Preliminary Root Causes Analysis of Failures of the Oroville Dam Gated Spillway

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This Preliminary Root Cause Analysis of the failures of the Oroville Dam gated spillways is based on current publically available photographic and written documentation included and cited at the end of this document.

Design Defects and Flaws

The origins of the gated spillway failures are deeply rooted in pervasive design defects and flaws developed by the California Department of Water Resources (DWR). These design defects and flaws included the following:

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 Defects and Flaws

The design defects and flaws were propagated by DWR during construction of the spillway. These construction defects and flaws included the following:

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 'blankets' of permeable materials in which water could collect and erode.

[1] Amended to include references and citations to photographs and graphs attached to the Preliminary Root Causes Analysis document.

Maintenance Defects and Flaws

The design and construction defects and flaws were propagated by DWR during maintenance of the spillway. These maintenance defects and flaws included the following:

1. Repeated ineffective repairs made to cracks and joint displacements to prevent water stagnation and cavitation pressure intrusion under the base slabs with subsequent erosion of the spillway subgrade; and
2. Allowing large trees 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.

February 2017 spillway releases

By the time of the February 2017 spillway releases, the gated spillway had become heavily undermined and the subgrade eroded by previous flood releases. The first spillway release completed the undermining of the spillway slabs, allowing water cavitation and stagnation pressures to lift the 'weak' slabs and break them into pieces (25, 26).[2]

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

Root Causes Analysis

Currently available information indicates the Root Causes of the gated spillway failures are founded primarily in 'Extrinsic' uncertainties (human and organizational task performance and knowledge development and utilization) developed and propagated by DWR during the gated spillway design, construction, and maintenance activities (1).

A key question that can not be answered at this time is: "why did DWR and the responsible State and Federal regulatory agencies (California Water Commission, Federal Energy Regulatory Commission) allow these Root Causes to develop and persist during the almost 50 year life of the gated spillway?"

One answer that has been offered is that the spillway was designed and constructed according to the 'Standards of the time." While that answer may or may not be factual or true, current evidence indicates the original spillway design and construction does not meet current guidelines and standards (24).

Another answer that has been offered is that the spillway operated for almost 50 years and was subjected to water discharges that exceeded those developed during 2017 without failure. Recent inspections indicated that the spillway was in 'satisfactory condition' (5 - 17). The conclusion prior to the February 2017 discharges was the gated spillway consequently was 'suitable for service.' The experience prior to the DWR attempt on February 11 to use the Emergency

[2] References and citations ordered alphabetically at end of this report.

Spillway showed that conclusion was not valid. The gated spillway failed during discharges that were much less than the design conditions.

The author's previous experiences with investigations of failures of public infrastructure systems (e.g. New Orleans hurricane flood protection system during Hurricanes Katrina and Rita) leads to a conclusion that it is likely that the wrong standards and guidelines are being used to re-qualify many critical infrastructure systems for continued service. The majority of these standards and guidelines were originally intended for design, not re-qualification or re-assessment of existing aged infrastructure systems that have experienced 'aging,' 'technological obsolesce,' and increased risk (likelihoods and consequences of major failures) effects. Inappropriate standards and guidelines are being used to re-qualify these infrastructure systems for continued service. The currently available information indicates this is one of the primary Root Causes of the failures of the Orville Dam gated spillway.

References

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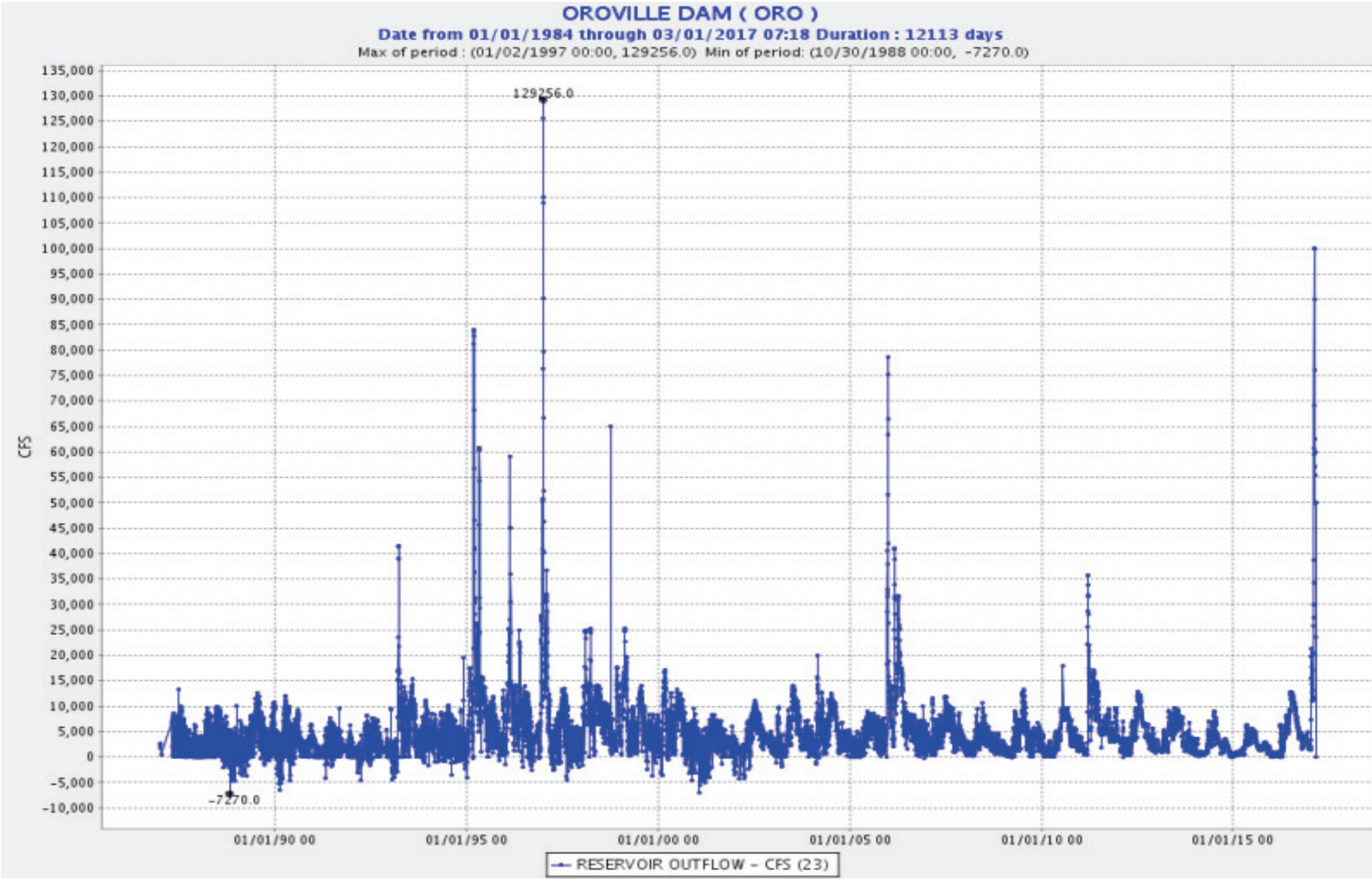
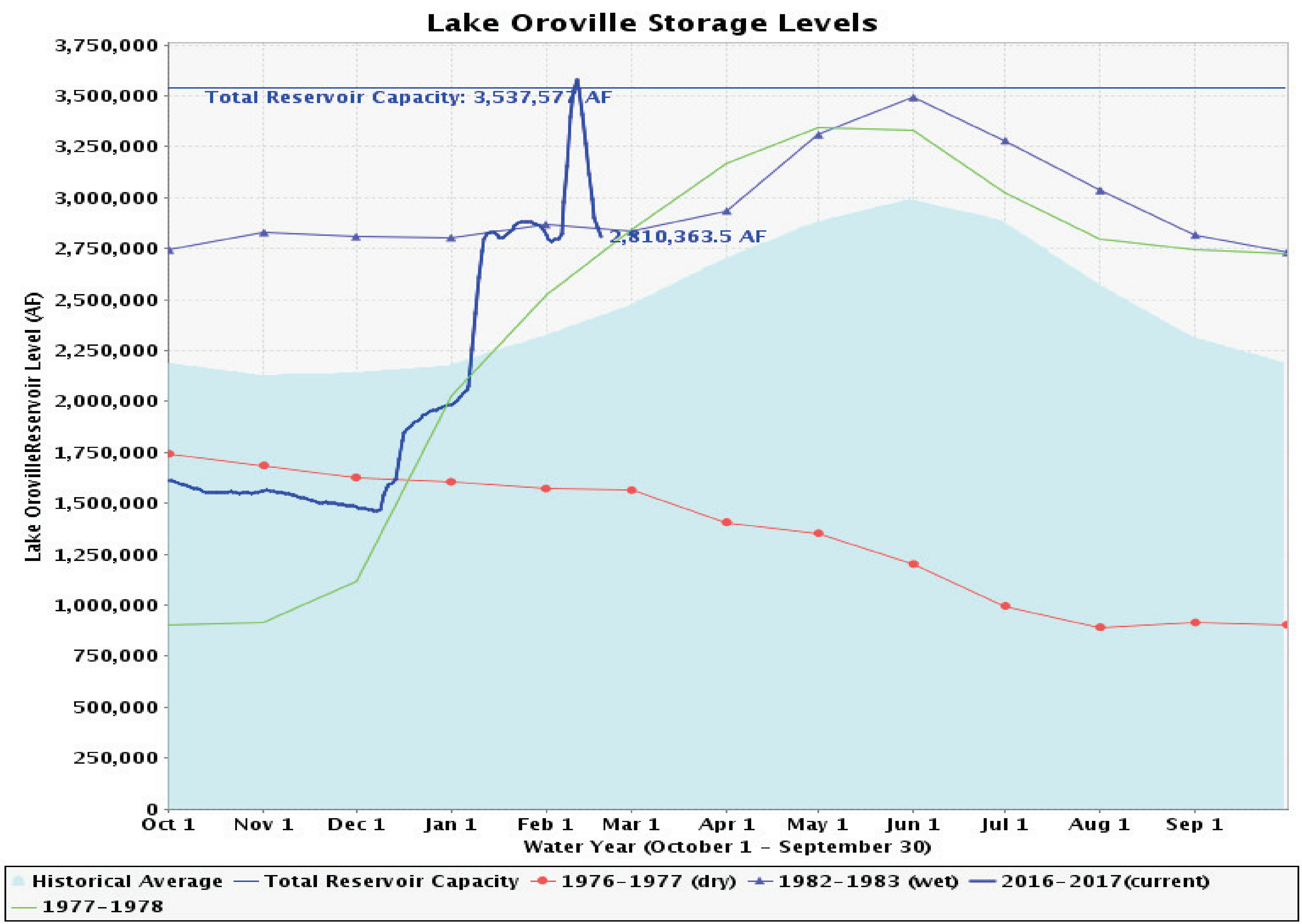
Spillway Discharges



