catastrophic outcomes. Efficient organizations practice stable activity patterns and unpredictable cognitive processes that often result in errors; they do the same things in the face of changing events, these changes go undetected because people are rushed, distracted, careless, or ignorant. In non-HRO expensive and inefficient learning and diversity in problem solving are not welcomed. Information, particularly ‘bad’ or ‘useless’ information is not actively sought, failures are not taken as learning lessons, and new ideas are rejected. Communications are regarded as wasteful and hence the sharing of information and interpretations between individuals is stymied. Divergent views are discouraged, so that there is a narrow set of assumptions that sensitize it to a narrow variety of inputs.

In LRO success breeds confidence and fantasy, managers attribute success to themselves, rather than to luck, and they trust procedures to keep them apprised of developing problems. Under the assumption that success demonstrates competence, LRO drift into complacency, inattention, and habituated routines which they often justify with the argument that they are eliminating unnecessary effort and redundancy. Often down-sizing and out-sourcing are used to further the

drives of efficiency and insensitivity is developed to overloading and its effects on judgment and performance. Redundancy is eliminated or reduced in the same drive resulting in elimination of cross checks, assumption that precautions and existing levels of training and experience are sufficient, and dependence on claimed levels of competence.

With outsourcing, it is now the supplier, not the buyer, that must become preoccupied with failure. But, the supplier is preoccupied with success, not failure, and because of low-bid contracting, often is concerned with the lowest possible cost success. The buyer now becomes more mindless and if novel forms of failure are possible, then the loss of a preoccupation with failure makes the buyer more vulnerable to failure. LRO tend to lean toward anticipation of 'expected surprises,' risk aversion, and planned defenses against foreseeable accidents and risks; unforeseeable accidents and risks are not recognized or believed.

Weick, Sutcliffe, and Obstfeld finally characterize LRO as:

*"organizations in which people shuffle papers and lose a few, attend meetings and solve nothing, catch airplanes and miss connections, conduct briefings and persuade no one, evaluate proposals and miss the winners, and meet deadlines for projects on which the plug has been pulled."*

Haber, et al (1991) and Wu, et al (1989) have advanced the concepts of HRO in a development applied to the operating safety of nuclear power plants. Their approach is focused on five sets of organizational factors that address:

- Communications,
- Organizational culture,
- Decision making (including problem solving),
- Standardization of work processes, and
- Management attention, involvement, and oversight

The discriminating elements involved in each of these five sets of factors are developed. A protocol was developed to allow assessors to observe the management and operations of a given power plant and develop gradings of the factors. These gradings were then used to modify plant operator error rates (influence factors) in an event-tree, fault-tree based probabilistic risk analysis model of the 'critical' power plant operations (that could lead to a core meltdown). This approach allows organizational influences to be integrated into the probabilistic risk analysis results. A demonstration exercise was conducted with a power plant to illustrate how the approach might be used (Wu, et al, 1989). It was concluded that the approach was workable and produced useable results.

Bellamy, et al, (1986, 1990), Bellamy and Geyer (1992), and Hurst, et al (1989-1992) addressed organizational, management and human factors in quantified risk assessment for the U. K. Health and Safety Executive. The objective of this work was to develop a method to incorporate organizational influences in quantified risk analyses (QRA). Bellamy and Geyer develop the basis for a system that is identified as MANAGER. MANAGER can be used in modification of risk audits. At the core of this approach is a 'sociotechnical pyramid' that was adapted from Hurst et al (1989). This approach focused on five 'levels:'

**System climate** – reflecting technological know-how, lessons learned from previous incidents, industry norms and standards, legislation and regulatory systems, economic climate, location, nature of hazard, etc.

**Organization and management** – reflecting establishment of organizational goals, maintaining and improving standards, formation and organization of groups, coordination, allocation of resources, data gathering, determination of resource allocations, and definition of lines of responsibility and accountability.

**Communication, information, and feedback control** – reflecting formal and informal communications, frequency and duration, documentation, information availability, equipment availability, data availability, supervision, and individual – group performance measures.

**Operator reliability** – reflecting task demand characteristics, operator understanding and skills, quality of man-machine interface design, stresses, social effects, environment, and access to information.

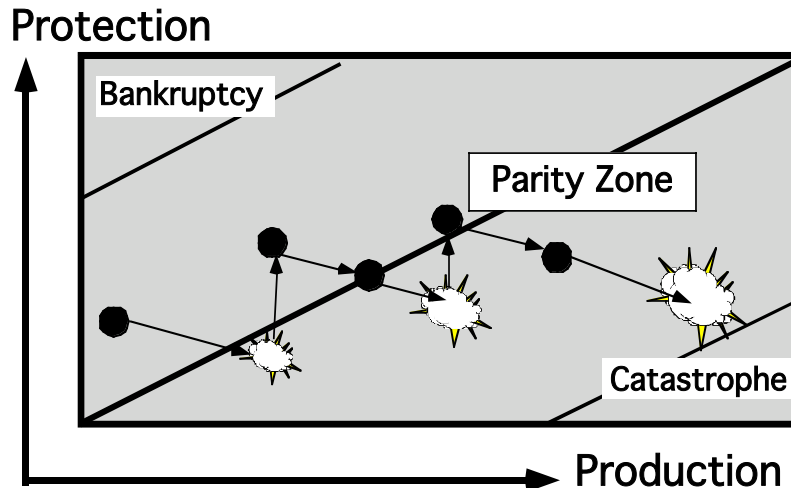
**Engineering reliability** - reflecting hardware and software of the facility and the process.

An extensive list of questions – considerations were developed guide development of the assessments of the levels. Grading guidelines were developed and the gradings were weighted with ‘contribution scores.’ The multiple influences were then used to modify ‘standard failure frequencies’ and these were then summed to give an overall failure frequency for the facility (Hurst, et al, 1990-1992).

The approach was applied by Harrison (1992) to an existing database of failures in piping systems. It was concluded that this was a workable approach to integrate organizational factors into QRA. The report by Wright, et al (1992) continued this development with an aim of evaluating alternative approaches that would allow the use of statistical data and sociotechnical system modeling and to compare alternative sets of questions that had been developed by different organizations.

Reason (1997) in expanding his work from the individual to the organization, develops another series of important insights and findings. Reason observes that all technological organizations are governed by two primary processes: production and protection. Production produces the resources that make protection possible. Thus, the needs of production will generally have priority throughout most of an organization’s life, and consequently, most of those that manage the organization will have skills in production, not protection. It is only after an accident or a near-miss that protection becomes for a short period time paramount in the minds of those that manage an organization.

The history of the organization’s walk through the protection – production – time space is characterized with the black circles in Fig.A.5 (Reason, 1997). The history starts in the left-hand corner where the organization begins production with a reasonable margin of protection. As time passes, the protection is reduced in a drive for greater efficiency until a low-cost accident (or near-miss) occurs. The event leads to an improvement in protection, but again, this improvement is traded off for a production advantage until another, more serious accident occurs. Again, the level of production is increased and again the level of protection is eroded by an event free period. The end of the history is a catastrophe. Risk compensation, an exponential decay in ‘awareness’ of the lessons of the last accident or fear of the next accident, and simply increasing production without increasing protection leads to the catastrophic accident.



**Figure A.5: Life of an organization through production – protection space (Reason, 1997)**

Reason observes that production and protection are dependent on the same underlying organizational processes. If priority is given to production by management and the skills of the organization are directed to maximizing production, then unless other measures are implemented, one can expect an inevitable loss in protection until significant accidents cause an awakening of the need to implement protective measures. The organization chooses to focus on problems that it always has (production) and not on problems it almost never has (major accidents). The organization becomes ‘habituated’ to the risks it faces and people forget to be afraid: “chronic worry is the price of safety.”

Reason advances the following in-depth defenses for managing ‘the risks of organizational accidents’:

- creation of understanding and awareness in the organization
- provision of guidance on the management of active (unsafe acts) and latent (inherent weaknesses) conditions
- provision of warnings and alarms that will provide signals of degradations
- development of restoring systems (provision of damage tolerant – robust systems)
- utilization of safety barriers to provide early warnings to operators and managers
- development of procedures to contain and eliminate hazards

Reason cites a number of ‘dangerous defenses’ developed by organizations in response to accidents:

- excessively complex systems and procedures: ‘killed by their armor;’
- over-automation and computation: ‘radar assisted collisions;’
- excessive formal procedures: ‘violations are the only way left to do what needs to be done;’
- reactive prevention: ‘causing the next accident while trying to prevent the last one,’ frequently taking the form of ‘kill the victim;’
- defenses in depth: ‘dangerous concealment;
- too sensitive alarms: ‘cry wolf’ reactions; and
- fuses: ‘unnecessary complexity’



Reason advances observations regarding ‘the unhappy lot of regulators:’

*“Regulators tend to become reliant on the regulated to help them acquire and interpret information; consequently, they obtain filtered information, tend to sympathize with the regulated, and develop a compromised ability to identify, report, or sanction violations. The requirement for the regulator to compromise with the regulated is an enforcement pattern that is systematically generated by the structure of inter-organizational relations (Vaughn, 1996; 1997).”*

Two structure systems operations oriented safety management instruments are discussed by Reason: Tripod Delta (Hudson, et al, 1994; 1996a; 1996b) and Tripod Beta (Groeneweg, 1994). Both of these instruments will be discussed later in this work.

As a result of a 3-year duration joint industry – government sponsored project, Moore and Bea (1993a) developed a human error safety index method (HESIM). For a given ‘system,’ an operator safety index was developed from the product of five contributing safety indices: operating team index, organizational index, performance factors index, system factors index, and environmental factors index. Based on published information on operator task error rates (e.g. Swain, 1963; 1978; Swain and Guttman, 1983), the base probability for operator error in a given task was estimated. This base probability was then modified by the product of the safety indices. An accident investigation instrument was developed that with time and application could be used to develop the operator error rates and influence factors. The organizational index included top level and middle level management influences that included: overall commitment to safety, commitment to long-term safety goals, cognizance of problems, competence to correct problems, and sufficiency of resources.

HESIM was used in a detailed study of the Piper Alpha accident (Moore, Bea, 1993b; 1993c) and the Exxon Valdes grounding (Moore, 1993; 1994; Moore, Bea, 1993c; 1995). Influence diagram methods were used in an analysis of the primary tasks and elements involved in the Piper Alpha and Exxon Valdes ‘systems.’ These applications indicated that the method was workable and developed realistic results. The approach was used to study how the reliability of the systems might be improved.

Murphy and Pate-Cornell (1996), and Pate-Cornell and Murphy (1996) have developed a system-action-management (SAM) approach that involves use of four models for the evaluation of the link between management factors and human actions. Three of these models attempt to represent the intentions of the organization and one is intended to address the execution of actions. The models are:

- Rational actor – decisions determined by the set of alternatives considered, the information available, consequences, and preferences.
- Bounded rationality – when an alternative that satisfies defined goal is found, the search ends without further analysis.
- Rule-based – organizations uses a catalogue of pre-established rules that specifies the action appropriate for each circumstance.
- Execution – organizations defined based on their capabilities and likelihood of error versus task demands are assessed.

Murphy and Pate-Cornell cite four strategies that influence the decisions made by an organization:

- Incentives,
- Resources,
- Information, and
- Change of preferences through socialization.

One of the factors that is repeatedly cited in discussions concerning the influences of organizations on reliability of systems is the ‘Safety Culture’ of the organization. The safety culture is concerned with the beliefs, values, attitudes and behaviors of people in an organization (Pidgeon, 1991; Pidgeon and O’Leary, 1994). The culture of an organization reflects its history and its identity (Zohar, 1980; Meshkati, 1995).

The culture of an organization is influenced by the local and national social cultures. Studies of HRO indicate that once the safety culture of an organization is or is not established, it is extremely difficult, if not impossible to change it (Roberts, 1990). The study for the Nuclear Regulatory Commission reported by Haber, et al (1991) defined 12 different ‘styles’ that characterized the safety culture of an organization. These ranged from humanistic and affiliative to perfectionistic and self-actualizing cultures. Merry (1998) defined 11 key attributes that characterized ‘World Class Safety Cultures:

- visible leadership and commitment of top management
- safety role of line management
- strategic business importance of safety
- supportive organizational practices
- involvement of all employees
- learning organization
- safety performance measurement
- mutual trust and confidence between management and workforce
- openness of communications
- absence of safety versus production conflicts
- demonstration of care for those affected by business

These attributes reflected three key aspects of the safety culture: the safety climate, the safety management, and the safety behavior. Application of these attributes to two organizations indicated that the attributes did a good job of reflecting the safety culture (Merry, 1998).

Meshkati (1995) performed an extensive study of the concept of safety culture as it applied to nuclear power plants. Meshkati found that an organization’s safety culture is a system composed of behaviors, practices, policies, incentives / rewards, communications, and structural components, and that this system can not survive without interactions and harmony with the societal or national culture. Meshkati identifies the following issues that determine the safety culture of nuclear power plants:

- risk perception
- attitude toward work
- work group dynamics
- attitude toward technology
- attitude toward organization, hierarchy, procedure, and working habits
- attitude toward time and time of the day

- religious duties and their effects on work
- achievement motivation and orientation
- population stereotype (e.g. color association)
- the ‘if it ain’t broke, don’t fix it’ attitude

Risk perception is influenced or moderated by such safety culture issues. The result ‘elevates some risks to high peak and depresses other below sight.’

According to the U. S. Regulatory Commission, nuclear safety culture is a prevailing condition in which each employee is always focused on improving safety, is aware of what can go wrong, feels personally accountable for safe operation, and takes pride and ownership in the plant (General Accounting Office, 1990). Safety culture is a disciplined, crisp approach to operations by highly trained staff who are confident but not complacent, follow good procedures, and practice good team-work and effective communications. Safety culture is an insistence on a sound technical basis for actions and a rigorous self-assessment of problems (General Accounting Office, 1990).

