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CONSTRUCTION TO COPE WITH FAST-FLOWING WATER

by

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CONSTRUCTION TO COPE WITH FAST-FLOWING WATER*

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1. The importance of constructing engineering structures to cope with fast-flowing water can be realized only when those in charge of the work fully understand what takes place when high-velocity water passes over constructed surfaces. The purpose of this talk will be to point out some of the actions which occur when this is the case, and how they affect construction.

2. The two most troublesome of these actions are eddying and cavitation. Both result in erosion of the surfaces. High-velocity eddies will pick up loose material from a riverbed or adjacent banks and cause erosion by abrasion while cavitation will cause damage by pitting.

3. Eddying is usually caused by unbalanced flow conditions set up by construction requirements or unsymmetrical operation of a structure after completion. The concentration of large quantities of water over only a portion of the normal flow channel, as was necessary during the construction of Grand Coulee Dam, is an example. The eddy current shown in figure 1 moved large quantities of rock, huge boulders, steel piles, and other construction material (figure 2) dropped near the toe of the dam, upstream into the bucket section where severe erosion occurred as shown by figures 3 and 4. The eroded material has smooth irregular surfaces which in the case of concrete, have the appearance of having been ground and polished; and in the case of metal, appear as grooves having been gouged out with a chisel. Precautions against this type of damage during construction and operation would include:

a. Evenly distributing the flow, if possible
b. Removal of loose material in the eddy area
c. Preventing debris or other construction materials to accumulate in possible eddy areas and
d. Stabilizing the ground surfaces in the eddy area by placing heavy rock or other material on them.

Although of considerable concern to the construction engineer, the eddying action is usually, but not always, of a temporary nature and of short duration and can be tolerated as such. On the other hand, once conditions are present to induce cavitation the action will take place whenever there is flow unless some corrective measure is taken.

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*For presentation at Conference for Construction Engineers of the Bureau of Reclamation; Denver, Colorado, February 6-10, 1950.

4. The damage produced by cavitation occurs in regions of low-pressure and high-water velocities where there are severe changes of alinement in the surface over which the water is flowing as indicated in figure 5, or where there is too rapid an increase in cross-sectional area of the water passage. The surface is rough and has the appearance of being formed of numerous small crater-like depressions or pits and thus the action is called pitting. The piece of steel and concrete test specimens on this platform are examples. (Section of Ross Dam penstock and concrete blocks.)

5. Before discussing the subject of cavitation further, an attempt will be made to define the word in as nontechnical terms as possible.

6. Cavitation is the action which takes place in an extremely low-pressure region at the boundary of the flowing water when the pressure is reduced to the vapor pressure of the water. The action consists of the formation, movement, and collapse of vapor cavities (often called bubbles) in the low-pressure region. The cavities or bubbles form at the upstream edge of the region and are carried downstream to a point where the pressure increases and where they collapse or implode (opposite of explode) instantaneously. This action will be shown clearly in motion pictures shown to you at the end of this discussion.

7. The instantaneous collapse causes the water particles surrounding the bubble to move toward the center at an extremely high velocity and the impact of the water particles on each other as they come together produces a tremendous concentrated force which causes disintegration of a minute area of any surface on which this action occurs.

8. For many years the words "cavitation" and "pitting" have been used interchangeably as referring to both the cavitation action and the damage this action inflicts. Recently the engineering profession has attempted to limit the word "cavitation" to the action of, the formation, movement, and collapse of the vapor cavities, and the word "pitting" to the actual damage to materials by the cavitation action. This damage, therefore, is now termed pitting or cavitation-erosion--not cavitation.

9. The general appearance of cavitation is a white, milky cloud resembling steam, as shown in figure 6. As a matter of fact, the cloud is a cold, low-pressure steam in the form of bubbles (cavitation bubbles). The cavitation action occurs with such rapidity that it cannot be studied in detail visually. Motion pictures taken at speeds up to 20,000 frames per second have been used to study the phenomenon. These will be shown later.

10. Considerable noise and vibration accompanies cavitation. The noise may be of a hissing, crackling, or popping sound, depending upon the intensity of the cavitation and other physical flow characteristics such as the masses of water and structure involved. For instance, the noise accompanying the cavitation in this small venturi meter (demonstration model), where the water velocity is relatively low, is of a hissing nature,

while that in a test apparatus in the laboratory is more of a crackling or popping nature as indicated by the sound from this speaker which is attached to the apparatus operating in the laboratory. Figure 7 shows a section through this apparatus. (Note the expanding section and position of concrete test blocks.) Some of the damaged test blocks are shown in figure 8.