Source: (21)


Lake Oroville Storage Levels
Lake OrovilleReservoir Level (AF)
3,750,000
3,500,000
3,250,000
3,000,000
2,750,000
2,500,000
2,250,000
2,000,000
1,750,000
1,500,000
1,250,000
1,000,000
750,000
500,000
250,000
0
Total Reservoir Capacity: 3,537,577 AF
2,810,363.5 AF
Oct 1
Nov 1
Dec 1
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Water Year (October 1 - September 30)
Historical Average
Total Reservoir Capacity
1976-1977 (dry)
1982-1983 (wet)
2016-2017(current)
1977-1978

Source: (21)

Lake Oroville Spillway Incident: Timeline of Major Events February 4-25

Oroville Spillway Public Info Line: (530) 538-7826

❶ February 7: As water releases from the flood control spillway ramp up to 54,500 cubic feet per second (cfs), in anticipation of inflows expected from rainfall, DWR employees notice an unusual flow pattern. Spillway flows stop for investigation. Engineers find large area of concrete erosion.

❷ February 8: DWR begins ongoing consultation with FERC and other dam safety agencies. DWR runs test flows down the damaged spillway, monitoring further erosion, and prepares for possible use of emergency spillway. 24/7 emergency interagency operations centers activate to study and implement response to flood control spillway and related structures, with careful study of weather forecasts.

❸ February 11: Inflow to Lake Oroville brings lake level above 901 feet. This engages the emergency spillway for the first time in the history of the facility.

❹ February 12: Anticipated erosion begins to progress faster than expected at the base of the emergency spillway. The Butte County Sheriff's Office issues mandatory evacuation orders for the Oroville area. To ease pressure on the emergency spillway, the flood control spillway outflow is increased to 100,000 cfs. After several hours, inflows decrease and overflow stops at the emergency spillway. Erosion to the emergency spillway hillside is assessed.

❺ February 13: DWR crews begin working around the clock to repair the emergency spillway. Evacuation orders remain in effect.

❻ February 14: As the lake level continues to drop, the mandatory evacuation order is modified to an evacuation warning. Crews continue working around the clock to repair the emergency spillway. An elevation of 850' is targeted for lake level.

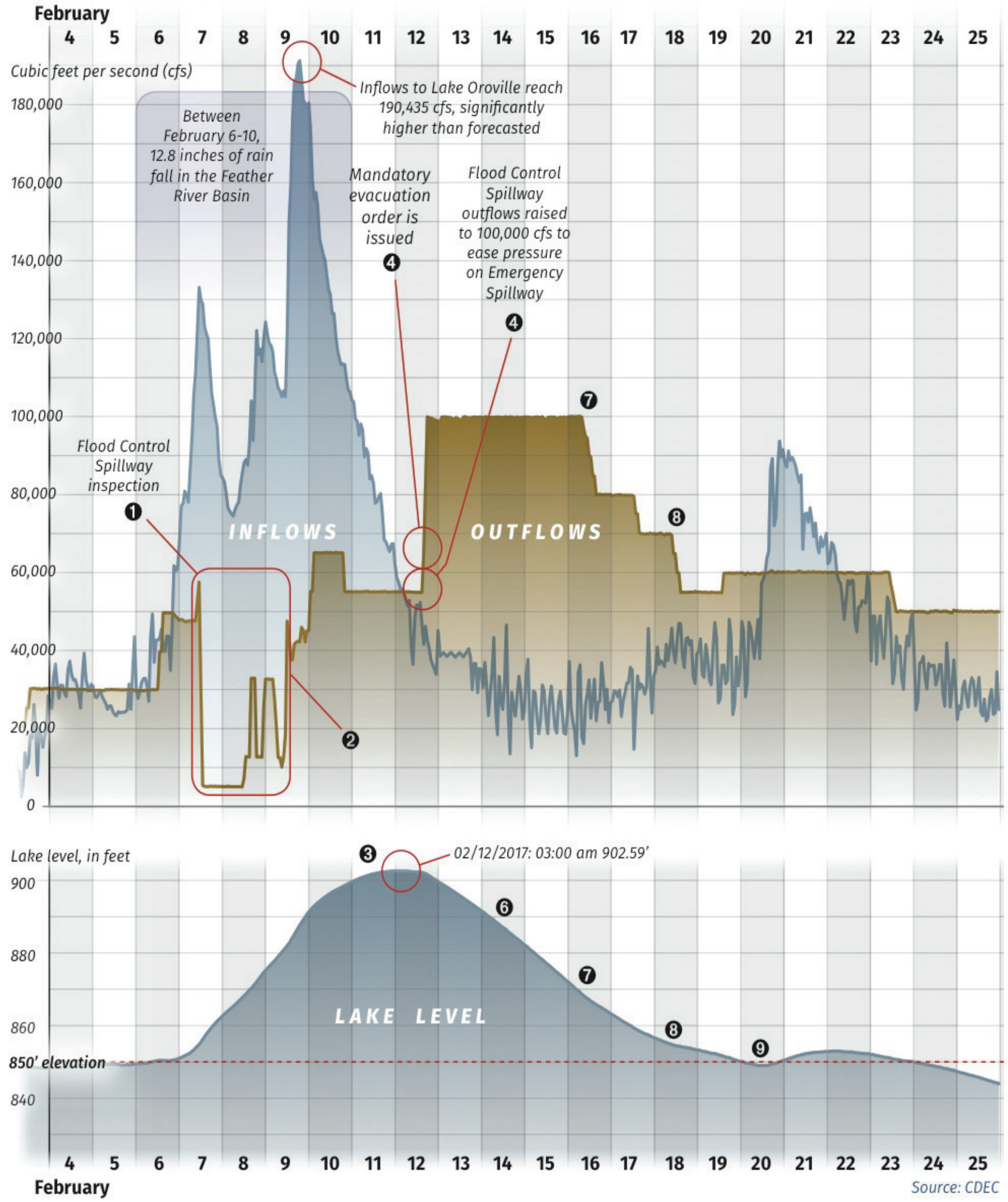
❼ February 16: Flood control spillway flows are reduced below 100,000 cfs to facilitate the clearing of debris from below the spillway. Lake levels continue to drop. Construction to armor the emergency spillway continues.

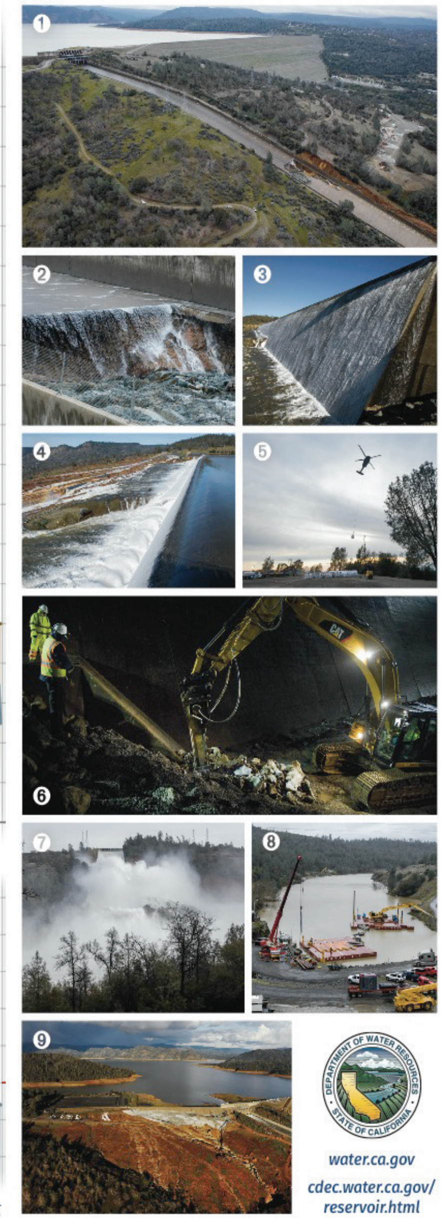
❽ February 18: Lake level down to 854 feet. Flood control spillway flows are reduced to 55,000 cfs. Barge construction begins in order to remove debris from the diversion pool beneath the spillway.