Based on the research performed by Pidgeon (1991), a safety culture can be characterized as the set of beliefs, norms, attitudes, roles, and social and technical practices that are concerned with minimizing the exposure of employees, managers, customers, and members of the public to conditions considered dangerous or injurious. Schein (1985) defines the organizational culture as a pattern of basic assumptions, invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think and feel in relation to those problems. Culture is a way of life of a people – the sum of their learned behavior patterns, attitudes, customs, and material goods. Gould (1981) observes that even engineering and scientific theories are strongly culturally based:

*“Facts are not pure and unsullied bits of information; culture also influences what we see and how we see it. Theories, moreover, are not inexorable inductions from facts. The most creative theories are often imaginative visions imposed upon facts; the source of imagination is also strongly cultural.”*

**It is obvious that both industrial – regulatory cultures and engineering cultures exert powerful influences on the potentials for and effects of Human and Organizational Factor Malfunctions – often referred to as “Human Errors”.**

## **Taxonomies for Root Causes Analyses**

The foregoing background was used as a basis for development of a set of human and organizational malfunction taxonomies (classifications and descriptions) appropriate for the purposes of performing Root Causes Analyses of major failures of Engineered Systems. The taxonomies are based on studies of more than 600 well-documented accidents, disasters, and catastrophes. The proposed taxonomies are phenomenological and heuristic.

The taxonomies go beyond Human and Organizational Factor malfunctions and include structure-hardware malfunctions, procedure malfunctions, and environmental influences. Other taxonomies generally associated with accident and failure investigation databases also have been reviewed and their best aspects incorporated into these taxonomies.

The proposed taxonomies do not define the why's of errors. Rather, they define how's of errors; the generic categories of actions or activities that can result in errors. This approach was taken so that when the activities or actions were identified they could be remedied or corrected.

## Operator Malfunctions

As discussed earlier, there are many different ways to define, classify and describe operator (individual) malfunctions. Operator malfunctions can be defined as actions taken by individuals that can lead an activity to realize a lower quality than intended. These are malfunctions of commission.

Operator malfunctions also include actions not taken that can lead an activity to realize a lower quality than intended. These are malfunctions of omission. Operator malfunctions might best be described as action and inaction that result in lower than acceptable quality to avoid implications of blame or shame. Operator malfunctions also have been described as mis-administrations and unsafe actions. Operator errors result from operator malfunctions.

Operator malfunctions can be described by types of error mechanisms. These include slips or lapses, mistakes, and circumventions. Slips and lapses lead to low quality actions where the outcome of the action was not what was intended. Frequently, the significance of this type of malfunction is small because these actions are not easily recognized by the person involved and in most cases easily corrected.

Mistakes can develop where the action was intended, but the intention was wrong. Circumventions (violations, intentional short-cuts) are developed where a person decides to break some rule for what seems to be a good (or benign) reason to simplify or avoid a task. Mistakes are perhaps the most significant because the perpetrator has limited clues that there is a problem. Often, it takes an outsider to the situation to identify mistakes.

Based on studies of available accident databases on engineered systems, and studies of case histories in which the acceptable quality of the systems has been compromised, a taxonomy of Operator malfunctions are summarized in Table A.5. The sources of mistakes or cognitive malfunctions are further detailed in Table A.6.

**Table A.5: Taxonomy of operator malfunctions**

<b><i>Communications</i></b> – ineffective transmission of information
<b><i>Slips</i></b> – accidental lapses
<b><i>Violations</i></b> – intentional infringements or transgressions
<b><i>Ignorance</i></b> – unaware, unlearned
<b><i>Planning &amp; Preparation</i></b> – lack of sufficient program, procedures, readiness
<b><i>Selection &amp; Training</i></b> – not suited, educated, or practiced for the activities
<b><i>Limitations &amp; Impairment</i></b> – excessively fatigued, stressed, and having diminished senses
<b><i>Mistakes</i></b> – cognitive malfunctions of perception, interpretation, decision, discrimination, diagnosis, and action

## Organization Malfunctions

Analysis of the history of failures of engineered systems provides many examples in which organizational malfunctions have been primarily responsible for failures. Organization malfunction is defined as a departure from acceptable or desirable practice on the part of a group of individuals that results in unacceptable or undesirable results. Based on the study of case histories regarding the failures of engineered systems, studies of High Reliability Organizations (Roberts, 1990), and managing organizational risks (Reason, 1997), a classification of organization malfunctions is given in Table A.7.

The goals promulgated by an organization may induce operators to conduct their work in a manner that management would not approve if they were aware of their reliability implications. Excessive risk-taking problems are very common in highly structured systems (protected by anonymity). Frequently, the organization develops high rewards for maintaining and increasing Production; meanwhile the organization hopes for Protection (Safety): **Rewarding ‘A’ while Hoping for ‘B’**. The formal and informal rewards and incentives provided by an organization have a major influence on the performance of operators and on the reliability of ocean systems.

Several examples of organizational malfunctions recently have developed as a result of efforts to down-size and out-source as a part of re-engineering organizations. Loss of corporate memories (leading to repetition of errors), creation of more difficult and intricate communications and organization interfaces, degradation in morale, unwarranted reliance on the expertise of outside contractors, cut-backs in quality assurance and control, and provision of conflicting incentives (e.g. cut costs, yet maintain quality) are examples of activities

**Table A.6: Classification of mistakes – cognitive processing errors**

<b>Perception</b> – unaware, not knowing
<b>Interpretation</b> – improper evaluation and assessment of meaning
<b>Decision</b> – incorrect choice between alternatives
<b>Discrimination</b> – not perceiving the distinguishing features
<b>Diagnosis</b> -incorrect attribution of causes and or effects
<b>Action</b> - improper or incorrect carrying out activities

**Table A.7: Taxonomy of organizational malfunctions**

<b>Communications</b> – ineffective transmission of information
<b>Culture</b> – inappropriate goals, incentives, values, and trust
<b>Violations</b> – intentional infringements or transgressions
<b>Ignorance</b> – unaware, unlearned
<b>Planning &amp; Preparation</b> – lack of sufficient program, procedures, readiness
<b>Structure &amp; Organization</b> – ineffective connectedness, interdependence, lateral and vertical integration
<b>Monitoring &amp; Controlling</b> – inappropriate awareness of critical developments and utilization of ineffective corrective measures
<b>Mistakes</b> – cognitive malfunctions of perception, interpretation, decision, discrimination, diagnosis, and action

that have lead to substantial compromises in the intended quality of systems.

Experience indicates that one of the major factors in organizational malfunctions is the culture of the organization. Organizational culture is reflected in how action, change, and innovation are viewed; the degree of external focus as contrasted with internal focus; incentives provided for risk taking; the degree of lateral and vertical integration of the organization; the effectiveness and honesty of communications; autonomy, responsibility, authority and decision making; rewards and incentives; and the orientation toward the quality of performance contrasted with the quantity of production. The culture of an organization is embedded in its history.

## Structure and Hardware malfunctions

Human malfunctions can be initiated by or exacerbated by poorly engineered systems and procedures that invite errors. Such systems are difficult to construct, operate, and maintain. Table 3.8 summarizes a classification system for hardware (equipment, structure) related malfunctions.

New technologies compound the problems of latent system flaws. Complex design, close coupling (failure of one component leads to failure of other components) and severe performance demands on systems increase the difficulty in controlling the impact of human malfunctions even in well operated systems.

Emergency displays have been found to give improper signals of the state of the systems. Land based industries can spatially isolate independent subsystems whose joint failure modes would constitute a total system failure. System malfunctions resulting from complex

designs and close coupling are more apparent due to spatial constraints onboard systems. The field of ergonomics has largely developed to address the human – machine or system interfaces. Specific guidelines have been developed to facilitate the development of people friendly systems.

The issues of system Robustness (defect or damage tolerance), design for constructability, and design for IMR (Inspection, Maintenance, Repair) are critical aspects of engineering systems that will be able to deliver acceptable quality. Design of the system to assure robustness is intended to combine the beneficial aspects of redundancy, ductility, correlation and excess capacity (it takes all four). The result is a defect and damage tolerant system that is able to maintain its serviceability characteristics in the face of HOF. This has important ramifications with regard to structural design criteria and guidelines. Design for constructability is design to facilitate construction, taking account of worker qualifications, capabilities, and safety, environmental

**Table A.8: Taxonomy of structure & equipment malfunctions**

***Serviceability*** – inability to satisfy intended and required purposes for intended, expected, and unexpected, unintended (accidental) conditions

***Safety*** – excessive threat of harm to life and the environment, demands exceed capacities, Risks of major accidents that are not ‘acceptable’, ‘tolerable’, and ‘As Low As Reasonably Practicable.’

***Durability*** – occurrence of unexpected decay and degradation, maintenance and less than expected useful life

***Compatibility*** – unacceptable and undesirable economic, environmental, productivity, schedule, aesthetic, and public – government approval characteristics



conditions, and the interfaces between equipment and workers. Design for IMR has similar objectives.

## Procedure & Software Malfunctions

Based on the study of procedure and software related problems that have resulted in failures of engineered systems, Table A.9 summarizes a classification system for procedure or software malfunctions. These malfunctions can be embedded in engineering design guidelines and computer programs, construction specifications, and operations manuals. They can be embedded in how people are taught to do things. With the advent of computers and their integration into many aspects of the design, construction, and operation of engineered systems, software errors are of particular concern because the computer is the ultimate fool.

**Table A.9: Taxonomy of procedure and software malfunctions**

<i><b>Incorrect</b></i> - faulty
<i><b>Inaccurate</b></i> - untrue
<i><b>Incomplete</b></i> - lacking the necessary parts
<i><b>Excessive Complexity</b></i> - unnecessary intricacy
<i><b>Poor Organization</b></i> - dysfunctional structure
<i><b>Poor Documentation</b></i> - ineffective information recording and transmission

Software errors in which incorrect and inaccurate algorithms were coded into computer programs have been at the root cause of several major failures of systems. Guidelines have been developed to address the quality of computer software for the performance of finite element analyses (Basu, Kirkhope, Srinivasan, 1996a; 1996b). Extensive software testing is required to assure that the software performs as it should and that the documentation is sufficient (Bea, et al, 1994). Of particular importance is the provision of independent checking procedures that can be used to validate the results from analyses. High quality procedures need to be verifiable based on first principles, results from testing, and field experience.

Given the rapid pace at which significant industrial and technical developments have been taking place, there has been a tendency to make design guidelines, construction specifications, and operating manuals more and more complex. Such a tendency can be seen in many current guidelines used for design of engineered systems. In many cases, poor organization and documentation of software and procedures has exacerbated the tendencies for humans to make errors. Simplicity, clarity, completeness, accuracy, and good organization are desirable attributes in procedures developed for the design, construction, and maintenance, and operation of systems.

## Environmental Influences

Environmental influences can have important affects on the performance characteristics of individuals, organizations, hardware, and software. Environmental influences include:

- **External** (e.g. wind, temperature, rain, fog, time of day),
- **Internal** (lighting, ventilation, noise, motions), and
- **Sociological factors** (e.g. values, beliefs, taboos).

All three of these environmental influences can have extremely important effects on error rates.

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## **APPENDIX B**

### **Root Cause Analysis of the Initiating Blowout Failure of the Oroville Dam Gated Spillway**

#### **Failure Background**

On January 27, 2017, a 'hole' in the Oroville Dam concrete gated spillway 'chute' was discovered and documented by photographers. Eleven days later, on Feb 7, 2017, the spillway catastrophically broke apart forming a gaping hole where a number of spillway concrete slabs were fractured, separated and lifted away. The Spillway flow was at 18% of its design ratings when the blowout failure occurred.

For the failure to occur at such a low margin of the rated structural capacity when it had survived much larger flow rates indicates that a degradation of the integrity of the spillway occurred over time. Original design defects and flaws were ingrained into the spillway from construction decisions [1]<sup>1</sup>, which over time were compounded by ineffective inspections and maintenance to address the degradation effects induced from the original defects and flaws and from spillway operations.

The spillway operated at 162,500 cubic feet per second flows in the "New Years Flood" in January 1997 with no incidents [2]. This high spillway flow rate was at an operational level of 55% of the rated spillway design capacity, yielding a 45% remaining margin of capacity. This evidence establishes a reference to an "empirical uneventful performance" in a spillway operational structural condition that was near 300% above the failure in 2017, while uneventful at 55% of the rated spillway structural capacity in 1997. This evidences a structural capacity reference to the severity of the "degradation" of the integrity of the spillway over time.

#### **Defects, Flaws, and Maintenance Degradation to Failure**

Examination of 1969 photographs reveal that the initial drainage of the spillway showed very little water drainage flows (Fig. B.1). Faint moisture marks are observable as darkening from wetting of the sidewall concrete. The spillway water flow was light.

Comparing near identical conditions to those of the January 27, 2017 photograph (Fig. B.2) reveals "jetting" drainage flows from a lighter water flow to the identical sidewall drain locations (a, b, c, d, in Fig. B.1). Large foundation voids and flow channels under the concrete slabs would be required for this volume of water flows from the drains. Further, the January 2017 image reveals this volume of underflow is "recaptured" through water re-penetration into the gaps, seams, and drain line cracks in the slabs. Fig. B2 reveals the full extent of the evidence of the extensive foundation gaps, voids, and channels that have formed over time resulting in the

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<sup>1</sup> References at the end of Appendix B.

current state of "jetting" sidewall drains from a simple "light flow". To some degree, there is a complex "secondary spillway" flow system parallel to and beneath the concrete 'surface' spillway.