11. The noise accompanying cavitation is known to all hydraulic engineers as crepitation.

12. From our discussion of cavitation, it is evident that the best method of preventing its occurrence from the construction standpoint is to see that the surfaces over which high-velocity water is to pass are smooth, continuous, and free of offsets and undulations.

13. The commonest sources of dangerous irregularities are the offsets which often occur at construction joints. It is not easy to prevent these offsets but they can be eliminated, and they must be eliminated if these channels for fast-flowing water are to operate freely from damage due to cavitation.

14. Hydraulic engineers have realized for a long time that it is extremely difficult and in many cases impracticable to eliminate completely these surface irregularities, and some tests have been conducted to determine what tolerances could be permitted. It has been difficult to make the test facilities represent the field conditions where wide variations in water depth and velocity are encountered, and the data on surface tolerances for high-velocity flow are still meager. The specifications for the surfaces of the Hungry Horse Dam Spillway Tunnel and other similar structures are based on this information.

15. The irregularities in the surfaces of the Hungry Horse Spillway Tunnel, where high-velocity flow is expected, are limited to gradual depressions or rises in which the slopes or bevels to and from the low or high points vary from 1/4 inch in 20 inches to 1/4 inch in 100 inches. The flatter bevel is specified for the lower vertical bend of the tunnel and in the bottom portion of the horizontal section downstream from the bend where the velocities will be the highest, and where water passes over the surfaces whenever the spillway operates. The steeper bevels are permitted in other sections where the velocities are lower and the tendency for cavitation is much less.

16. The tolerances may or may not be on the conservative side. It is hoped that they are and that future investigation will show that they can be eased. However, until such time as we have proof that these tolerances are too strict, we must continue to use them.

17. We have many examples which will illustrate the importance and necessity of using tolerances which will prevent damage by cavitation. One example concerns erosion by cavitation of the draft-tube surfaces of one of the units of the right powerhouse at Grand Coulee Dam when needle

valves were placed to discharge their flow into the tubes for the release of water during the repair of underwater portions of the spillway. Figure 9 shows the extent of damage after 23-hour operation of one of the valves. A survey of the area revealed that the surface was not continuous but had an offset of one-half inch as illustrated in figure 10. Through inquiry, it was learned that during construction one edge of a steel form had been deformed to coincide with the edges of the already placed adjacent concrete. The change in the form resulted in a one-half inch discontinuity, ideal for producing cavitation when high-velocity water passed over it. An area in which the pressure was reduced to the vapor pressure of water formed immediately downstream from the discontinuity. Cavitation occurred in this area and caused pitting a short distance downstream. The damage was accelerated when an old patch in the area was torn out by the pressure changes and vibrations accompany the cavitation. As a corrective measure, the concrete was removed from the area to a depth of about 18 inches and the surface repaired to eliminate the severe recession in the surface as illustrated in figure 10. There was no damage in this area by subsequent operations as shown in figure 11, although above the repair further damage was caused by loss of a patch.

18. It should be pointed out here that had the draft tube been used only for handling the usual discharge from the turbine, the velocities would have been low and there would have been no cavitation.

19. The motion picture "Formation and Collapse of Cavitation Cavities," to be shown in concluding this discussion will show the cavitation action as described at the beginning of this talk.

20. After viewing the film, you will realize that the designer can do much to eliminate cavitation in his designs, but that the surfaces must be smooth and continuous if the design is to remain free of cavitation. In other words, we must stress that clean, smooth, continuous surfaces free of offsets and irregularities must be provided where fast moving water is concerned. A "gob" of set concrete clinging to the surface is sufficient to induce cavitation, and care should be taken to remove any "foreign" material from the flow surfaces before a structure is placed in operation. The responsibility to provide satisfactory surfaces must be assumed by the construction men. It is better to keep within the specified close tolerances during construction rather than grind or repair the surfaces after construction is complete or damage has been done after the structure is placed in operation.