❾ February 20: Lake Oroville elevation reaches 848.95 feet at 11 a.m. Repairs and preparations continue around the clock.

Cooperating Agencies: California Department of Water Resources, Butte County Sheriff, CAL FIRE, Oroville Police Department, Butte County OES, Oroville Fire Department, Butte County Public Works, Oroville Hospital, Caltrans, California Highway Patrol, California State Parks, California Conservation Corps, California National Guard, California Department of Fish and Wildlife, PG&E, Red Cross, Bureau of Indian Affairs, CAL OES, USACE, FERC, FEMA

For more imagery, see DWR Pixel Library

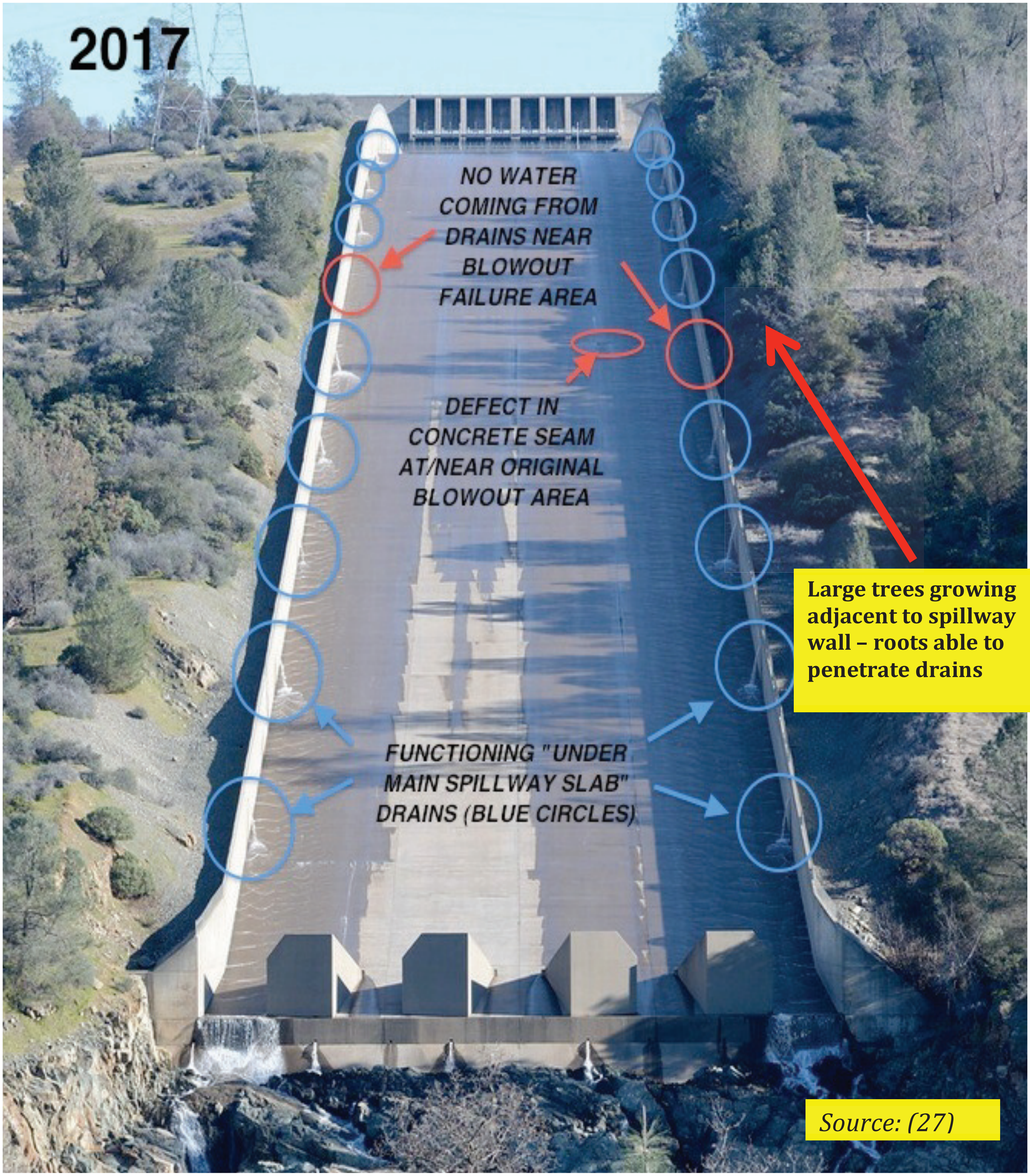




water.ca.gov
cdec.water.ca.gov/reservoir.html

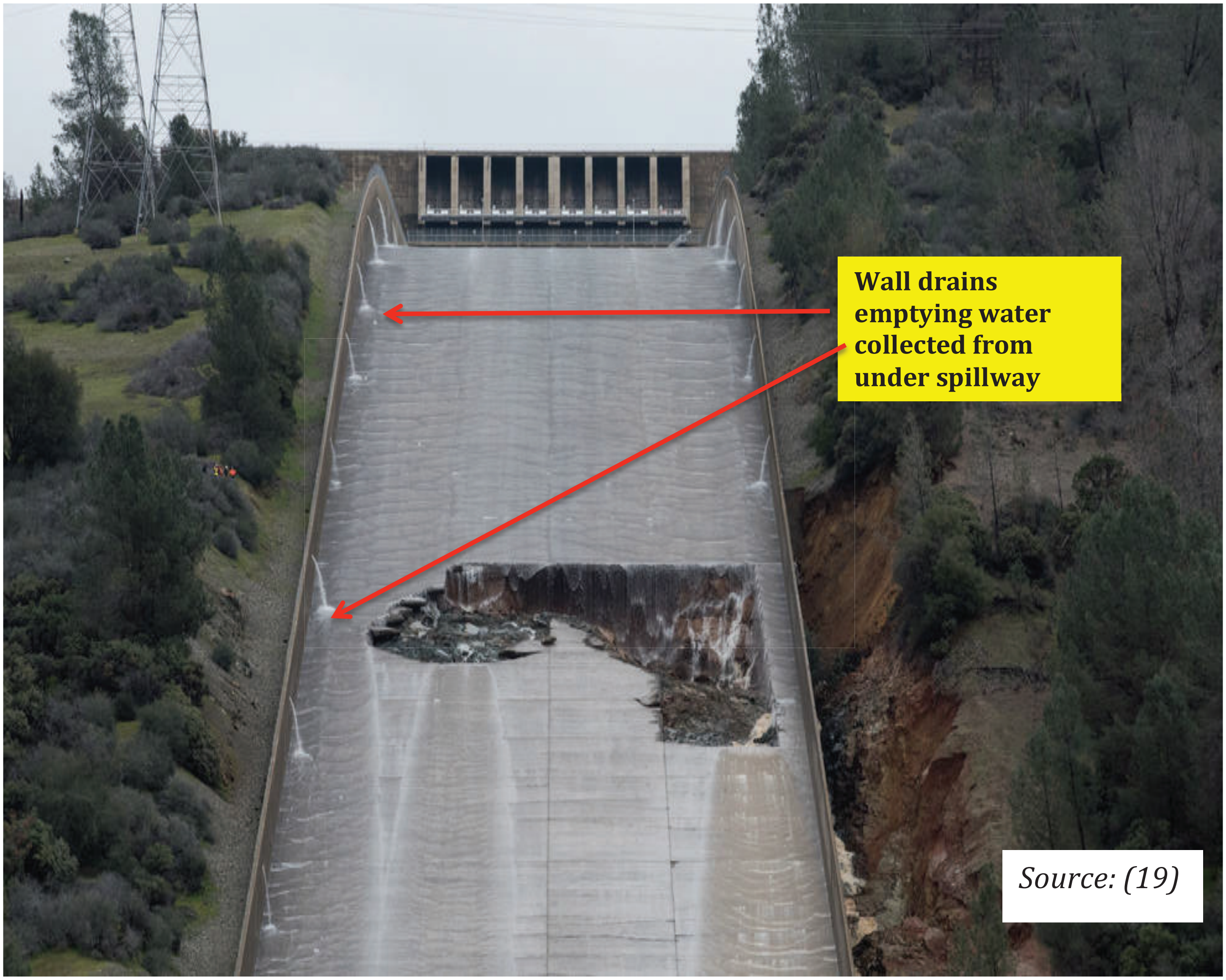
Source: (18)