## **Degradation of the Spillway from Flaws, Decisions, Maintenance over Time**

California Department of Water Resources (DWR) Final Construction Report FCR 65-09 [13] and DWR Final Geology Report C-38 [12] reveal that DWR constructed the spillway with serious design flaws that led to a significant structural integrity loss over time, and which ultimately resulted<sup>2</sup> in the blowout failure seen on February 7, 2017. **Included in these critical design flaws were decisions made by DWR Field Engineers to restrict contractors from following design specifications [15] to excavate to sound competent rock or remove incompetent rock and soil and fill the voids with concrete, thus constructing large parts of the invert chute concrete on highly erodible foundation materials.**

The following sequence of developments evidences the answer to the 1969 to 2017 comparison photograph of critical changes to the spillway over time - changes developed by operational flood control releases:

1. **DWR Field Engineer restricts contractor from following excavation specifications to competent rock.** (Fig. B.17). Thus, large and deep seams of clay or highly erodible soil-like material remain - open to deep erosion - open to forming large voids, and open to significant degradation of slab anchorage upon future spillway operation.
2. **DWR Geology Engineering design changed from the original HYD-510 and Bulletin 200 design drawings [15] (noted as emplaced upon rock or base concrete) to the change to allow emplacement upon a layer of clayey "fines" before pouring the spillway concrete slabs.** (Fig. B.16) [12, 13].
3. **DWR used compacted clayey material (fines) to level the irregular subsurface rock grade (Fig. B.18).** This material was highly erodible from subsurface water flow. In addition, the degraded and erodible 'incompetent rock' (Fig. B.10 and Fig. B.11) was not excavated and backfilled with concrete as required by the spillway design.<sup>1</sup>
4. **Construction used wide amounts of side drain "round gravel filter rock" next to drain pipes forming a larger area of loss of slab structural integrity - thus contributing to the consistent pattern of drain line cracks in slabs above drain lines in conjunction with the flawed design of emplacing the drains within the slab causing a "thinning" the slab thickness dimensions (Fig. B.19, Fig. B.12).**
5. **DWR allowed the slab anchors to be installed in clay seams.** Anticipated that the anchor bars would work in the "worst foundation available". Did not take into account any water penetration from slab seams and scouring erosion of these areas of "worst foundation available". Anchorage thus reduced to a highly degraded ability to perform (or

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<sup>2</sup> "Resulted" from decades of lack of proper recognition and understanding of these original flaws and the lack of appropriate effective remedial actions.

none). (Fig. B.20). Blowout failure area evidences that anchorage loss was a primary structural contributor to the failure.

## **Loss of Spillway Structural Foundation over Time**

Due to the Design Flaws, Design Changes, Construction Flaws, and Flawed Field Engineering decisions, each flood control operation of the Oroville Spillway degraded the concrete spillway in its foundational and anchorage structural integrity. Penetrating water flows into and under the slabs created "scouring erosion" conditions to where the compacted clay "fines" layer was carried off through the coarse drain rock and out through the drains to the spillway. This same process eroded and transported fines deeper within the slab foundation to where voids formed (Ref. [17], Figs. B.3, B.4, B.5).

Continued flood control operational spills developed piping channels and voiding areas to where "void repairs" became necessary. As the foundation became less structurally sound, and the slabs had the design "flaw" of wide base "thin" zones from the upward emplaced drain pipe, cracks formed pervasively in the slabs (Fig. B.7, Fig. B.19) [1][16]. These near 5 linear miles of cracks above the drains (Ref. [16], Fig. B.1) created a significant increase in pressurized water flow penetration into and under the slabs, thus accelerating the piping erosion process. The 2017 Board of Consultants recognized a high water flow problem and noted: ***"The amount of drain water flowing from the pipe discharge openings along the spillway training walls seems extraordinarily large."***[4]. The loss of spillway structural foundation developed over time due to the following:

1. **Excessive Foundation loss from High Volume Scouring Under-slab Erosion [1].** The March 10, 2017 BOC report revealed that this serious issue of "void" formation has been "found and repaired in the past". Quoting the report: "It seems likely that piping of foundation material beneath the chute slab may be responsible for the voids that have been found and repaired in the past."
2. **Evidence of Voids forming to 9+ feet deep. [17].** DWR maintenance repairs clogging drains by injecting deep void filling material (concrete/grout) to where drain sections became non-functional (up to 1,780 feet of drains broken that service 36,500 square feet of two spillway areas) Fig. B.2 - circled sidewall drains to a non-functional total 1,780 feet of drains. Thus forcing erosive flow deeper and re-routing the deeper channels to other areas beneath the spillway.
3. **Excessive Drain Flow 'Jetting' from Sidewall Outlets signal Alarm in Spillway Slab Cracks & Poor Sealing of Slab seams (photograph of fire-hose "jetting" of sidewall drains) [16].**
4. **Excessive pressurized subsurface slab water flows.** The DWR Board of Consultants (BOC) confirming the issue of the volume of the pressurized subsurface slab water flows in their March 10, 2017 BOC Memorandum No. 1 [4]. Quoting the report: "The amount of drain water flowing from the pipe discharge openings along the spillway training walls seems extraordinary large." "It appears also that the drains are collecting leakage through cracks in the chute slab and/or defects in the construction joints between the slabs. The drains appear to flow for some appreciable time after the gates are closed."



The DWR Oroville Dam Spillway Incident Forensic Investigation Team recognized these issues; from May 5, 2017 Memorandum [9] - items from list:

1. "16. Weathered rock and completely weathered rock that is soil-like material as slab foundation, without appropriate modification of the chute slab design, resulting in potentially erodible material beneath the slab and lack of foundation bond with concrete;"
2. "17. Less rigorous foundation preparation, resulting in lack of foundation bond with concrete."
3. "19. Insufficient anchorage, due to limited anchor development in the concrete, short anchor length, inadequate grouting or grout strength, and/or installation in weak foundation material."

## **Flawed Maintenance Repairs Propagated and Increased the Spillway Degradation**

In 2009, DWR Spillway repair bids and line item documentation, prepared by DWR engineering, noted that 240 linear feet of drains were identified to be repaired [7][11]. A 2007 photograph reveals that one section of the spillway drains (10 drains spaced 20 feet apart servicing 18,250 square feet of spillway drainage area) were non-functional revealed by the sidewall drain non-operation (Fig. B.4).

After the 2009 contract repairs, the same drain section remained non-functional as evidenced in a 2013 photograph (Reference [17] Figs. 1 and 14). 2017 photographs reveal that 1,780 linear feet of slab drains that service 36,500 square feet of spillway drainage area were non-functional (Fig. B.2). Despite the DWR drain repair identification of 240 linear feet, **the drains were not repaired.**

Inspections by the Division of Safety of Dams (DSOD), and the Federal Energy Regulatory Commission (FERC) should have identified such a severe non-functional drainage condition in the spillway. As the non-functioning drain state is observable from the sidewall drain & water seepage patterns, a visual inspection would have discovered this issue. **The cited evidence documents that this non-functional drain state was not recognized nor repaired for close to 10 years (Nov 2007 to Jan 2017).**

Had DSOD, or FERC properly recognized this issue, an investigation would have revealed the source of the widespread ‘clogging’ of the drains and remedial action could have been initiated. **This Failure of Inspection from multiple agencies, and for nearly a decade, is perhaps one of the greatest failures in the critical process of insuring the safety and integrity of the spillway.**

In summary:

1. **DSOD, and FERC failed to recognize the significant problem of two non-functional sidewall drains which serviced 36,500 square feet of under-slab drainage for a span of 9 years 3 months.**
2. **DWR engineering noted 240 linear feet of drain line were to be repaired in 2009**

[11]. In 2013 the drains remained non-functional (Reference [17] Fig. 14). DWR Maintenance and Engineering failed to address this issue.

3. Evidence identifies that Maintenance repairs of "deep void" filling (forming Large Concrete Slab blocks), with up to 9+ feet deep voids under the spillway, would have clogged the open ends of "dropped" drains [17] (Reference [17], Figs. 3, 4, 5, 6, 8, 10).
4. Seepage Evidence in 2013 identifies that water flow submarines below the large void block concrete filled non-functional drain area (left side view Ref [17], Fig. 14) and the seepage re-appears immediately downslope.
5. Evidence DWR failed to notify FERC on the issue of "deep void" filling repairs. Dam owners are required to notify FERC of any serious Potential Failure Modes (PFM's) [18].
6. The second non-functional drainage area is directly upslope to the blowout failure initiation location (Fig. B.5). This condition would combine a large volume of non-captured under-slab flow to the next set of downslope drains. A higher volume of pressurized water flow increases the scouring erosion of weak foundation material identified in the blowout failure region. From the evidence of the "clogging" of injection of large "void filling" from Reference [17], the same process of deep erosion (and potential injecting induced "clogging") could render drains inoperable by either "dropping" drain pipe or "clogging" to where they are unable to service flows.

The DWR Oroville Dam Spillway Incident Forensic Investigation Team recognized "plugging" or "collapse" of drains; from May 5, 2017 Memorandum [9] – items:

1. "11. Plugging or collapse of drains or collector pipes, including potential plugging by tree roots."
2. "12. Flow into the foundation that exceeded the capacity of the drain pipes, including flows from areas adjacent to the chute."

## Loss of Anchorage

**The loss of the spillway foundation integrity caused a significant structural integrity degradation of slab anchorage in the spillway anchor bars.** DWR engineers had not considered the design consequences that would result in the high volume of pressurized water flow under the spillway slabs. Using the experimental data generated by the U.S. Bureau of Reclamation (Fig. B.13), a single drain system (10 drains spaced 20 feet apart) with a simple example of one seam per slab (0.125 effective seam width, 1/2 inch offset, 90 feet per second flow rate) could yield up to 55 cubic feet per second of total sub-slab water flow.

This example flow rate would scour the full length of a 200 foot (18,250 square feet) slab array of eight slabs plus the sidewall slab area. As anchor bars were intended to be emplaced in the "worst foundation available"; DWR Field Engineers restricted contractors from excavating to competent rock; and DWR Final Geology Report Spec 65-09 illustrated the poor quality highly

erodible foundation "wide seam area" (Fig. B.21); a significant penetrating pressurized sub-slab water flow in highly erodible foundation material, over time, would render the anchorage resistance to a dangerously degraded structural retention state.

In summary:

1. **Three 40 feet by 50 feet slabs, with a combined 60 anchor bars, failed in the initial blowout failure.** The fourth slab, to the left, was partially anchored on a section of "more competent rock" and it survived the initial blowout (Fig. B.10). This evidences the severe lack of structural integrity of the anchorage of the slabs as the image reveals the anchor bars were emplaced in highly weathered rock (poor) foundation material (light to brown color).
2. **Non-functional drainage increased a sub-slab scouring erosion flow at the blowout failure slabs.** The increased sub-slab scouring erosion on highly erodible material (noted in DWR Final Geology Report Spec 65-09 Fig. B.21) would have seriously degraded the anchorage strength in eroding at/near/around the anchor bar grout holes.

## **Structural Degradation from Reinforcement Steel Corrosion at Slab Cracks**

Post Spillway failure evidence reveals a highly corroded state of reinforcing bar across cracks in the slabs (Figs. B.14, B.15). The cracks (Fig. B.7) developed from the thinning zones or weak zones in the spillway slabs induced by the upward emplacement design flaw of the drain design, including the wide side slopes of filter gravel next to the pipe (Fig. B.19). The corrosion was so extensive in an investigative saw cut near a drain line in the upper spillway (Fig. B.15) that the crumbled remains of the original rebar formed an orange "stain" in the cut surface. Nothing remained of the original reinforcement steel core.

The severely corroded evidence in Fig. B.14 was in a multi-slab fracture above a drain line run. This evidences that the structural integrity of spillway slabs were greatly affected by the combination of slab cracks above the drain lines; where water flow penetrated these full depth slab cracks (Fig. B.7); and the water, over time, induced a significant degree of corrosion to where there was near total disintegration -if not fully- in the rebar transitioning these cracks. As each slab has 2 to 3 drain transverse under-slab drain lines, each slab thus faces a structural integrity risk along these cracks from the loss of reinforcement bar strength (tensile) in combination with a pre-cracked state (compressive) above the drains. Thus, this corrosion induced loss of reinforcement steel integrity, along drain line cracks, forced each "drain line separated" section of a slab to become highly dependent upon individual anchor bars. This would result in "highly degraded susceptible" areas of the spillway as there would be a loss of shared anchorage integrity to each slab in combination to the structural integrity losses from highly weathered rock foundation material.

In summary:

1. **Saw Cut in Upper Spillway (Fig. B.15), for a drain inspection, reveals a complete decomposition of a number of reinforcement bars transitioning the drain (upslope/downslope orientation across the drain).** The saw cut reveals an "orange stain" from the complete decomposition of the steel rebar.
2. **Fracture of Upper Spillway Failure section along a drain line reveals highly corroded reinforcing steel along the slab & drain line crack location.** Only one location shows sign of a thin diameter of remaining reinforcing steel.

The DWR Oroville Dam Spillway Incident Forensic Investigation Team recognized this potential failure contribution issue; from May 5, 2017 Memorandum [9] - "5. Corrosion and failure of reinforcing bars across cracks" .

## **A "Hole" in the Spillway - Blowout Failure Initiation**

High resolution original photographic forensic evidence reveals that a 7.9 foot by 14 inch "hole" was observed in the spillway Jan 27, 2017 (Fig. B.9). On Feb 7, 2017, at a flow rate of 54,500 cubic feet per second, DWR discovered a large amount of debris coming out of the concrete invert chute spillway [19]. DWR stopped all releases to inspect the spillway damage. What was discovered was a Blowout Failure area of nine slabs and partial destruction of four additional slabs (Fig. B.10).

The DWR Independent Board of Consultants (BOC) noted that the failure "initiated" at this "hole" in the spillway [3]. The BOC also noted that the hole was likely to the depth of the layer of the slab rebar. Other examples of concrete spalling and/or delamination, forming "holes", to the depth to the slab reinforcing steel is revealed in the Upper Spillway (Fig. B.6, 2017 photograph).

In summary:

1. March 17, 2017 BOC Memorandum No. 2 – “These photos show that failure was initiated at the hole at the left side of the chute near station 33+00. The failure, likely occurred as a result of high velocity flow (in the range of 85 to 90 feet per second), penetrating under the slab, causing a strong uplift force and causing the slab to lift, eventually causing all or part of the slab to break away. Subsequent erosion of foundation material caused progressive failure both upstream and downstream.”
2. DWR photographs of concrete spalling and/or delamination “holes” – workers observed patching “repairs” of the Upper Main Spillway of these holes. All “holes” observed at slab seam joints. Two “holes” observable in Fig. B.6 close to the Spillway Radial Gate Structure. Rows of “lines”, in a forensic zoom, infers concrete spalling or delamination depth to steel reinforcement layer in the slabs.