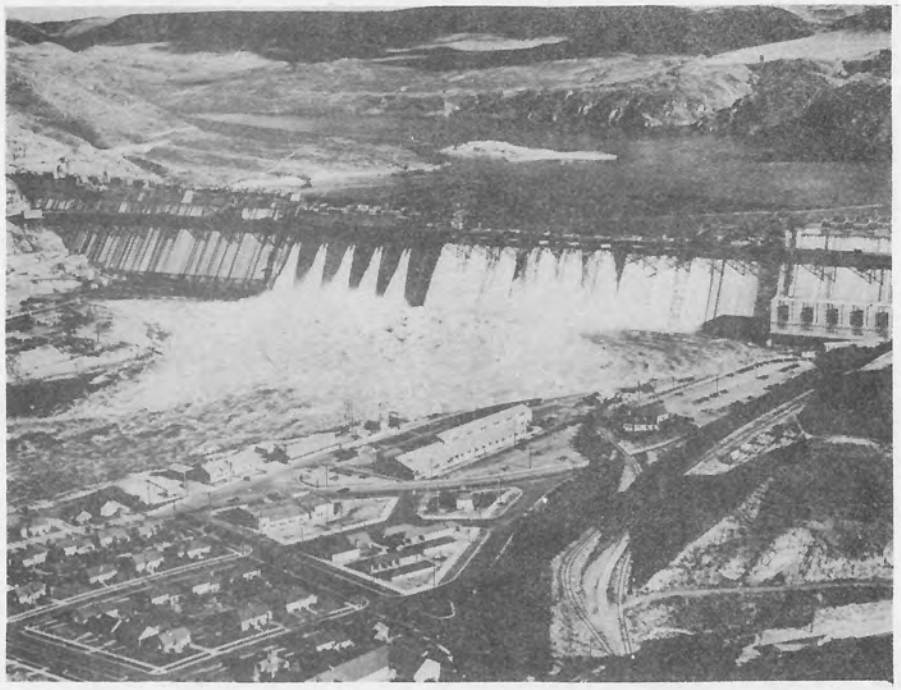
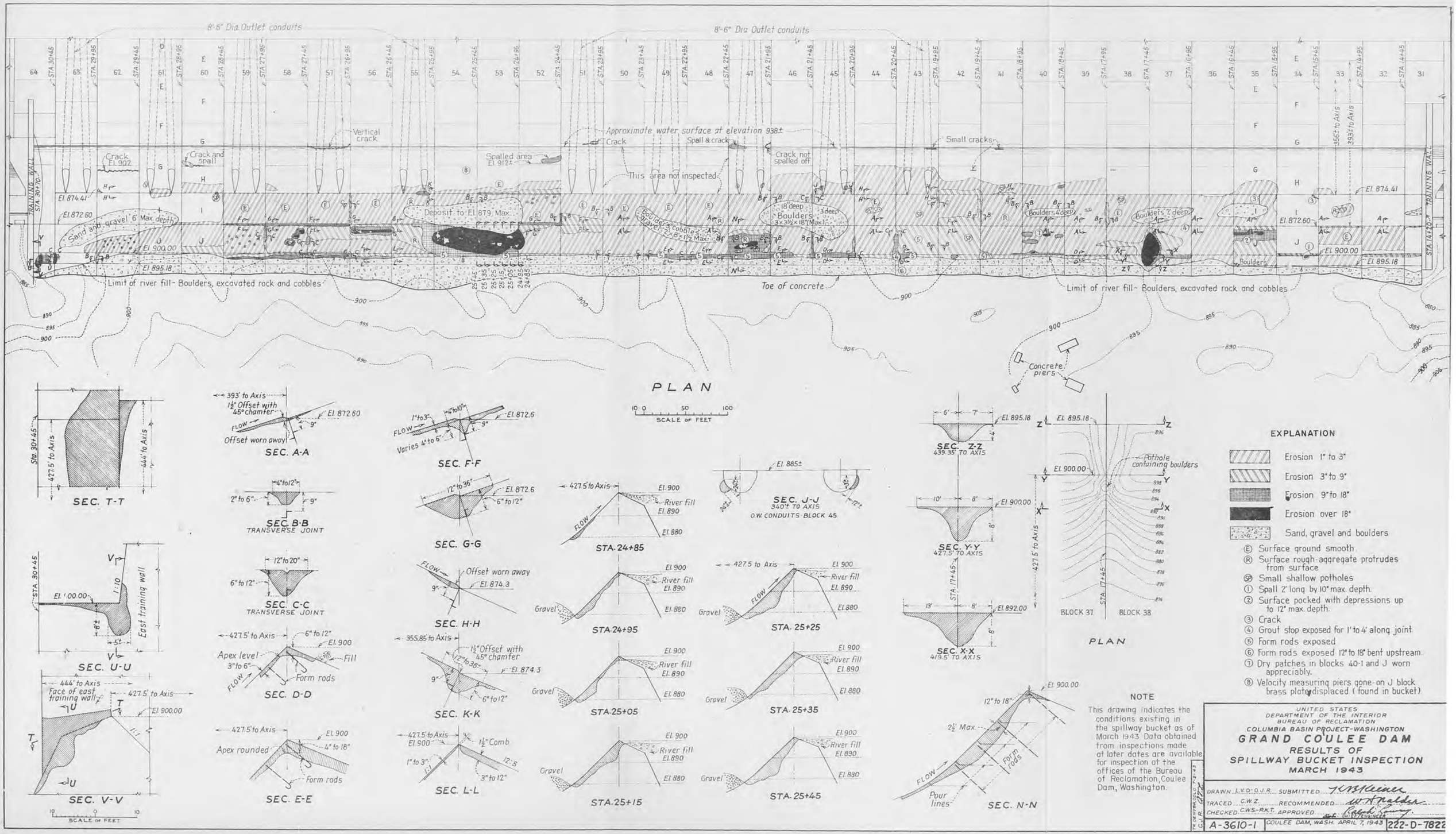