January 27, 2017

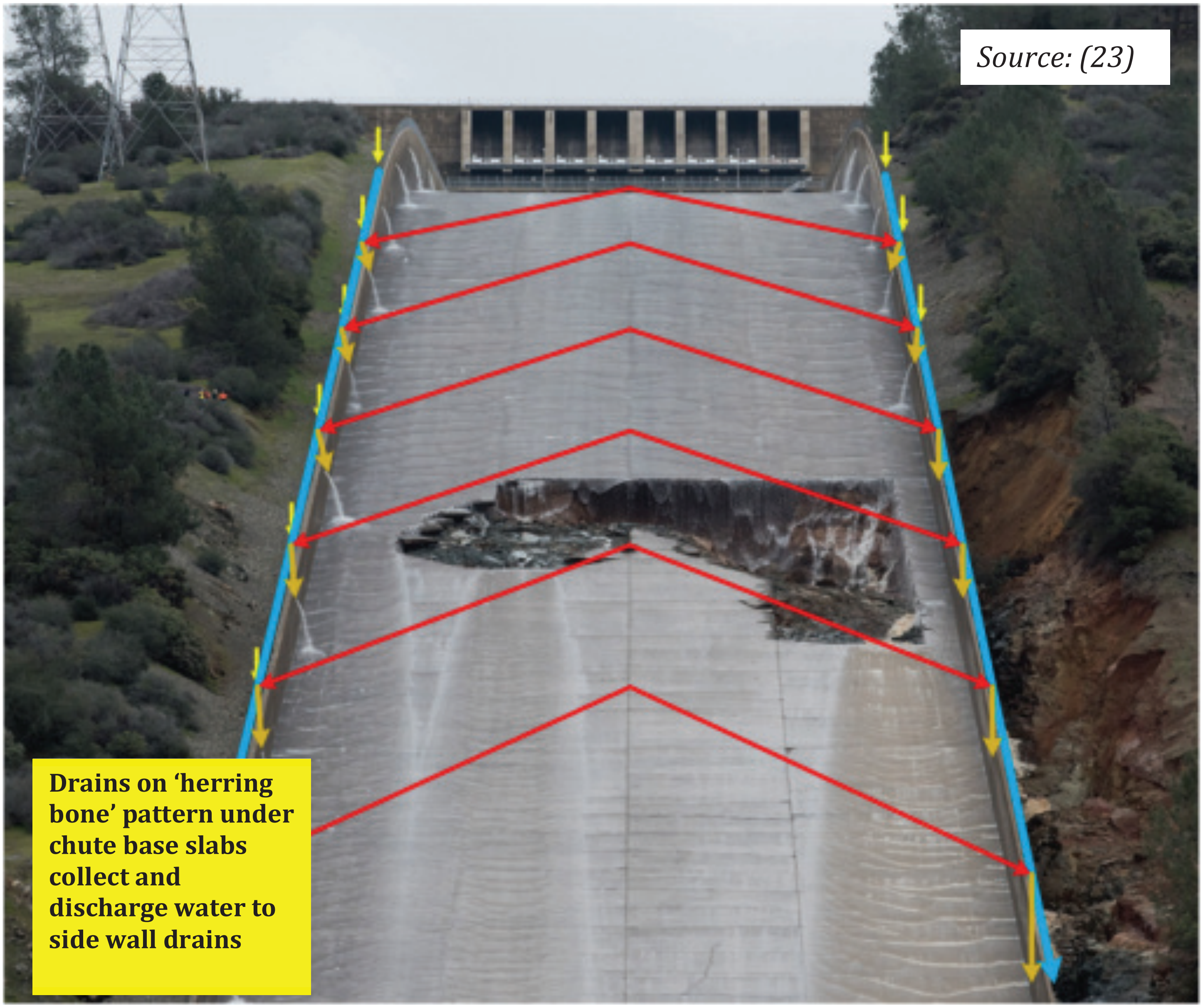


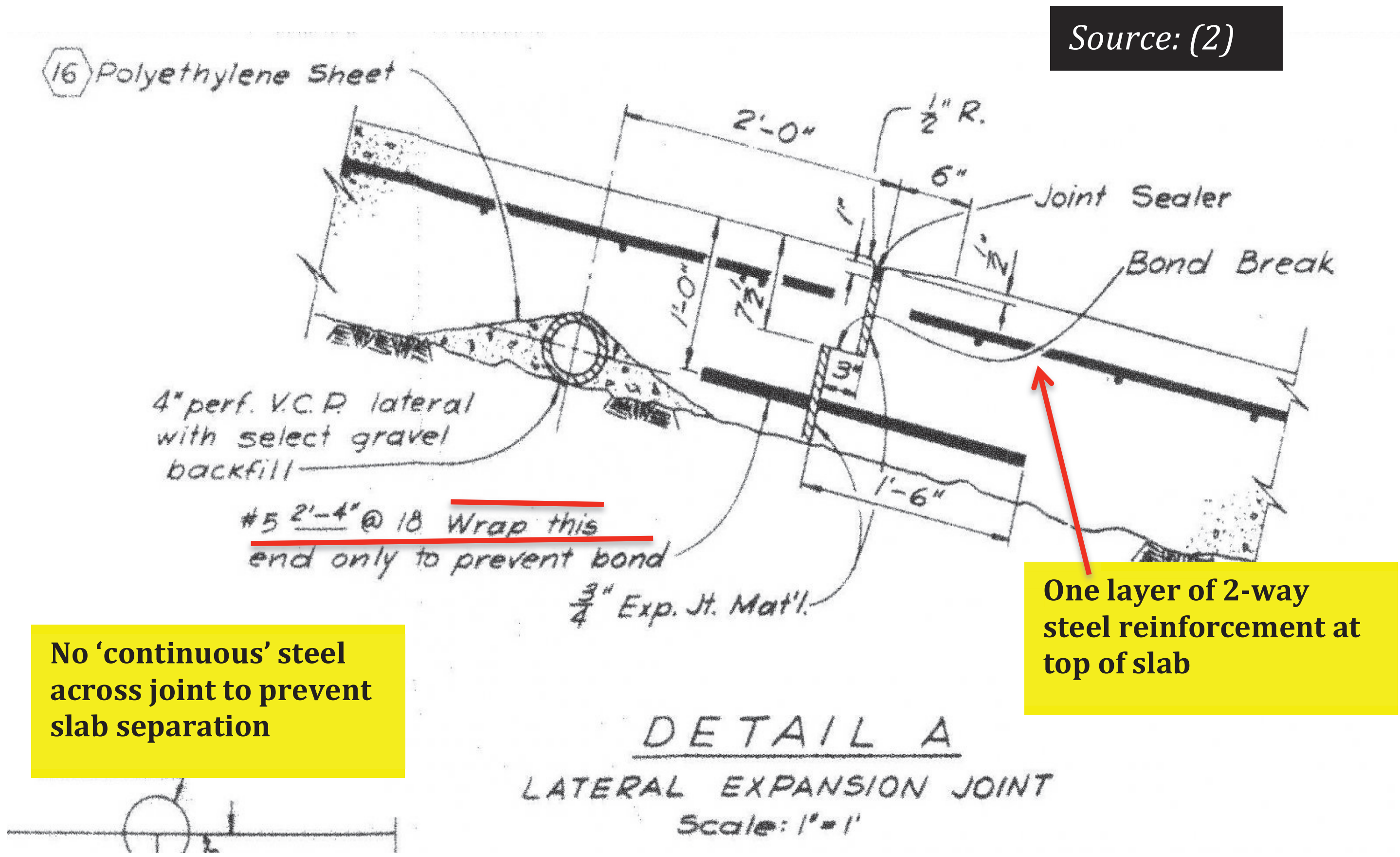
February 7, 2017 – Stage #1

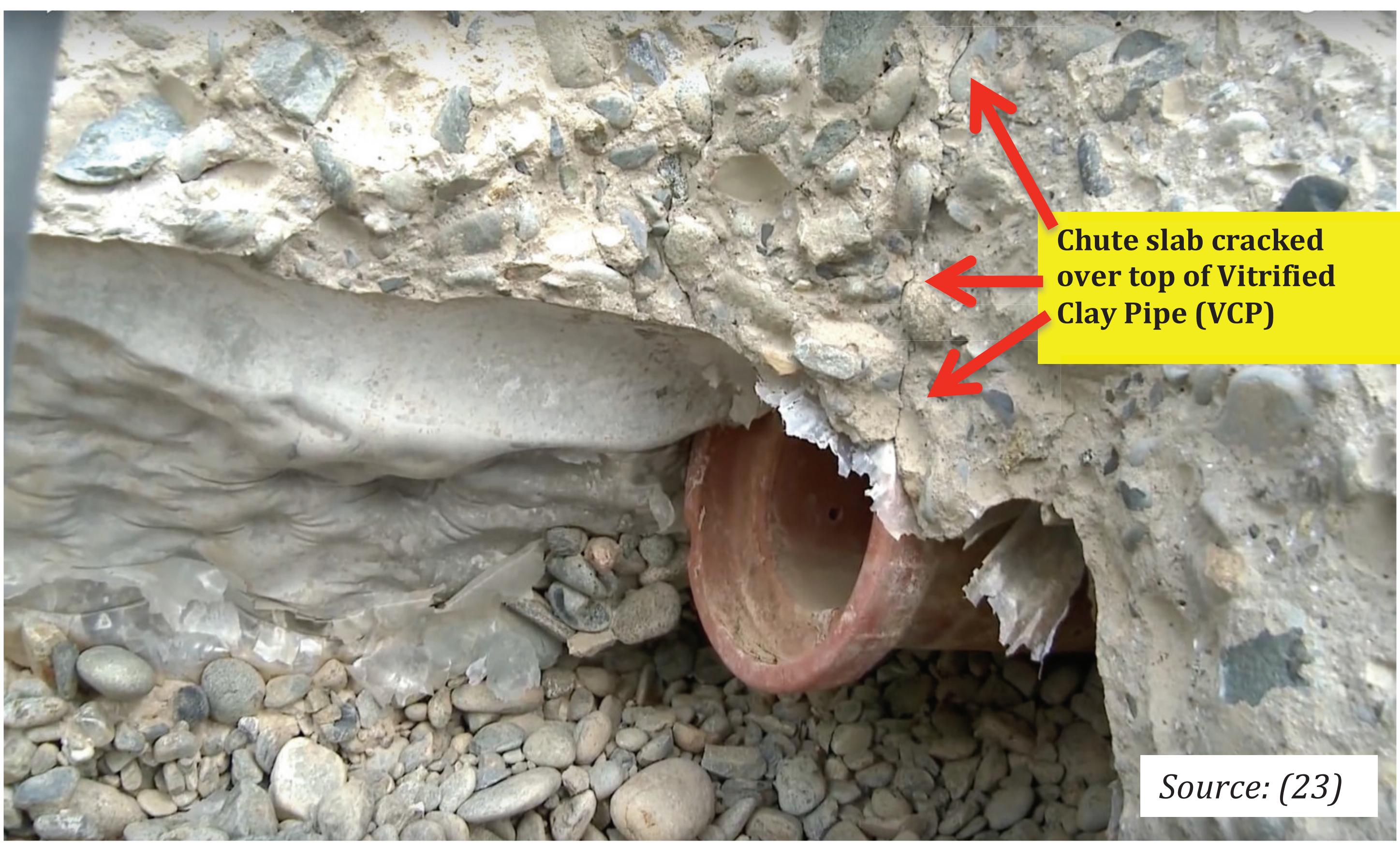

Exposed rock and erodible sediments under spillway
Source: (19)

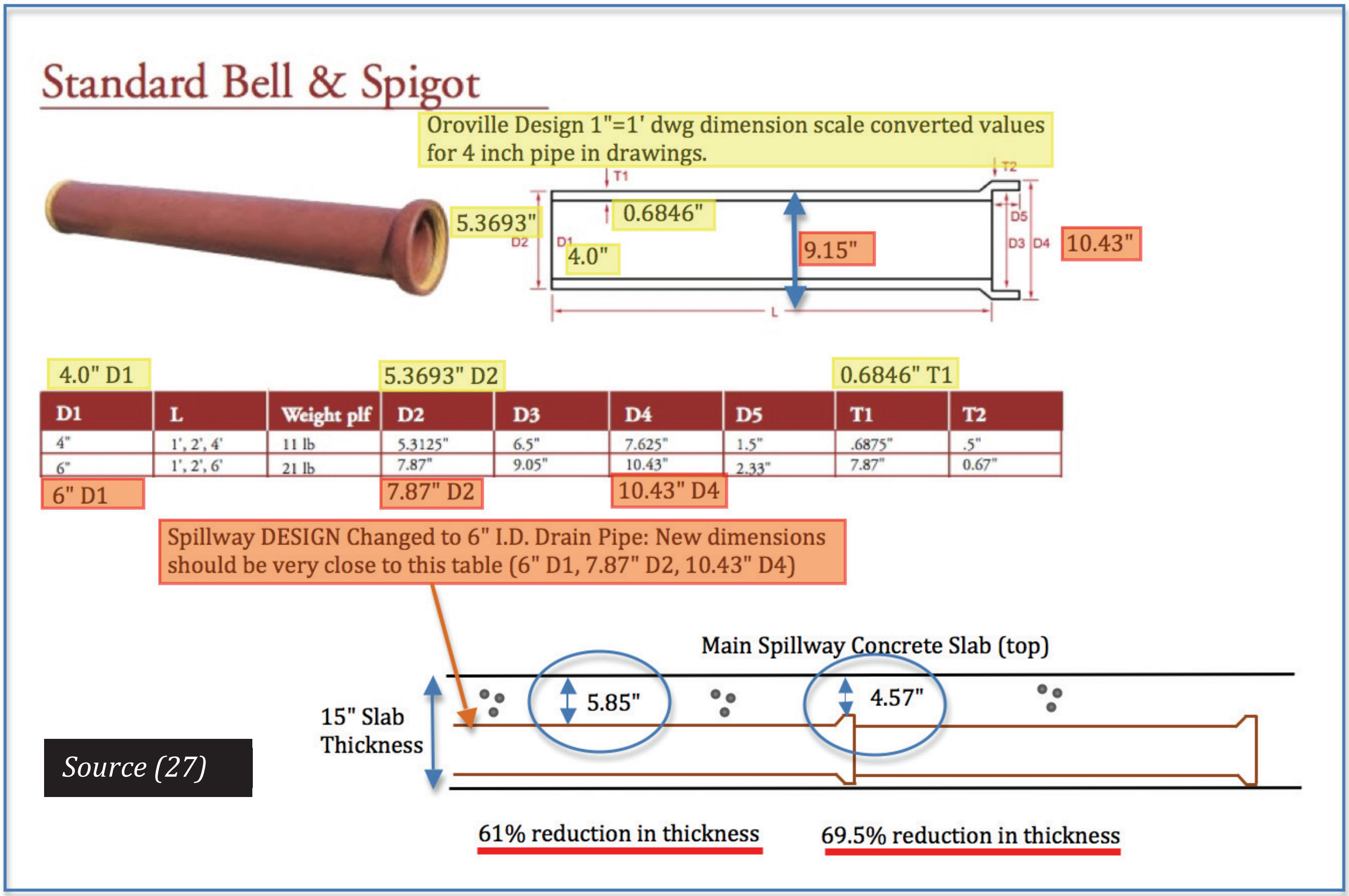

Wall drains emptying water collected from under spillway