The DWR Oroville Dam Spillway Incident Forensic Investigation Team recognized this potential failure contribution issue; from May 5, 2017 Memorandum [9] - "22. Spalling and/or delamination of concrete at slab joints."

## Initial Blowout Failure Forensic Analysis Processes

**Forensic Process (A):** Confirmation of evidence that the "hole" and the "blowout failure" initiated at the same spillway seam is revealed in a forensic overlay of high resolution photographs (Fig. B.2 Jan 27, 2017 hi-resolution photograph overlay with an aligned angle Post Blowout Feb. 7, 2017 photograph). Using a high-end workstation system with a hi-resolution graphics array, a process of pixelated shifting of the overlay transparency on the images allows a precision forensic analysis (i.e. all x,y dimensions scale matched in the image overlay alignment to a high degree of precision as revealed in the electrical towers, sidewalls, trees, headworks, and to the lower chute). The overlay included a side-by-side scaled alignment photograph of the turbulent erosion and breakup damage from flows in the "blowout hole" (source ref. [6]). Horizontal black lines provide reference points for forensic comparison of the turbulent erosion damage to the original blowout failure. The "hole" precisely aligns at the spillway slab seam that had the "blowout failure" (Fig. B.3). The image section to the right reveals the brown colored erosion flow that is following the section of destroyed downslope slabs.

**Forensic Process (B):** To determine important historical concrete repair evidence at this "failure seam", a high resolution image pixelated zoom provided the upslope x,y slab seam locations relative to the sidewall drain to locate the seam. Satellite imagery from multiple years provided the concrete cuts, patches, and repairs for this seam to the full width of the 178 ft. chute. It was discovered that this seam is one of two seams in the entire 3000+ foot spillway that has the most extensive concrete repairs, cuts, patching, and resurfacing across a full width of the concrete chute. (note: the other location is near 500 ft. of the Headworks in the Upper Spillway). The very extensive repair history on this 178 ft. wide seam strongly evidences a structural issue affecting the abutting upslope and downslope slabs. Fig. B.8 reveals this seam with graphic overlay of the extensive concrete repairs to these upslope and downslope slabs at this seam junction.

**Forensic Process (C):** Using the workstation and with a high resolution source photograph, the dimensions of the seam "hole" were measured to be 7.9 feet by 14 inches with a slight taper in the sidewall direction (Fig. B.9). Note: the Fig. B.9 image is a wide view image of the hole for seam reference notations - High resolution forensic photo zoom not included in this report. The seam "hole" is marked in red on the composite image.

## Physical Root Cause Failure Analysis

The Physical Root Cause Failure Analysis of initiating blowout sequence of the Spillway is summarized in the following:

1. **Fig. B.8. Initial failure "hole" defect** initiation point of the Initial Blowout Failure Area of slabs along this extensively repaired spillway seam. Hole dimension measured with forensic high resolution photographs to be near 7.9 feet along the seam by 14 inches downslope from the seam. White lines denote the drain line cracks in the slab surface. The depth of the "hole" is inferred to be three inches deep to the upper layer of rebar - as evidenced in prior concrete spalling spontaneous defect occurrences revealed in Fig. B.6. This depth was also noted by the DWR Board of

2. **Fig. B.10. Initiating Failure Hole location** reveals a deep seam of highly erodible foundation material that is many feet deeper than the grouted 5 foot deep slab anchor bars. Angle of seam inferred by dashed line. Image reveals the nature of why the "hole" location and that full 178 foot wide seam area was a structural problem area. The upslope "soil-like" foundation material is in a transition zone of more competent rock (downslope from the dashed line). Thus the "communicating" slab forces through the load transfer bars would have experienced a differential in structural integrity or stability.
3. **Fig. B.11. Blowout Failure slabs located** at a transition zone of higher integrity anchorage stability slabs verses slabs emplaced on poor anchorage stability based slabs above "soil-like" erodible foundation material. Net foundation structural anchorage "differential" placed forces on problem area seam as evidenced by the extensive concrete repairs along this full 178 foot wide seam area.
4. **Fig. B.21. DWR Official Final Geology Report Spec 65-09** denotes the foundation geology of the subgrade quality of foundation material that the invert concrete chute was constructed upon. The Seam (marked as a series of "S"s) follows the dashed line seam in Fig. B.10. This drawing reveals the same foundation structural integrity transition region of the quality of the foundation material as in the blowout failure erosion images in Fig. B.10 and Fig. B.11.
5. **Fig. B.20. DWR Final Construction Report FCR 65-09.** Critical Design Flaw linked to blowout failure. DWR reveals that the spillway foundation will include anchor bars emplaced in "clay seams". This evidences that DWR was allowing the slab design to have anchor bars to function from the "worst foundation available". This would include poor foundation materials such areas of clay and areas of soil-like highly erodible extensively weathered rock. The blowout failure area reveals this type of material (poor foundation materials). This evidences the non-ability of the anchor bars to maintain the integrity of anchorage in these clay and soil-like foundation materials. These materials are highly erodible in subsurface slab water flow. Scouring erosion would remove these seams of materials rendering a significant loss of pounds per square inch in anchorage strength of the anchor bars.
6. **Figs. B.14 and B.15.** Extensive corrosion of rebar at slab drain line cracks weakened the slab into a severely degraded structural condition (little to no remaining tensile strength. Reference "Slab Structural Degradation from Rebar Corrosion at Cracks".
7. **Fig. B.10. "Loss of Anchorage".** Evidence of little to no ground anchorage at the blow out failure area involving 60+ anchor bars in 3 main blowout failure slabs.
8. **Figs. B.8 and B.7.** Multi-slab long drain line slab fracture 5.3 feet from the originating failure "hole". Construction Design Flaw of emplacing drains within the slab, thus "thinning" the slab thickness resulted in chronic slab cracking over drain lines for the entire 3000+ feet of the spillway. Three rows of slab wide drain line cracks were in the initial blowout failure slab where the failure "hole" was identified. The first drain line crack "row" was 5.3 feet from the slab "hole".

9. Stagnation Pressure in combination with hydrostatic forces fractured the slab from the seam "hole" to the nearest slab drain line downslope. Pressure force analysis: A high velocity flow near 90 feet per second, at 54,500 cubic feet per second, produces extreme uplift forces from a small offset in the slab joint alignment from Stagnation Pressure. Whether the slab alignment is offset positive or negative, these extreme forces at the high velocity flow are significant and could easily fracture a highly structurally weakened slab. Reference - U.S. Bureau of Reclamation Stagnation Pressure Mean Uplift Pressure Plot [14], with an Initiating Failure point referenced to a flow velocity at or near 90 feet per second (near Station 33+00). A half-inch offset of an upslope slab joint induces an 86.3 feet of water in uplift pressure underneath the slab. This translates to 37.4 pounds per square inch in uplift given an amount of flow to some drainage. Applying this force to a 40 foot long seam would yield uplift pressures of 53.8 tons in a simple example square footage affecting a 40 foot x 6 inch under-slab area (note: effective seam gap of 0.125 inches).
10. This First major fracture blowout failure started with the sudden collapse and/or lifting of a 5.3 foot section of the slab. This created a large hole for the high velocity 90 feet per second, 54,500 cubic feet per second, flow to penetrate under the next 20 foot slab section - along the next drain line crack - of the slab and fracturing and lifting away of the slab. The next section was to the to this next cracked drain line region, then the remaining section to the downslope seam.
11. The extreme hydraulic turbulent forces and erosion development, generated from this initial slab blowout, developed laterally and downslope in continuing to fracture and lift away adjacent slabs. The initial blowout failure dimensions, of affected slabs, determined by the strength of the anchor bars from the foundation material. Poor foundation material resulted in full lifting-removal of 9 slabs with the partial destruction of 4 additional slabs.
12. Subsequent spillway operation of higher volume flows continued the lateral, upslope and downslope destruction of the spillway.

## Organizational Root Causes<sup>2</sup>

**The Oroville Dam Gated Spillway failure – self-destruction was preventable.** Over decades, there were many opportunities for DWR, DSOD, and FERC to recognize and investigate serious issues that could have led to effective remedial measures. Evidence documented in this Forensic Root Causes Analysis reveals the significant extent in decades of opportunities for DWR Engineering and Maintenance, DSOD, and FERC to detect and investigate severe anomalies.

The lack of recognition of the significance of the severe issues revealed in this report, from the beginning of the construction of the spillway to present, reveals the systematic failure of these organizations to identify and rectify critical components of the Oroville Dam Gated Spillway to

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<sup>2</sup> DWR- DOSD and FERC inspection, maintenance and repair document evidence of Human and Organizational Factor Root Causes is summarized in <https://drive.google.com/open?id=0Bz1I1mIutSENG1Vem9IYlFFcjA>

the required level of the required Operating “Standard of Care” and thereby violating the First Principle of Civil Law [20]: “**imposing risks on people if and only if it is reasonable to assume they have consented to those risks.**”

**The breakup failure of Oroville's Main Spillway was the direct result of DWR, DOSD, and FERC decisions, actions, non-actions, and lack of "combined functional competency".<sup>3</sup>**

The spillway was destroying itself from within from each flood control spill operation (erosive foundation degradation, anchorage degradation) and the progression of aging (corrosion) in the flawed drain design in chronic cracking in the slabs. This was an Organizational and Regulated Failure.

Perhaps the greatest failure was the deficiency of insuring the operational structural integrity, and the spillway's ultimate Safety and Reliability based on inspections and analyses of inspection results performed by DWR, DSOD, and FERC. This Root Causes investigation indicates that one of the critically important issues was the persistent inability of these responsible and accountable organizations to determine ‘accurately’ what was ‘Safe’ and ‘Fit-For-Purpose.’ The available DWR – DSOD and FERC spillway Inspection, Maintenance, and Repair documentation contain repeated references to spillway components that were thought to be ‘Safe’ and ‘Fit-For-Purpose’ when no ‘proof’ was provided to validate and substantiate those critically important conclusions.<sup>4</sup>

The failure of DWR Engineering, and Operations & Maintenance which allowed thousands of feet of drains to become inoperable; documented non-functional by photographs, noted "drain repair" in construction bids, and contract awards. Yet, the thousands of feet of inoperable spillway drains, in critical "steep slope" sections of the spillway's pre-blowout failure area, remained for years, even though DWR's original Spillway Design documentation specifically required (Report Section D. Spillway, page D-25): ***"The areas of maintenance to be checked include a yearly inspection of the under drains to see they have not plugged."***<sup>5</sup>

Given the evidence of the findings in this report, the Oroville Spillway was destroying itself over time until the weakest section would finally give way. This engineering situation was completely preventable. Recognition, Remedial Action, Correction, and the ultimate restoration of the spillway's structural integrity should have resulted many decades ago, especially when U.S. Bureau of Reclamation was warning dam owners of the dangers of sub-slab voiding and penetrating water flow risking the powerful Stagnation Pressure failure modes [14].

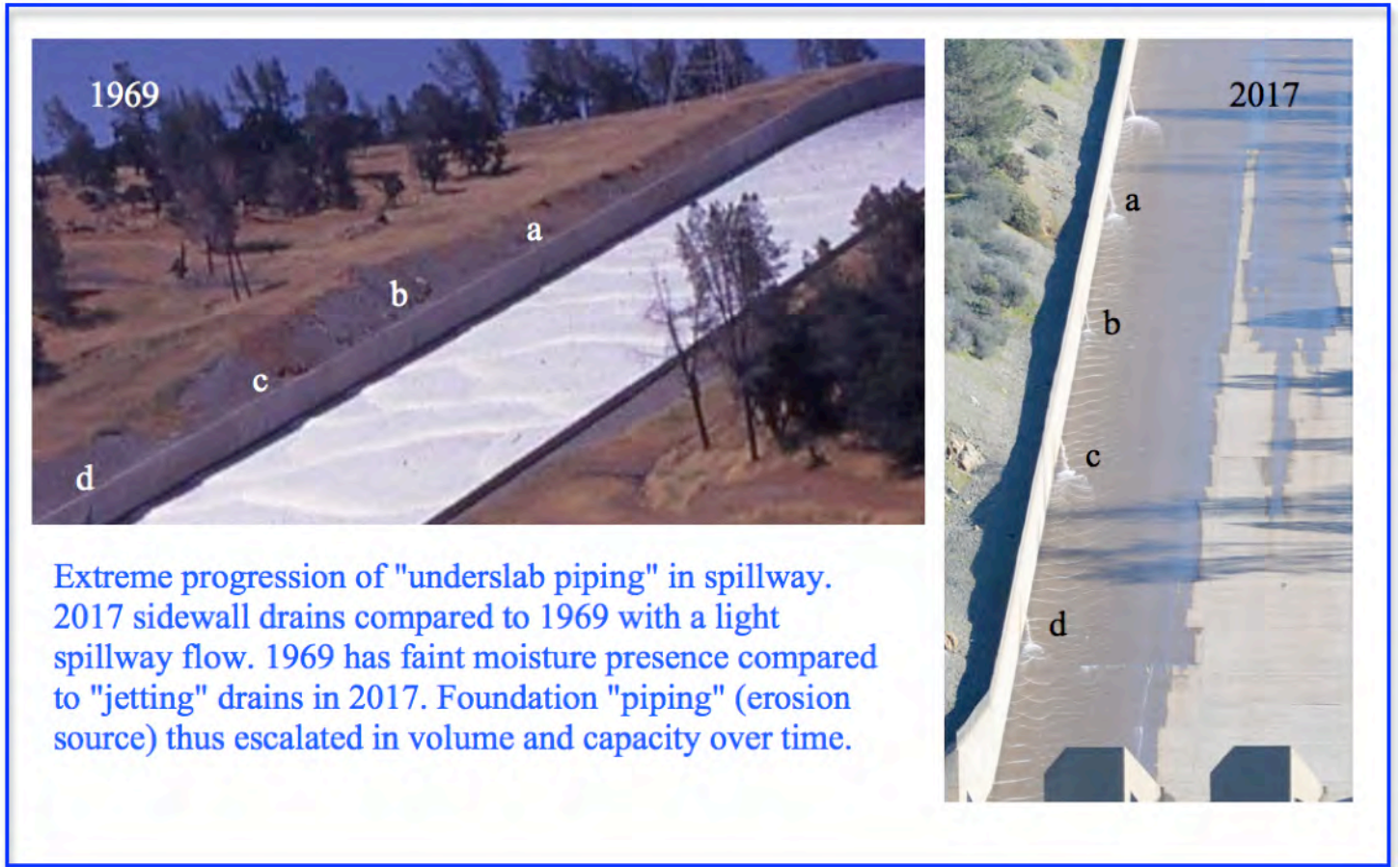
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<sup>3</sup> Summary of documentation cited available at -  
<https://drive.google.com/open?id=0Bz1I1mlutSEnWDRhODdRM3RLM1k>