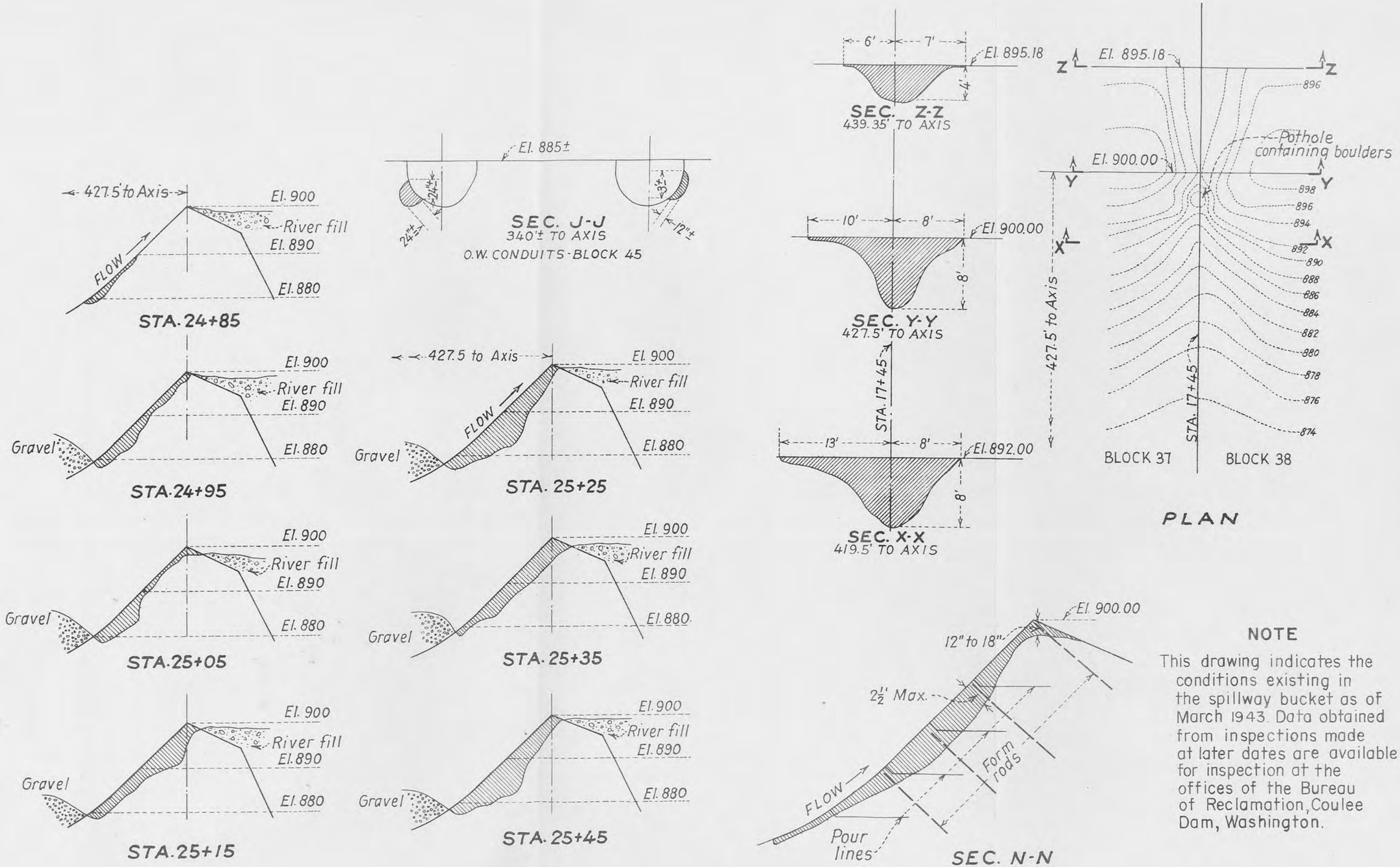