Source: (19)


Dirty water from under spillway
Wall drains on upper part of spillway indicate A Lot Of Water coming from under the spillway
Source: (21)

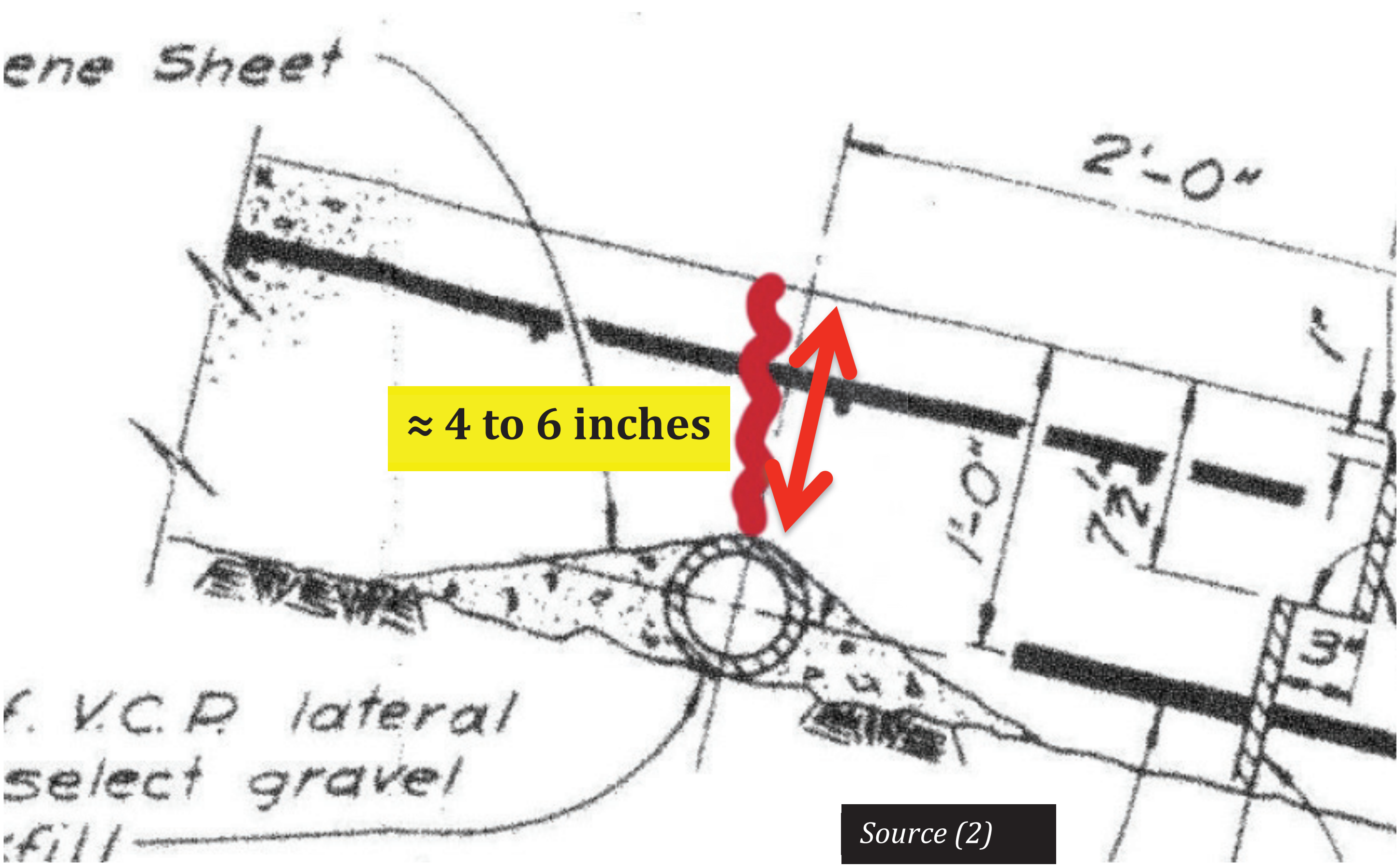

Source: (23)
Drains on 'herring bone' pattern under chute base slabs collect and discharge water to side wall drains