<sup>4</sup> Background on What is Safe? and How Safe is Safe? available at -  
<https://drive.google.com/open?id=0Bz1I1mlutSEnUgwUXZ6WXIYMmc>  
<https://drive.google.com/open?id=0Bz1I1mlutSEnUkpQcXRGQklDbHM>

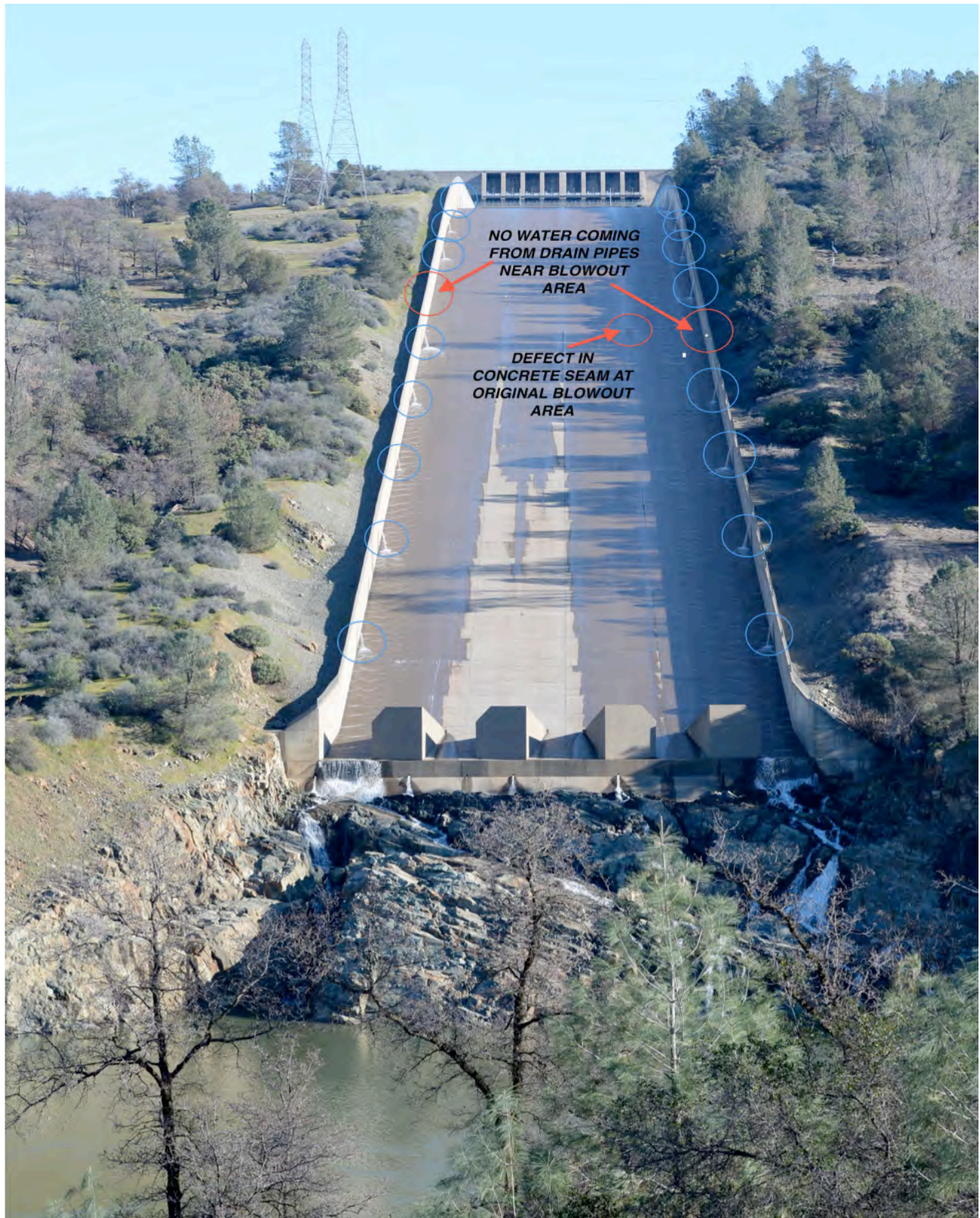
<sup>5</sup> Department of Water Resources (1967): *Design Engineer's Criteria for Operation and Maintenance*, State Water Facilities, Oroville Division, Oroville Dam and Reservoir, Oroville, California.





**Fig. B.1.** Comparison of 1969 and 2017 photographs reveals a significant underflow development underneath the spillway over time. Original Construction Defects, Flaws, and Maintenance contributed to the formation of a high volume channel system underneath the spillway concrete chute.





**Fig. B.2.** January 27, 2017 Pre-blowout failure photograph of 7.9 foot by 14 inch "hole" in the concrete slab in Oroville Spillway (circled). Note the non-functioning sidewall drains (circled).



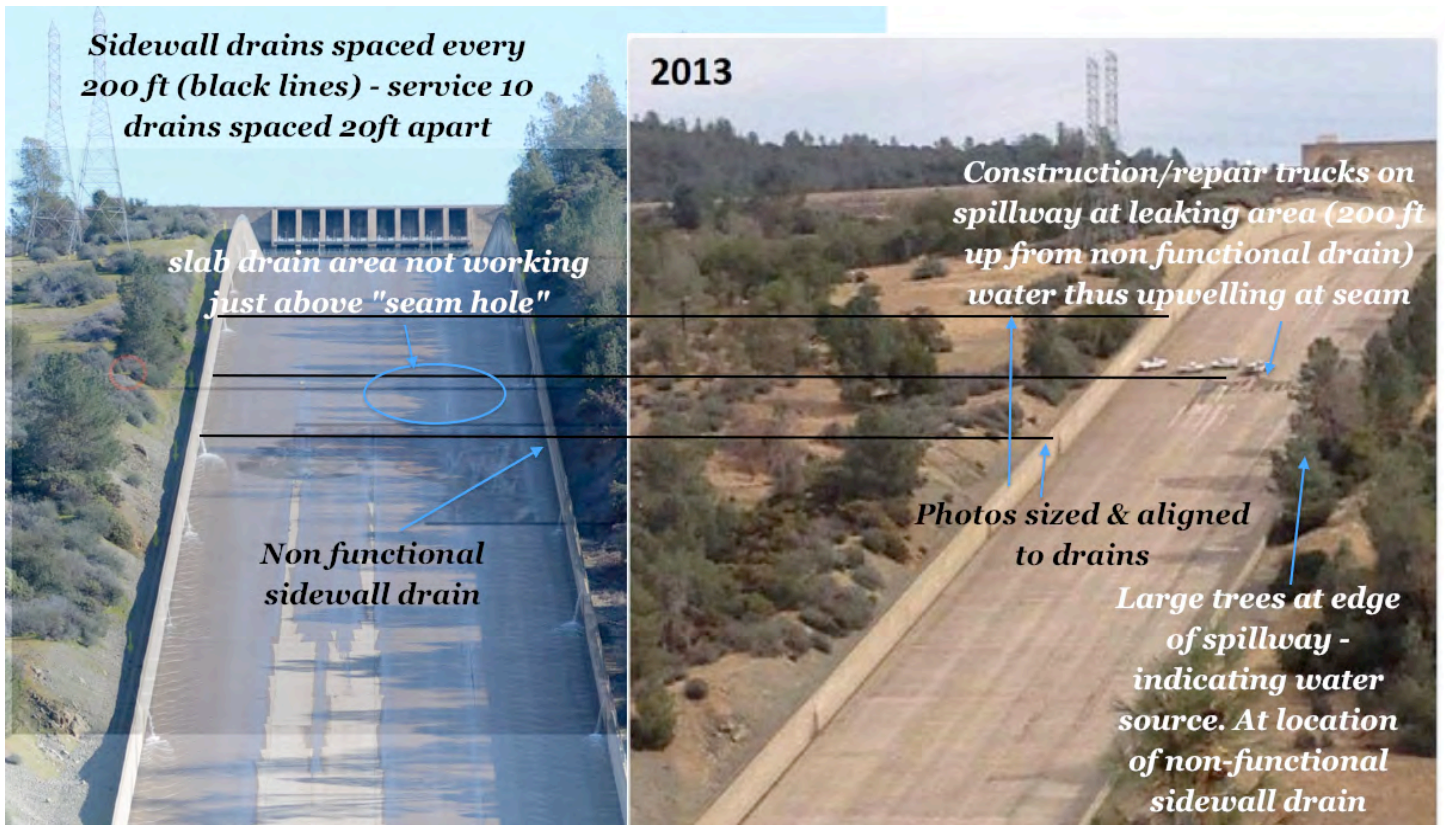


**Fig. B.3.** Forensic Photographic precision alignment of three photographs confirms the BOC assessment of the origin of the spillway blowout failure from a "hole", including subsequent slab(s) destruction and erosion. Contributing base photograph [6].



**Fig. B.4.** Non-Functioning Sidewall drain revealed in a Nov 9, 2007 spillway photograph (red arrow). Minor seepage reveals working sidewall drains (stains on sidewalls). Photograph - source [8].





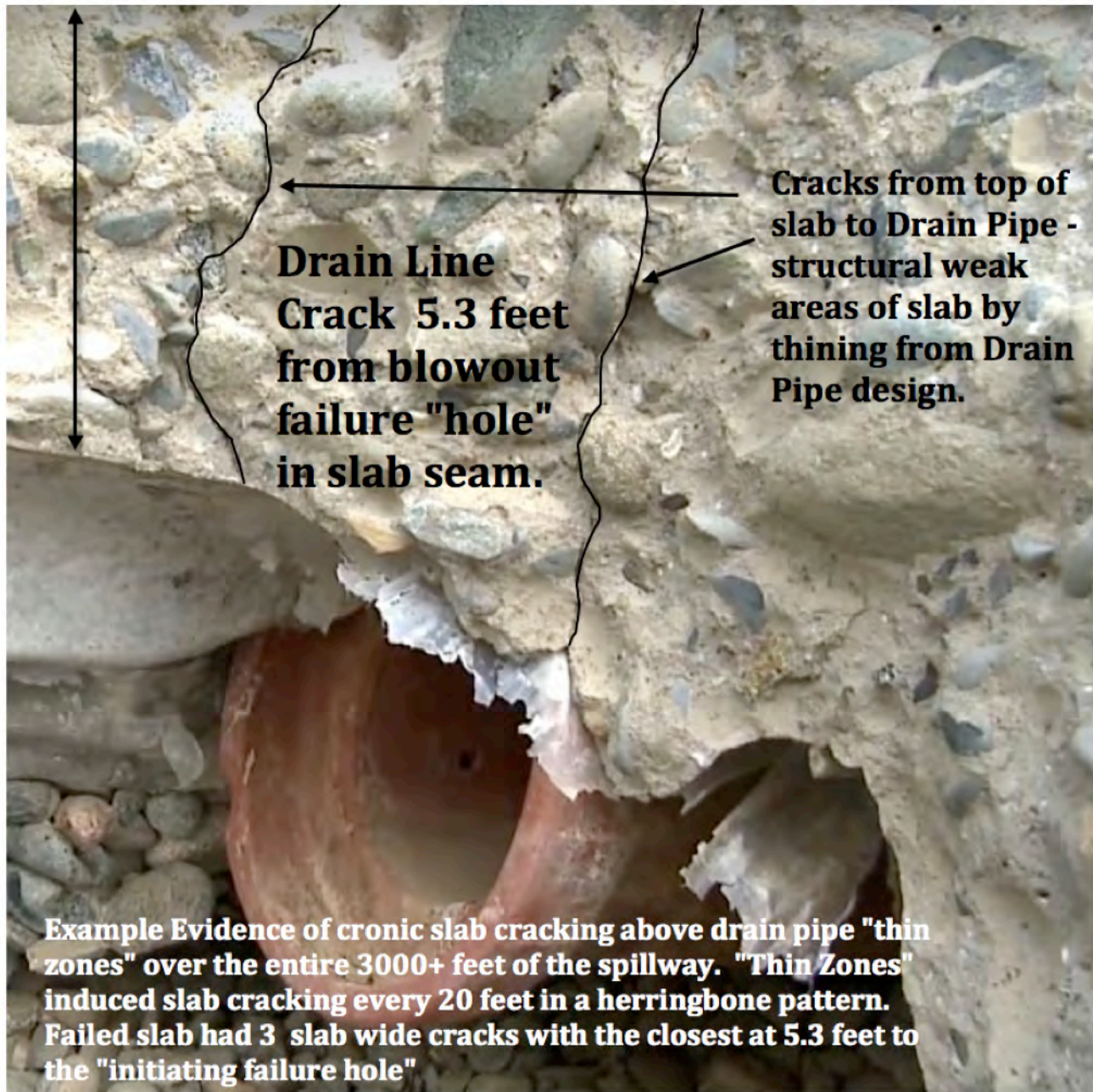
**Fig. B.5.** Clues to history of 1,780 linear feet of clogged drains, the two affected areas, and where the seepage reveals water "diving" under "void fill areas."



**Fig. B.6.** Evidence of Spontaneous Stress Induced Spalling of concrete at slab seams. The depth of the spalling "hole" reveals to a level to the upper rebar. This spalling of "holes" matches photographic evidence of a larger 7.9 foot by 14 inch "hole" found to be at the location of the initial blowout failure.

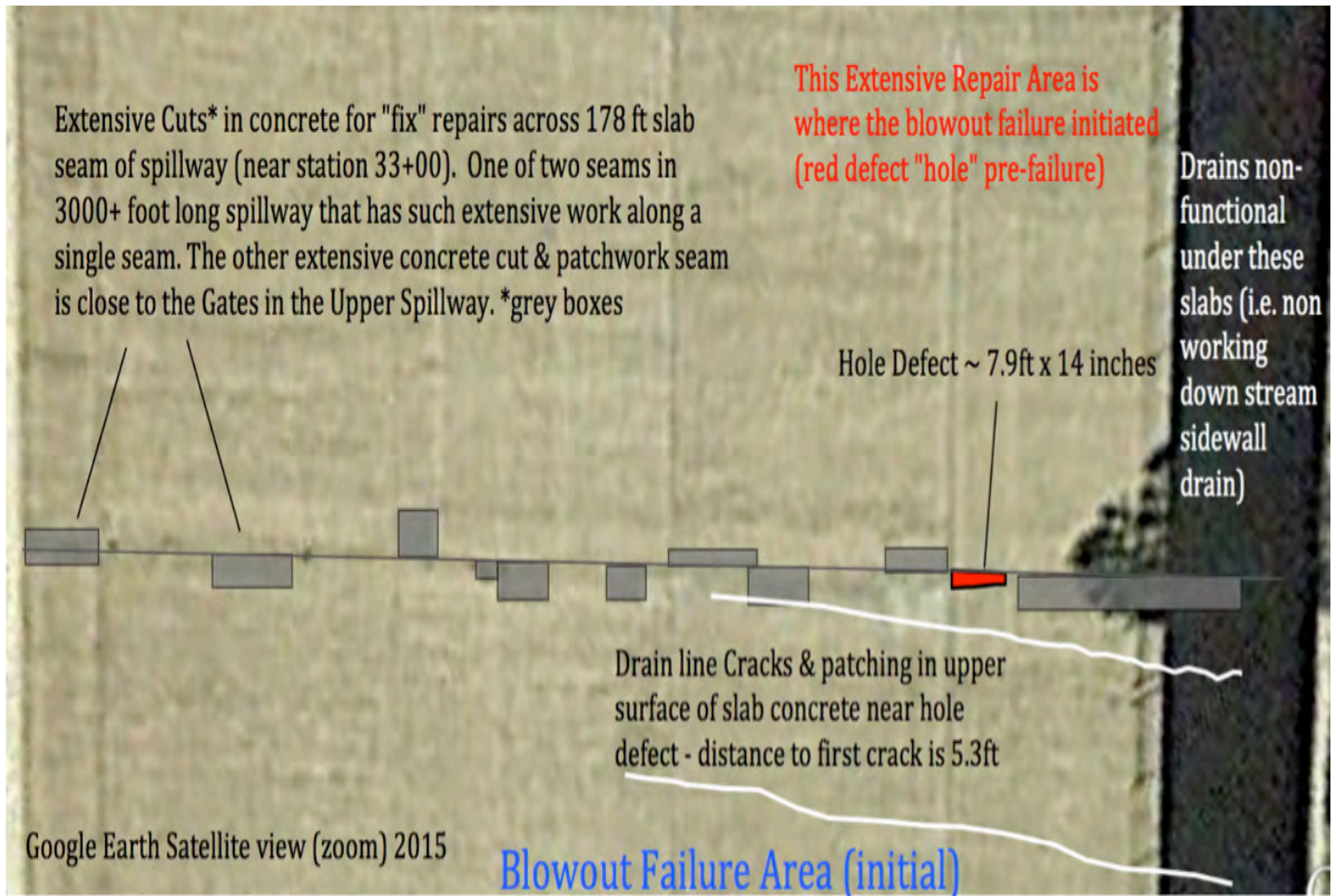


**Slab Failure - weakest point from thinning - pre-cracked before blowout failure near "seam hole", 5.3 ft away.**



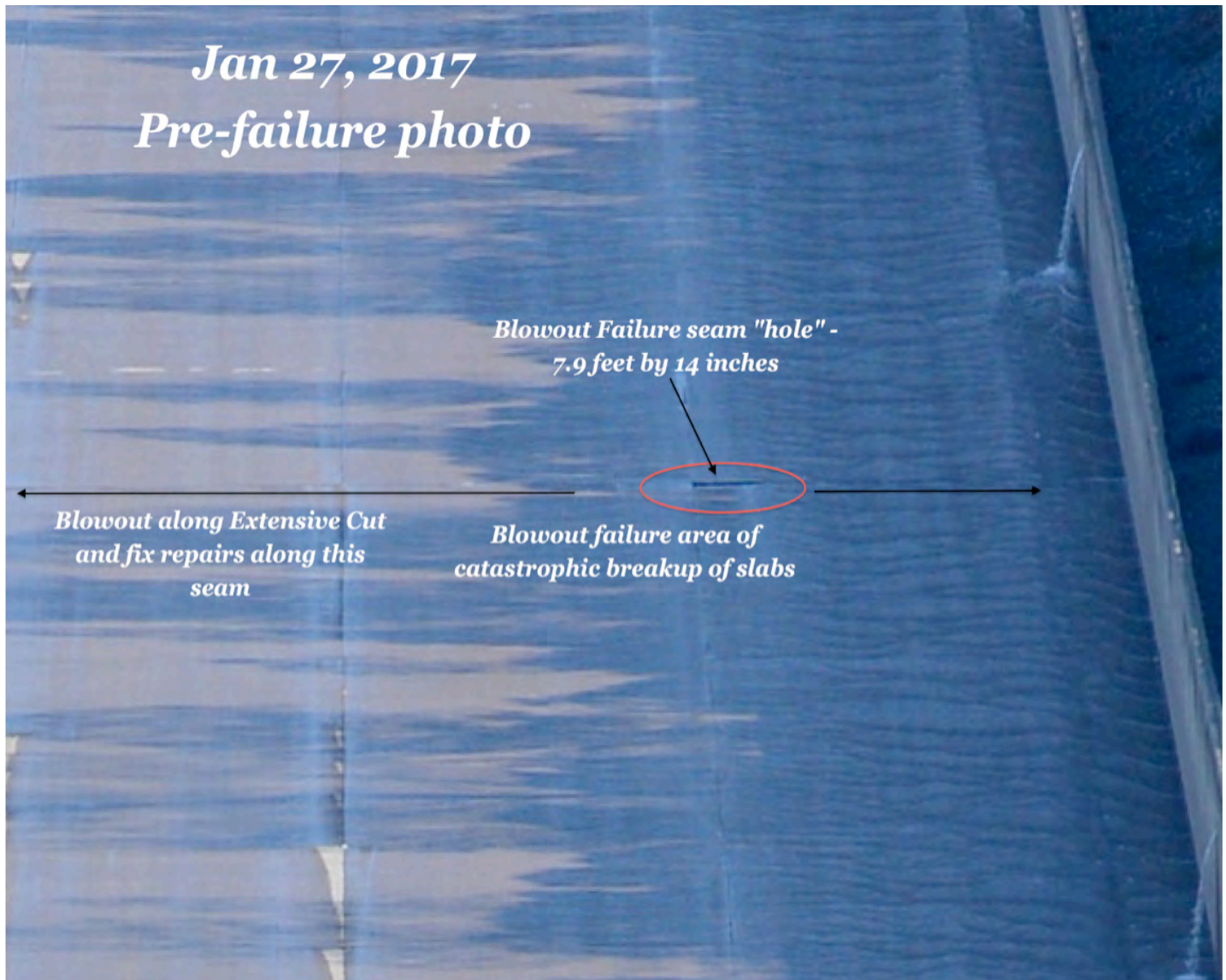
**Fig. B.7.** Construction Design Flaw of emplacing drains within the slab, thus "thinning" the slab thickness resulted in chronic slab cracking over drain lines for the entire 3000+ feet of the spillway. Three rows of slab wide drain line cracks were in the initial blowout failure slab where the failure "hole" was identified. The first drain line crack "row" was 5.3 feet from the slab "hole".





**Fig. B.8.** Initial failure "hole" defect. Initiation point of the Initial Blowout Failure Area of slabs along this extensively repaired spillway seam. Hole dimension measured with forensic high resolution photographs to be near 7.9 feet along the seam by 14 inches downslope from the seam. White lines denote the drain line cracks in the slab surface. The depth of the "hole" is inferred to be many inches deep to the upper layer of rebar - as evidenced in prior spalling spontaneous defect occurrences revealed in Fig. B.6. Also noted by the Board of Consultants Memorandum No. 2 (depth to rebar layer), page 8 [3].





**Fig. B.9.** Forensic Photographic of initiation failure "hole" at an upslope slab seam. Dimensions in a high-resolution zoom determined to be at or near 7.9 feet by 14 inches. This "hole" is located at a seam that has had extensive concrete patch, cuts, and repairs in maintenance work. Indicative of a structural "problem area" (see Fig. B.8).



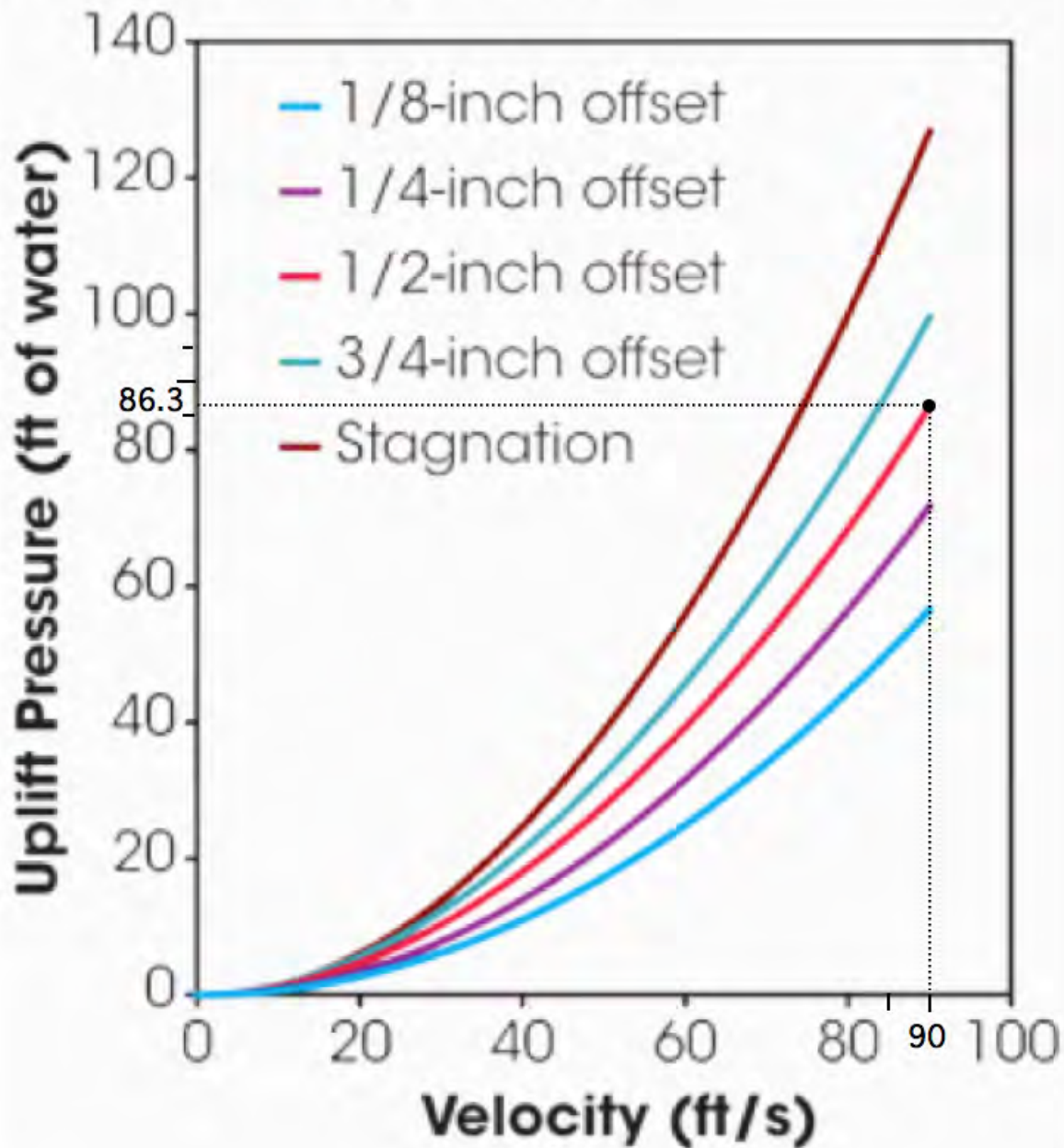
**Fig. B.10.** Initiating Failure Hole location reveals a deep seam of highly erodible foundation material (incompetent rock) that is many feet deeper than the grouted 5 foot deep slab anchor bars. Angle of seam inferred by dashed line. Image reveals the nature of why the "hole" location and the full 178 foot wide seam area was a structural problem area. The upslope "soil-like" foundation material is in a transition zone between the incompetent rock and the competent rock (downslope from the dashed line). Thus, the "communicating" slab forces through the load transfer bars would have experienced a differential in structural integrity or stability.





**Fig. B.11.** Blowout Failure slabs located at a transition zone of higher integrity anchorage stability slabs versus slabs emplaced on poor anchorage stability based slabs above "soil-like" erodible foundation material (incompetent rock).