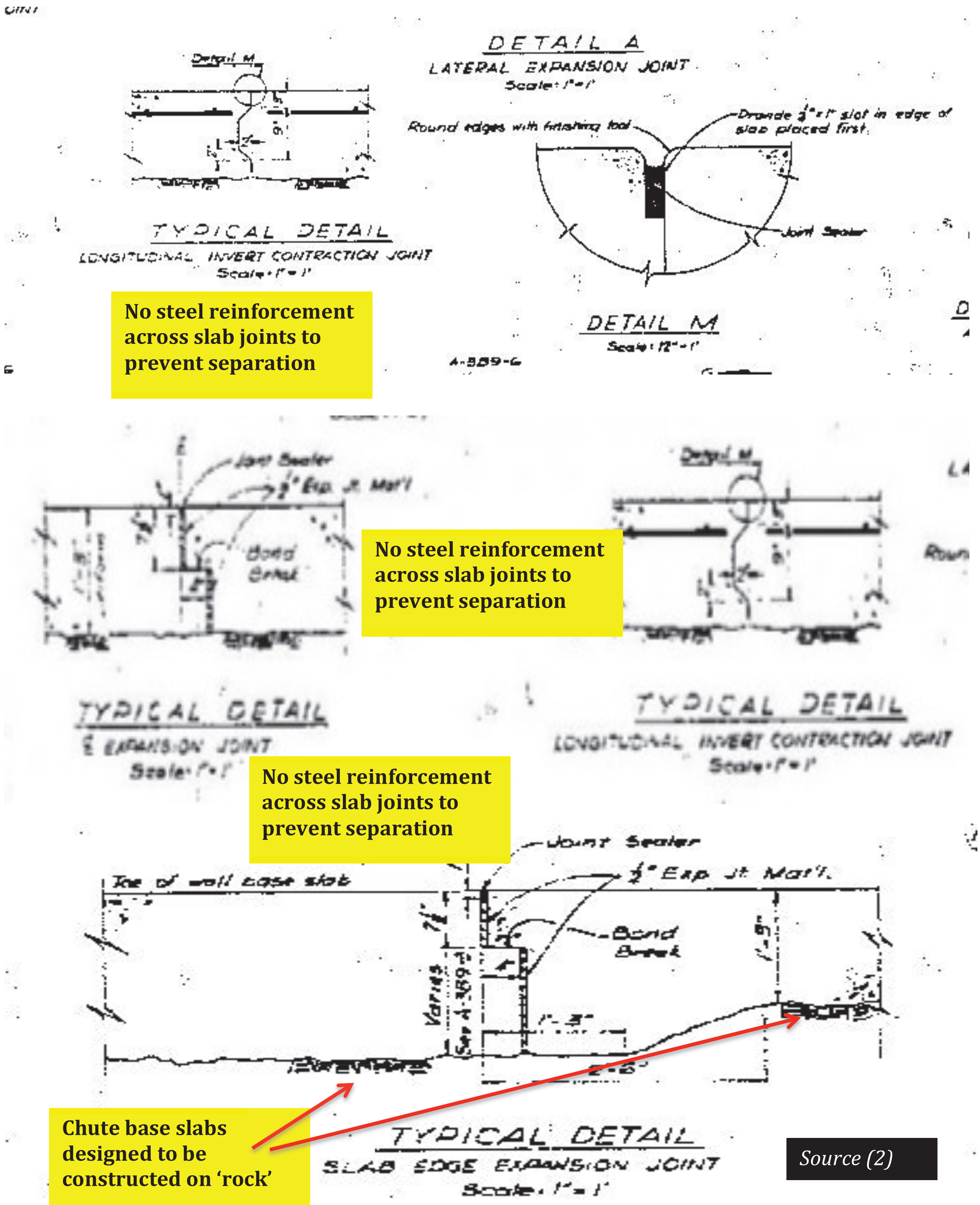

Source: (2)
16 Polyethylene Sheet
2'-0"
1/2" R.
6"
Joint Sealer
Bond Break
1'-0"
3"
4" perf. V.C.P. lateral
with select gravel
backfill
1'-6"
#5 2'-4" @ 18 Wrap this
end only to prevent bond
3/4" Exp. Jt. Mat'l.
One layer of 2-way steel reinforcement at top of slab
No 'continuous' steel across joint to prevent slab separation
DETAIL A
LATERAL EXPANSION JOINT
Scale: 1"=1'


Chute slab cracked over top of Vitrified Clay Pipe (VCP)
Source: (23)

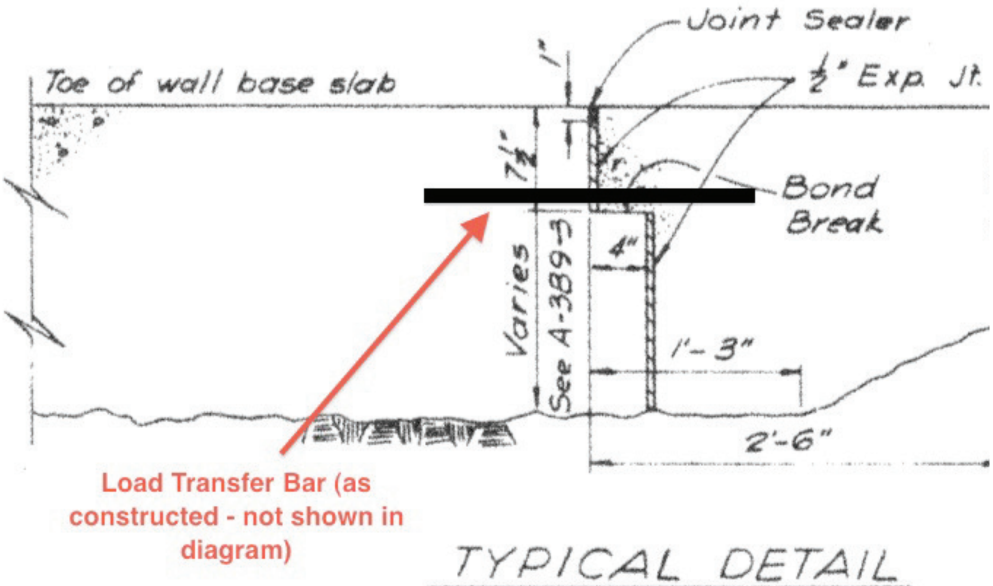


D1	L	Weight plf	D2	D3	D4	D5	T1	T2
4"	1', 2', 4'	11 lb	5.3125"	6.5"	7.625"	1.5"	.6875"	.5"
6"	1', 2', 6'	21 lb	7.87"	9.05"	10.43"	2.33"	7.87"	0.67"




DETAIL A
LATERAL EXPANSION JOINT
Round edges with finishing tool
Joint Sealer
DETAIL M
A-389-6
Detail M
TYPICAL DETAIL
LONGITUDINAL INVERT CONTRACTION JOINT
No steel reinforcement across slab joints to prevent separation
Joint Sealer
Bond Break
TYPICAL DETAIL
EXPANSION JOINT
No steel reinforcement across slab joints to prevent separation
Detail M
TYPICAL DETAIL
LONGITUDINAL INVERT CONTRACTION JOINT
No steel reinforcement across slab joints to prevent separation
Joint Sealer
Toe of wall base slab
Bond Break
Varies
TYPICAL DETAIL
SLAB EDGE EXPANSION JOINT
Chute base slabs designed to be constructed on 'rock'