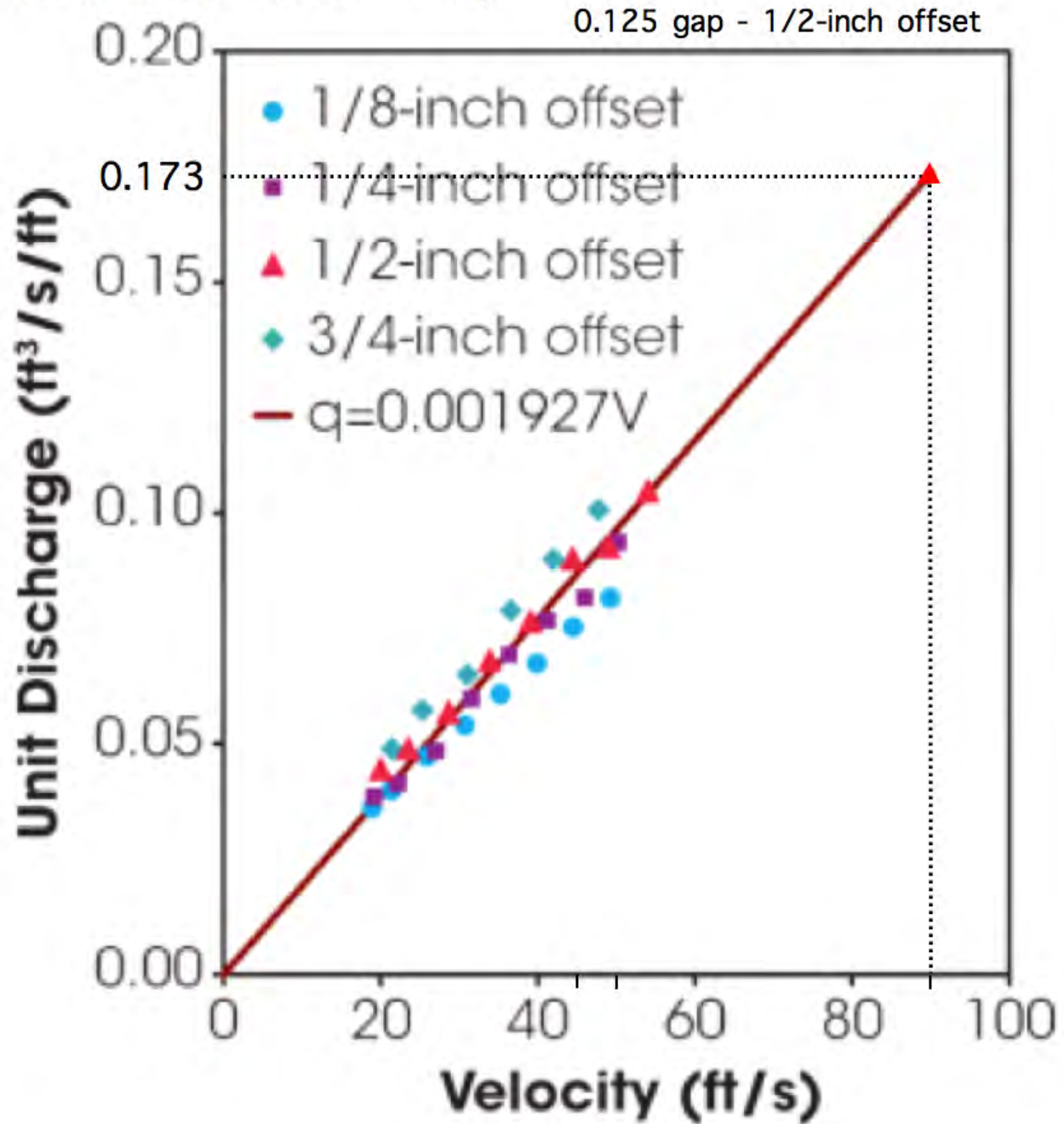
FIGURE 2 Mean Uplift Pressure



**Fig. B.12.** U.S. Bureau of Reclamation Stagnation Pressure Mean Uplift Pressure Plot [14]. Initiating Failure point referenced to a flow velocity at or near 90 feet per second (near Station 33+00). A half inch offset of an upslope slab joint induces an 86.3 feet of water in uplift pressure underneath the slab. This translates to 37.4 pounds per square inch in uplift given an amount of flow to some drainage. Applying this force to a 40 foot long seam could yield uplift pressures of 53.8 tons in a simple example square footage affecting a 40 foot x 6 inch under-slab area (note: effective seam gap of 0.125 inches). This exemplifies the importance of "sealing" slab joints with modern day "water stops" to prevent this dangerous spillway breakup failure mode.



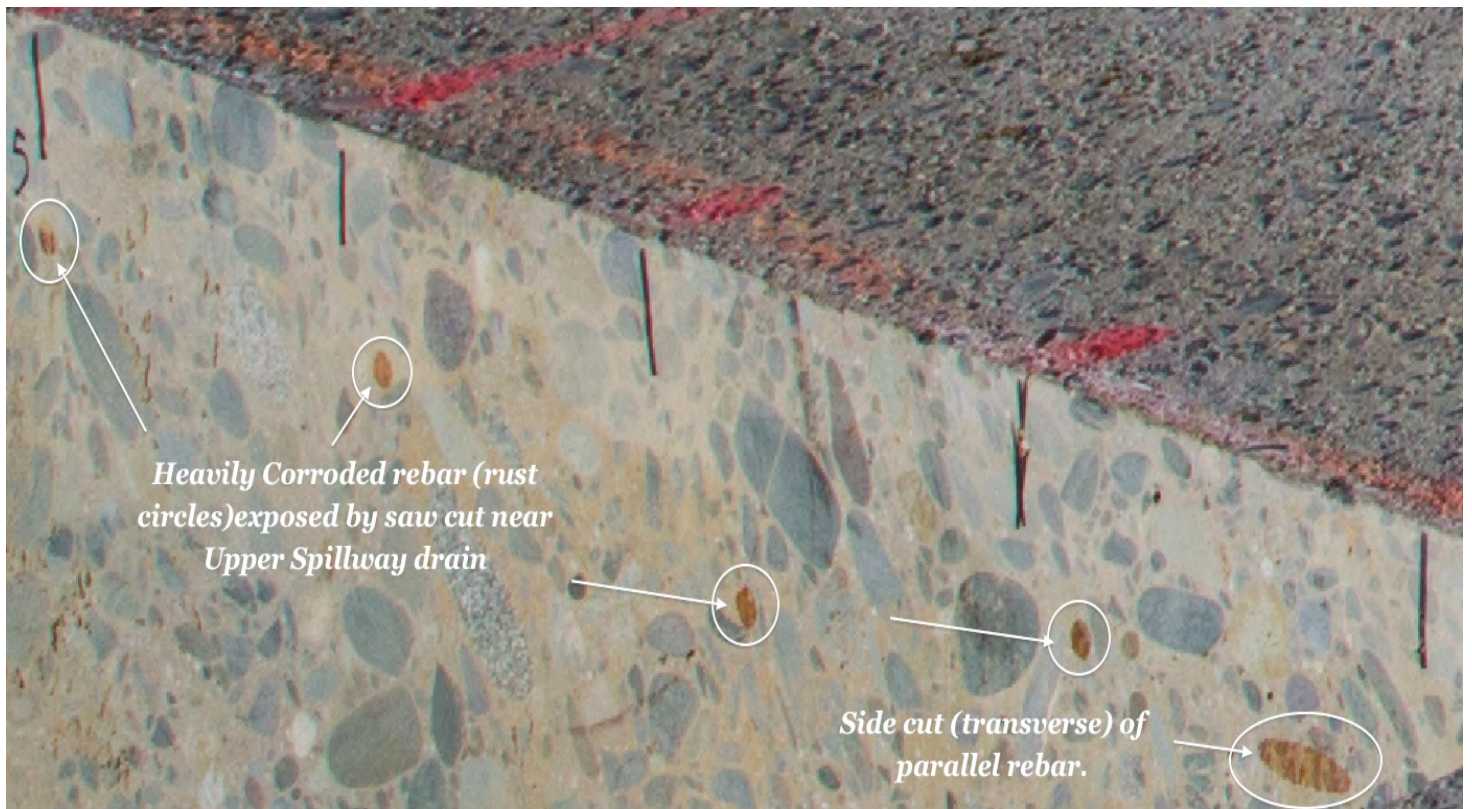
**FIGURE 3 Unit Discharge**



**Fig. B.13.** U.S. Bureau of Reclamation Unit Discharge water flow into a seam with an offset [14]. Initiating Failure point referenced to a flow velocity at or near 90 feet per second (near Station 33+00). A half inch offset of an upslope slab joint has the ability to induce a sub slab flow of 13.84 cubic feet per second for the width of two slabs in the initial blowout failure seam (0.125 effective seam gap with 1/2 inch seam offset). This is a significant volume of pressurized sub-slab water flow that has the ability to aggressively erode soil-like foundation material. This pressurized sub-slab water flow could "scour" the foundation creating "channels" and "large voids" underneath the spillway.



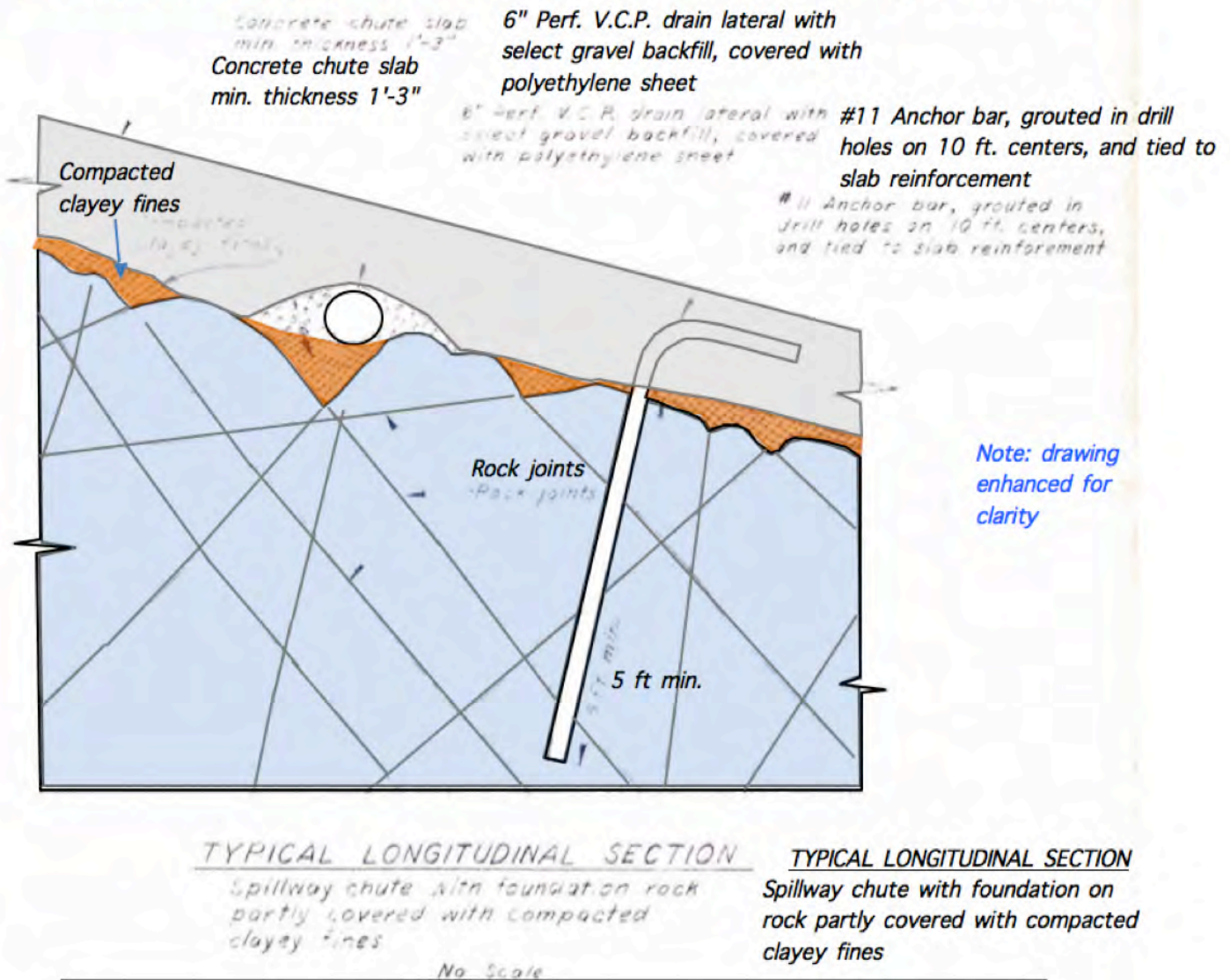
**Fig. B.14.** Evidence of extensive corrosion of rebar (circles) from slab penetrating water through cracks in the slab above drain lines. Any corrosion of the rebar above these chronic deep slab cracks in the drain line "thinning zones" creates a slab structural failure risk or collapse. This photograph is from a multi-slab breakage along a full drain line where the fracture is from the center of the spillway to the sidewall (near 90 feet). The fracture is centered above a drain line (See Fig. B.7). With the evidence of extensive corrosion of the rebar above this pre-cracked slab above the drain line, this combination forms the ideal failure weak zone in the spillway (near total loss of tensile strength and the concrete is already cracked from the thinning of the drain line). Thus the structural integrity of the slab becomes highly dependent on a solid foundation and also dependent upon the structural integrity of the distributed anchor bars.



**Fig. B.15.** Further Evidence of extensive corrosion of rebar in the spillway (circles). The corrosion is so extensive that the saw cut in the concrete left the granular remains of the rebar as an "orange" discoloration as "rust" remains. The elongated orange color stain is the remains of a transverse section of rebar. This "saw cut" examination hole is located next to a drain line in the slab. Construction workers were examining the state of the Upper Spillway near the under slab drain lines (drain pipe below & cut out in this image zoom view).



**OROVILLE SPILLWAY SPEC 65-09, DWG IF262, FINAL GEOLOGY REPORT -** slabs were built upon a layer of "compacted clayey fines" - counterdicts spec HYD-510 fig 93, detail A



Oroville Dam Spillway - Final Geology Report - Spec 65-09 - March 1970\_Part1 &2.pdf  
Drawing Number IF262, Approved 3-3-70

**Fig. B.16.** DWR Official Final Geology Report Spec 65-09 specifies that the Spillway slabs were built upon a layer of "compacted clayey fines". Original drawing number IF262 detail is enhanced for readability as the original is faded. This drawing conflicts with the HYD-510 spec that the slab be emplaced fully upon a continuous seam of rock (or backfill concrete in subgrade areas). Note: This report is not publicly available. This base image is from the report to reveal that the foundation of the spillway had a highly erodible layer of clay built into the design. This is a design flaw that reveals how the "progression" of voiding, piping, and high volume of under-slab water flow developed over time. Not shown in this drawing is up to the 45 deep layer areas (full blowout failure region) of erodible soil-like material (clay-clayey and highly erodible rock) to where large voids could form beneath the spillway in time.



There were two other problems that plagued the excavation for the major portion of the contract. One was the lack of cooperation received from the earthwork superintendent, and the other was a clause in the specifications under chute excavation: "Excavation for the chute shall be to

*"..problems that plagued the excavation.."*

*Dispute was over getting paid \$30.00 per cu yd to restore the frangible excavated subgrade to elevation grade.*

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*Final Construction Report FCR 65-09 page 20*

*Contractor wanted to excavate to strong fresh or to strong moderately weathered rock. The DWR Field Engineer intervened and directed to excavate "only" to grades shown on the drawing.*

*fresh or moderately weathered rock that cannot be further removed by heavy duty power excavating equipment." The Contractor considered that this statement gave him the right to overexcavate several feet below grade and then get paid for backfill concrete at \$30.00 per cubic yard to restore the subgrade to the elevation shown on the drawings. The Field Engineer directed the Contractor to excavate to the grades shown on the drawings*

**Fig. B.17.** Dispute arose between original specifications intended to excavate the spillway to strong fresh rock or strong weathered rock. Specification stated: "Excavation for the chute shall be to fresh or moderately weathered rock that cannot be further removed by heavy duty power excavating equipment." DWR Field Engineer intervened and directed the contractor to only "excavate to the grades shown on the drawings". The contractor was following specifications to where any poor foundation material would be backfilled with concrete to "grade level".

This report statement infers that DWR believed the contractor was using this specification in a desire for the additional pay of \$30 per cubic yard of concrete in backfill work. This DWR Field Engineer intervention "orders", in contrast to the accuracy of the "specifications" in excavation, is evidence that a financial decision was a basis to not excavate to strong competent rock. If this "intervention" by DWR Field Engineer had not occurred, it may be possible that the large seams of highly erodible soil-like foundation material would have been fully repaired to competent backfill of concrete. The DWR Field Engineer's "intervention" evidences that a serious flaw was introduced that was a primary cause for the instability and the subsequent "blowout failure".



Photo 37. Chute foundation in vicinity of Sta. 27+75, 20'L. Compacted, clayey fines cover most of the rock (hard & fresh) in this area. View east.  
Neg. No. 4632 9-28-66

*"Chute foundation in vicinity of Sta. 27+75, 20'L. Compacted, clayey fines cover most of the rock.."*

**Fig. B.18.** DWR Final Construction Report Photo No 4632, noting "Chute foundation in vicinity of Sta. 27+75, 20'L. Compacted, clayey fines cover most of the rock." Photograph confirms construction technique identified in DWR Final Geological Report Spec 65-09 where a "compacted clayey fines" layer was identified as a fill layer under the slab to facilitate irregular base rock or irregular highly weathered rock surfaces (see Fig. B.16).



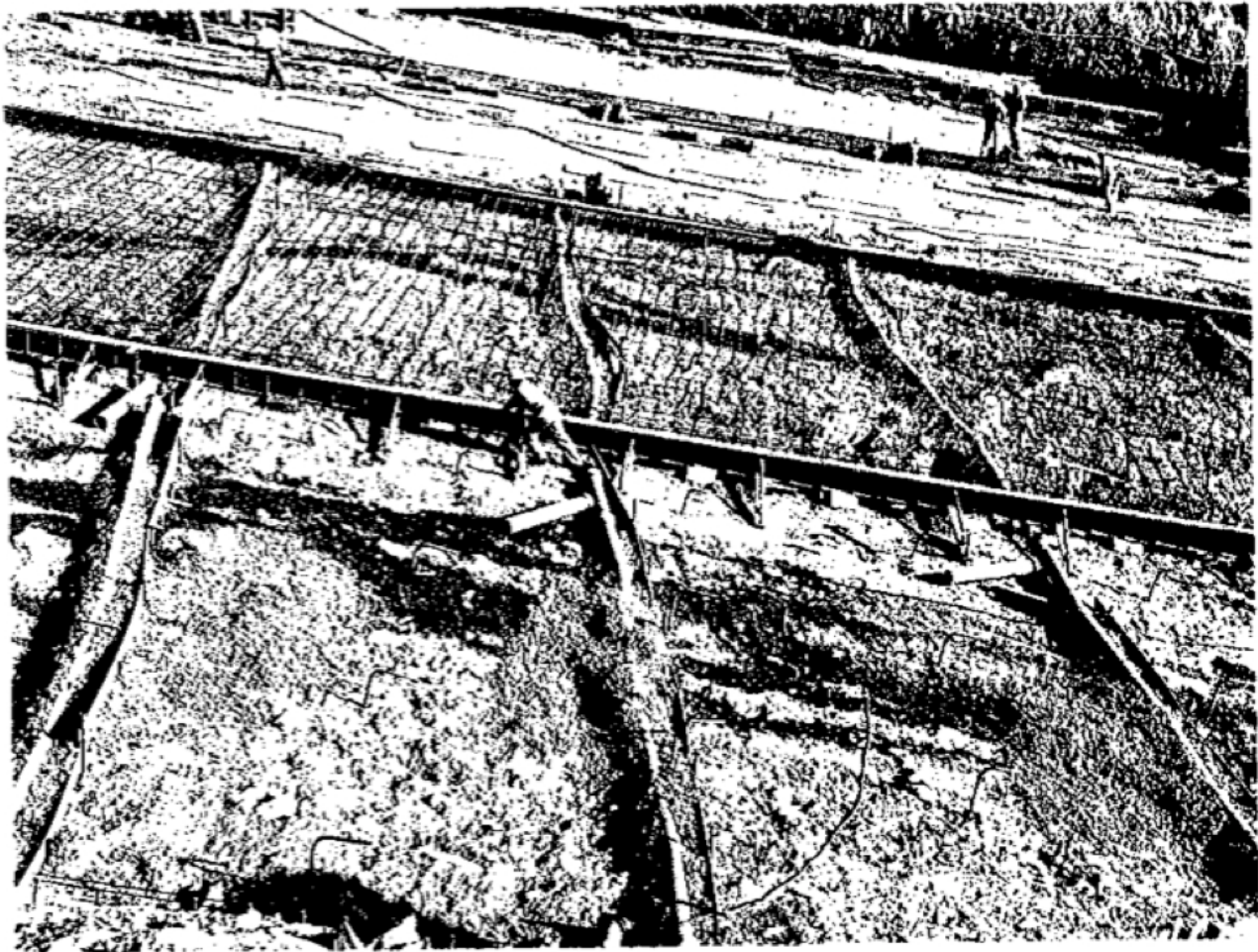


Photo 39. Chute foundation in vicinity of Sta. 33+60.  
Tile and gravel underdrains in lanes 2 and 3, rebar in  
lane 3. View southeast.

Neg. No. 4644

11-2-66

**Fig. B.19.** DWR Final Construction Report Photo No 4632, Pre-emplaced drain lines with gravel next to the pipes. Note the width area of the gravel. This forms a wide "tent" when covered in polyethylene plastic. This wide tent area weakens the slab as this area is non-structural. Note the "wavy" emplacement of the drain lines. This evidences the match to the "wavy" cracking observed in the spillway as the cracks are following the original emplacement.

Item 32 - Anchor Bars

Item 32 called for linear drilling 32,400 feet of holes and placing anchor bars. Bid price was \$1.75 per linear foot.

The actual quantity paid for under this item was 32,277.3 linear feet broken down as follows: test bars, 26 linear feet; blocks 25 and 26, 5,231.3 linear feet; and 27,010 linear feet in the chute foundation.

The specifications called for a tension test, but failed to spell out the required tension. The Department laboratory at Oroville did some research and came up with 30,000 pounds per square inch.

*Critical Design Flaw - the expectation that "anchor bars" would retain anchorage in "clay seams" over time when exposed to subsurface water flow (through seams) over time. Anchor Bars unable to prevent "blowout failure" in large seams of soil-like highly erodible foundation materials.*

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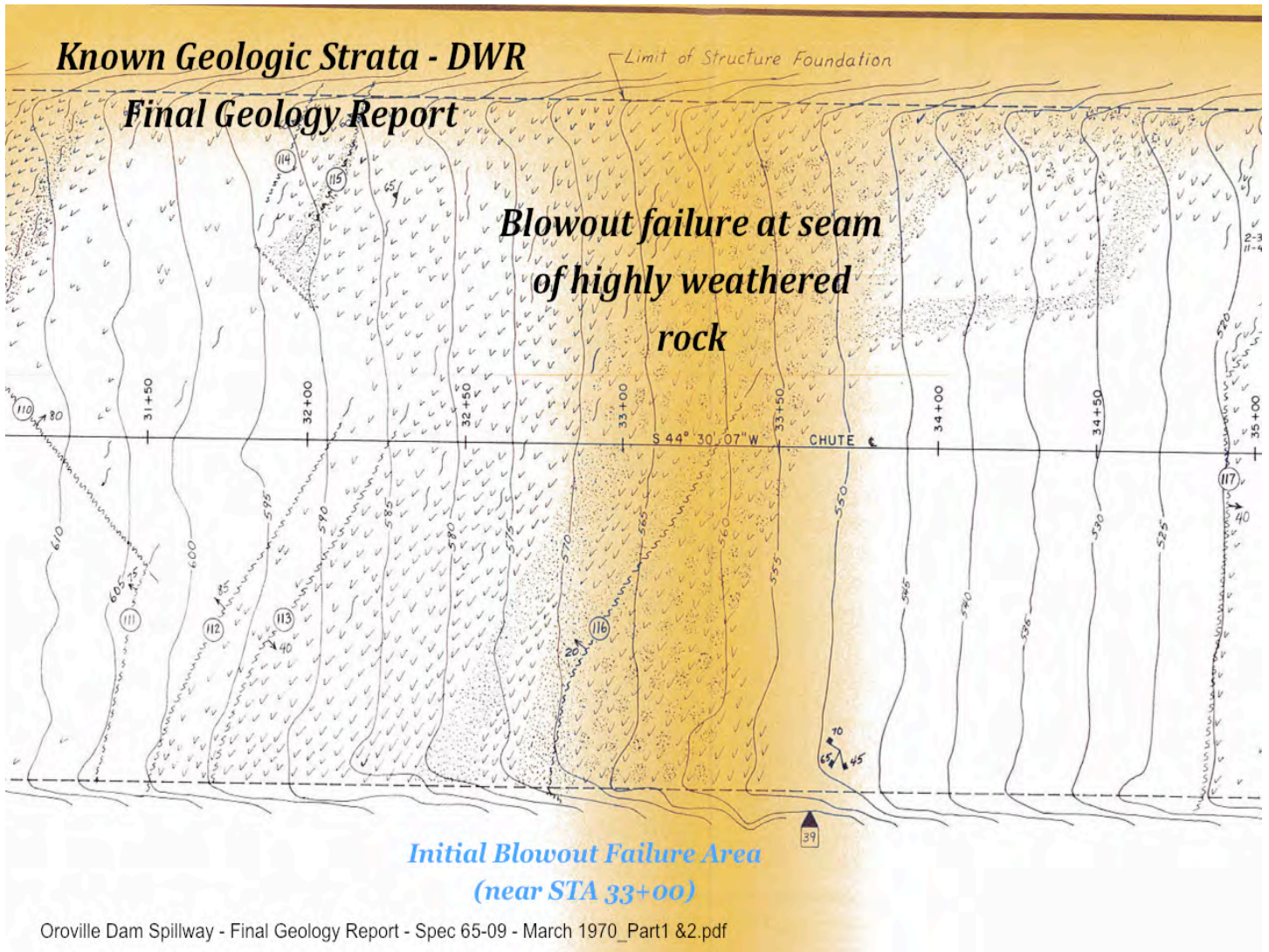
**DWR Final Construction Report FCR 65-09 pages 24, 25**

*"In each case, one hole was located in the worst foundation available, that is, clay seams, and the other hole was for average conditions"*

In order to determine what depths would be necessary to obtain the required tension, three sets of two holes each were drilled in the chute foundation; two 5-foot holes, two 6-foot holes, and two 7-foot holes. In each case, one hole was located in the worst foundation available, that is, clay seams, and the other hole was for average conditions. It was determined that the minimum depth of 5 feet would produce over 30,000 psi regardless of the type of foundation.

**Fig. B.20.** DWR Final Construction Report FCR 65-09. Critical Design Flaw linked to blowout failure. DWR reveals that the spillway foundation will include anchor bars emplaced in "clay seams". This evidences that DWR was allowing the slab design to have anchor bars to function from the "worst foundation available". This would include poor foundation materials such areas of clay and areas of soil-like highly erodible extensively weathered rock. The blowout failure area reveals this type of material (poor foundation materials). This evidences the non-ability of the anchor bars to maintain the integrity of anchorage in these clay and soil-like foundation materials. These materials are highly erodible in subsurface slab water flow. Scouring erosion would remove these seams of materials rendering a significant loss of pounds per square inch in anchorage strength of the anchor bars.





**Fig. B.21.** DWR Final Geology Report Spec 65-09 denotes the foundation geology of the subgrade quality of foundation material that the invert concrete chute was constructed upon. The Seam (marked as a series of "S"s) follows the dashed line seam in Fig. B.10. This drawing reveals the same foundation structural integrity transition region of the quality of the foundation material as in the blowout failure erosion images in Fig. B.10 and Fig. B.11. This geologic report drawing identifies that DWR was aware of the type of foundation material at this future blowout location. DWR BOC report Memorandum No. 1 notes that "Compacted clay is also a term sometimes used to describe highly weathered rock."

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