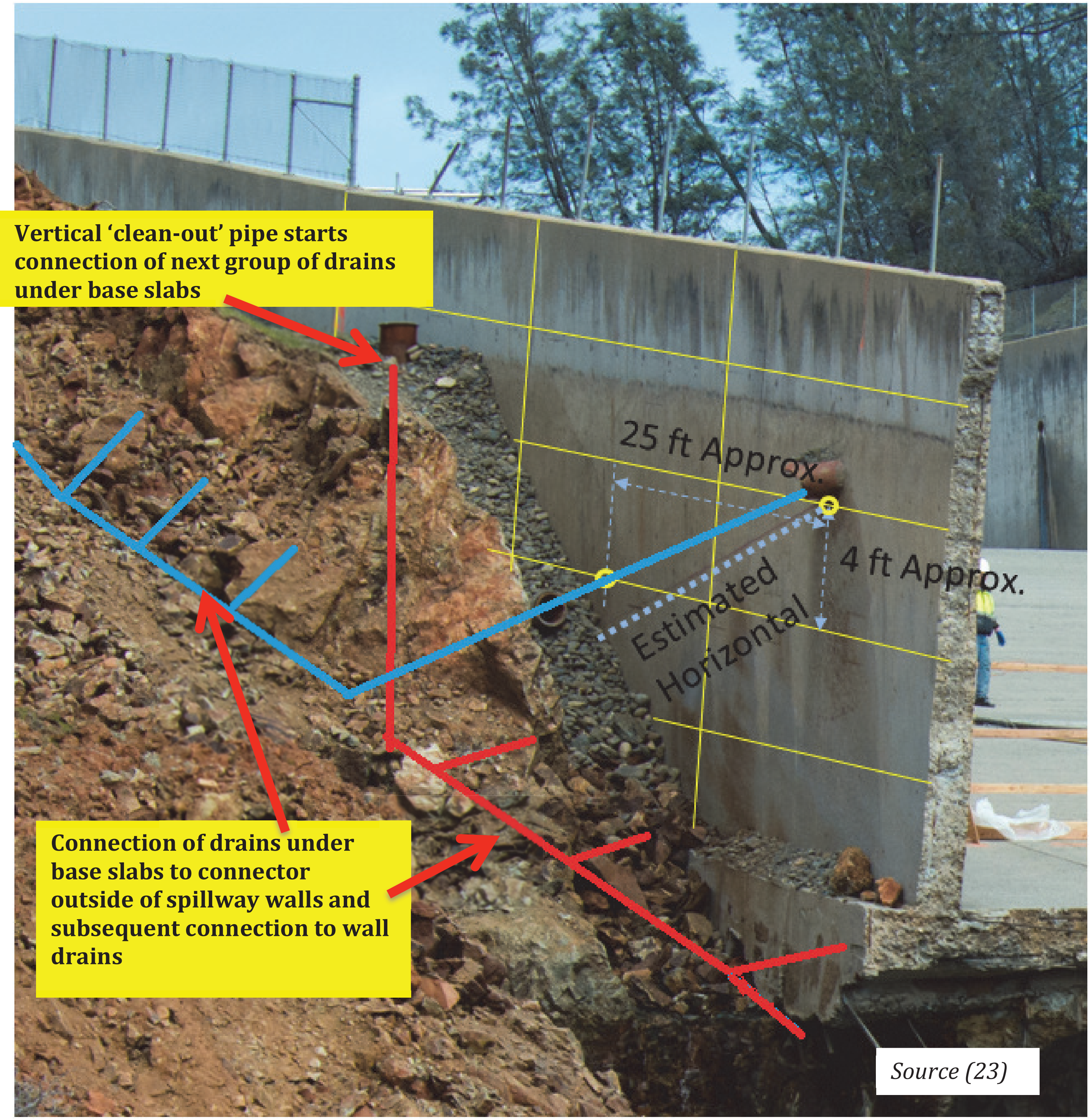
Source (2)

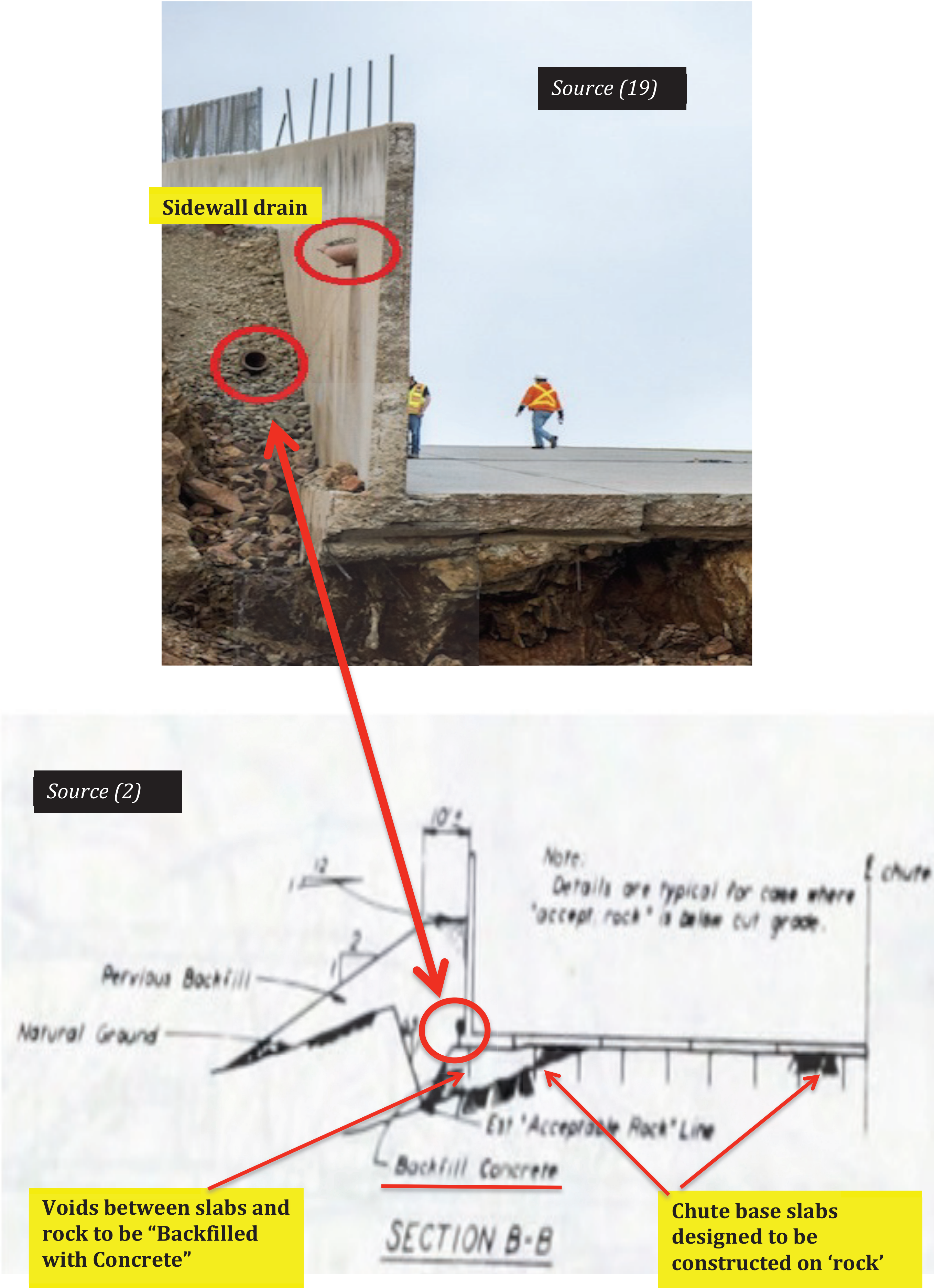


TYPICAL DETAIL
SLAB EDGE EXPANSION JOINT
Scale: 1" = 1'

Source (2)


Water flow pattern indicates slabs displaced vertically
Source (19)

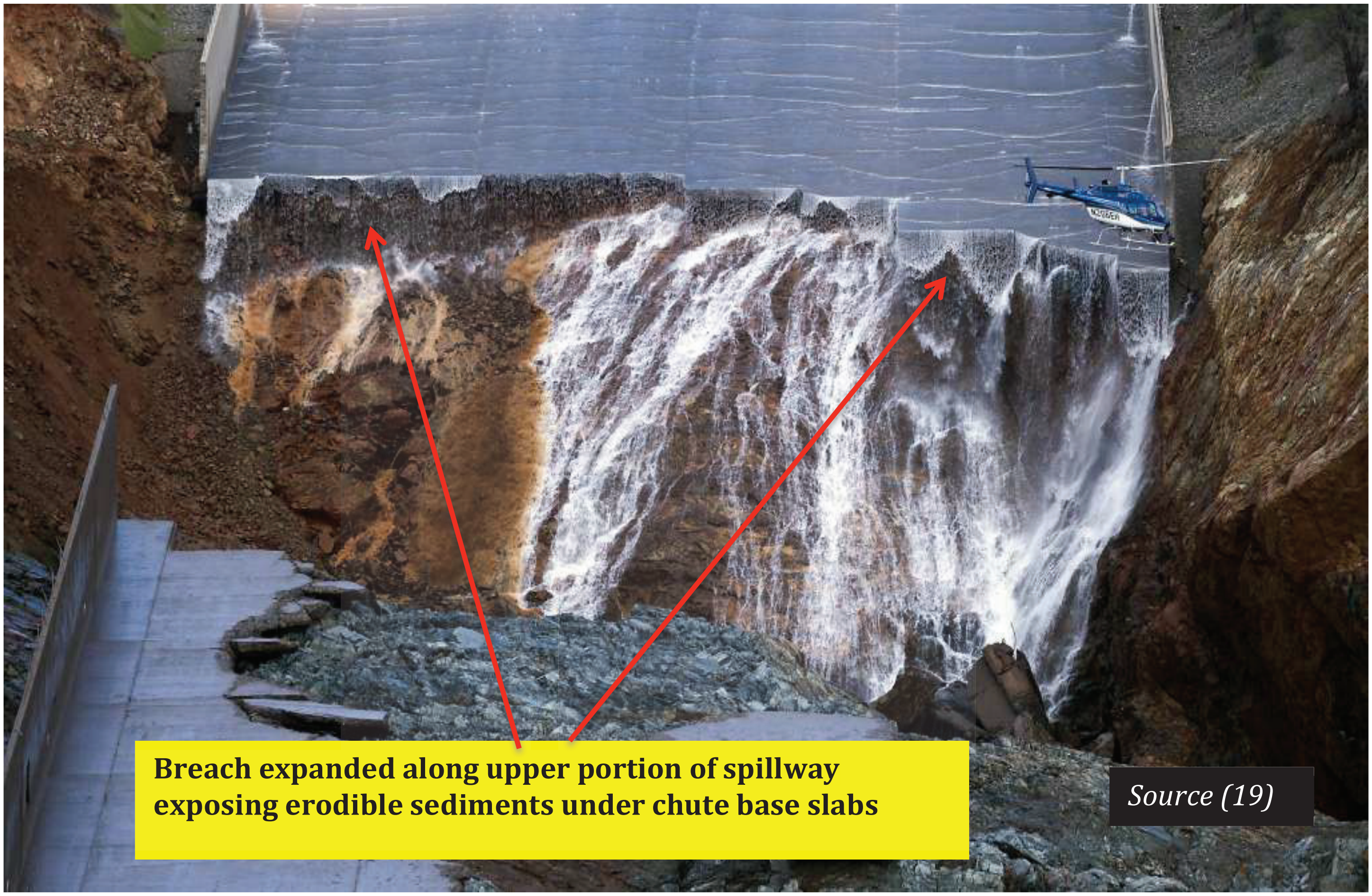

Vertical 'clean-out' pipe starts connection of next group of drains under base slabs
25 ft Approx.
4 ft Approx.
Estimated Horizontal
Connection of drains under base slabs to connector outside of spillway walls and subsequent connection to wall drains
Source (23)


Source (19)
Sidewall drain
Source (2)
Note:
Details are typical for case where "accept. rock" is below cut grade.
chute
Pervious Backfill
Natural Ground
Est 'Acceptable Rock' Line
Backfill Concrete
SECTION B-B
Voids between slabs and rock to be "Backfilled with Concrete"
Chute base slabs designed to be constructed on 'rock'

February 9, 2017 – Stage #2


Wall drain flowing ‘dirty’ water from under spillway with suspended sediments
Source (19)


Both sides of spillway chute walls breached and eroding sediment outside of spillway
Source (19)


Breach expanded along upper portion of spillway exposing erodible sediments under chute base slabs
Source (19)


'Incompetent' weathered rock
'Competent' non-weathered rock
Source (21)


'Incompetent' weathered rock
Source (21)

Stage 3 – February 16, 2017

Source (19)


Soils eroded from
under slabs
Source (19)


Eroded concrete surface
exposing reinforcing steel -
indicates water scouring
'cavitation' effects
Slab cracks
Source (19)

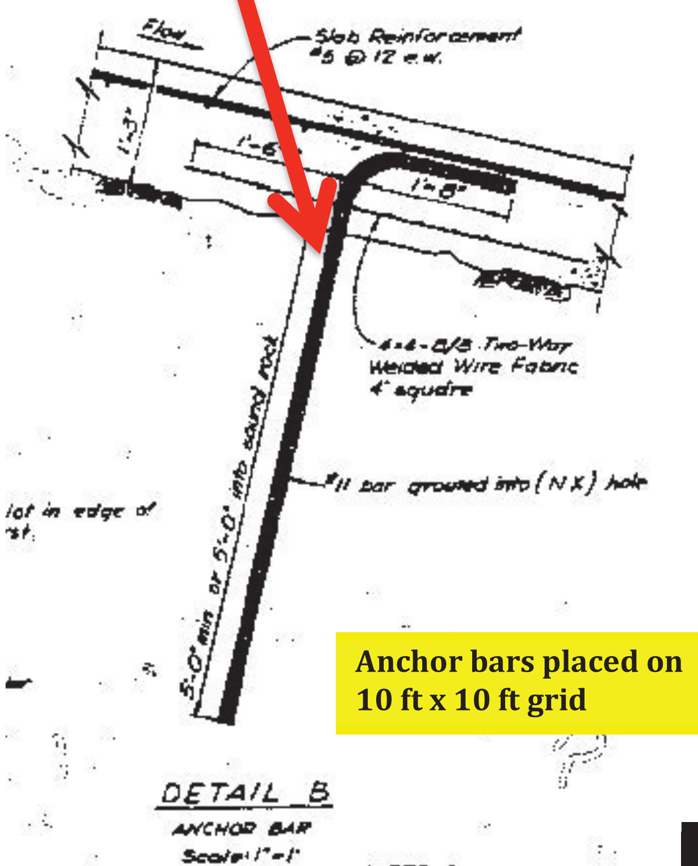
Source (19)


One layer of 2-way steel
reinforcement at top of chute slabs
34~

Source (19)

Source (19)


Steel reinforcement 'anchor' connecting spillway base slab to 'rock' – pulled away from slab
Source (19)

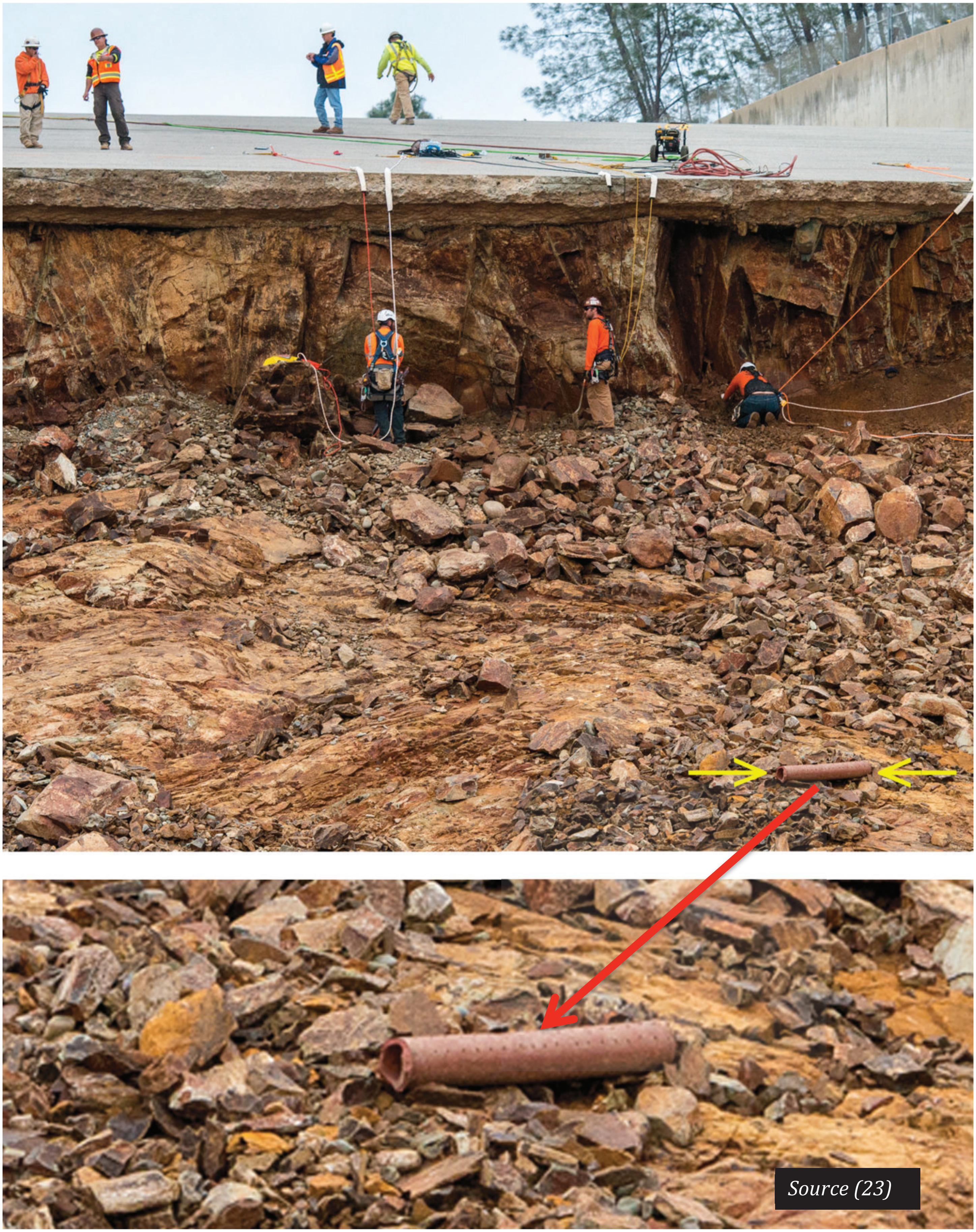

Flow
Slab Reinforcement
#5 @ 12 e.w.
1'-3"
1'-6
1'-8"
Two-Way
Welded Wire Fabric
4" square
#11 bar grouted into (NX) hole
5'-0" min or 5'-0" into sound rock
Anchor bars placed on 10 ft x 10 ft grid
DETAIL B
ANCHOR BAR
Source (2)

Stage #4 – Temporary Repairs to spillway chute


Source (19)


DANGER
Source (19)


Leakage water
draining into
transverse joints
Source (19)



Source (23)


Source (27)
Concrete fractured along
drain pipe emplacement


Flanged steel pipe
under spillway base
slabs ????