Figure 1. Eddy induced by flow distribution at Grand Coulee Dam--1940 Flood Season.

Figure 2. Material removed from spillway bucket--Grand Coulee Dam.


8'-6" Dia Outlet conduits
Approximate water surface at elevation 938±
Vertical crack
Crack El. 902
Crack and spall
Spalled area El. 912±
Crack
Spall & crack
Crack not spalled off
Small cracks
This area not inspected
Deposit to El. 879 Max.
Sand and gravel 6' Max. depth
Boulders, cobbles, gravel 2'-8' x 1½' Max.
18" deep
Boulders
3 x 3½ x 18" (Max.)
3' deep
Boulders 4' deep
Boulders 2' deep
Boulders
TRAINING WALL STA. 30+70
STA. 14+70
El. 874.41
El. 872.60
El. 900.00
El. 895.18
Limit of river fill - Boulders, excavated rock and cobbles
Toe of concrete
Concrete piers
356± to Axis
393± to Axis
PLAN
SCALE OF FEET
SEC. T-T
SEC. A-A
SEC. B-B
TRANSVERSE JOINT
SEC. C-C
TRANSVERSE JOINT
SEC. D-D
SEC. E-E
SEC. F-F
SEC. G-G
SEC. H-H
SEC. K-K
SEC. L-L
SEC. U-U
SEC. V-V
East training wall
Face of east training wall
Apex level
Apex rounded
Form rods
Offset worn away
Varies 4" to 6"
1½" Offset with 45° chamfer
1½" Comb
FLOW
Fill
STA. 24+85
STA. 24+95
STA. 25+05
STA. 25+15
STA. 25+25
STA. 25+35
STA. 25+45
River fill
Gravel
SEC. J-J
340' TO AXIS
O.W. CONDUITS - BLOCK 45
SEC. Z-Z
439.35' TO AXIS
SEC. Y-Y
427.5' TO AXIS
SEC. X-X
419.5' TO AXIS
Pothole containing boulders
BLOCK 37
BLOCK 38
PLAN
SEC. N-N
Pour lines
Form rods
EXPLANATION
Erosion 1" to 3"
Erosion 3" to 9"
Erosion 9" to 18"
Erosion over 18"
Sand, gravel and boulders
(E) Surface ground smooth.
(R) Surface rough-aggregate protrudes from surface
(SP) Small shallow potholes
(1) Spall 2' long by 10" max. depth.
(2) Surface pocked with depressions up to 12" max. depth.
(3) Crack
(4) Grout stop exposed for 1' to 4' along joint.
(5) Form rods exposed
(6) Form rods exposed 12" to 18" bent upstream.
(7) Dry patches in blocks 40-1 and J worn appreciably.
(8) Velocity measuring piers gone on J block brass plate displaced (found in bucket)
NOTE
This drawing indicates the conditions existing in the spillway bucket as of March 1943. Data obtained from inspections made at later dates are available for inspection at the offices of the Bureau of Reclamation, Coulee Dam, Washington.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT-WASHINGTON
GRAND COULEE DAM
RESULTS OF
SPILLWAY BUCKET INSPECTION
MARCH 1943
DRAWN L.V.D.-O.J.R. SUBMITTED
TRACED C.W.Z. RECOMMENDED
CHECKED C.W.S.-R.K.T. APPROVED
A-3610-1
COULEE DAM, WASH. APRIL 7, 1943
222-D-7822

FIGURE



NOTE

This drawing indicates the conditions existing in the spillway bucket as of March 1943. Data obtained from inspections made at later dates are available for inspection at the offices of the Bureau of Reclamation, Coulee Dam, Washington.

Figure 4. Erosion of Spillway Bucket--Grand Coulee Dam--Inspection March 1943.

Part of Drawing 222-D-7822 Blown up.

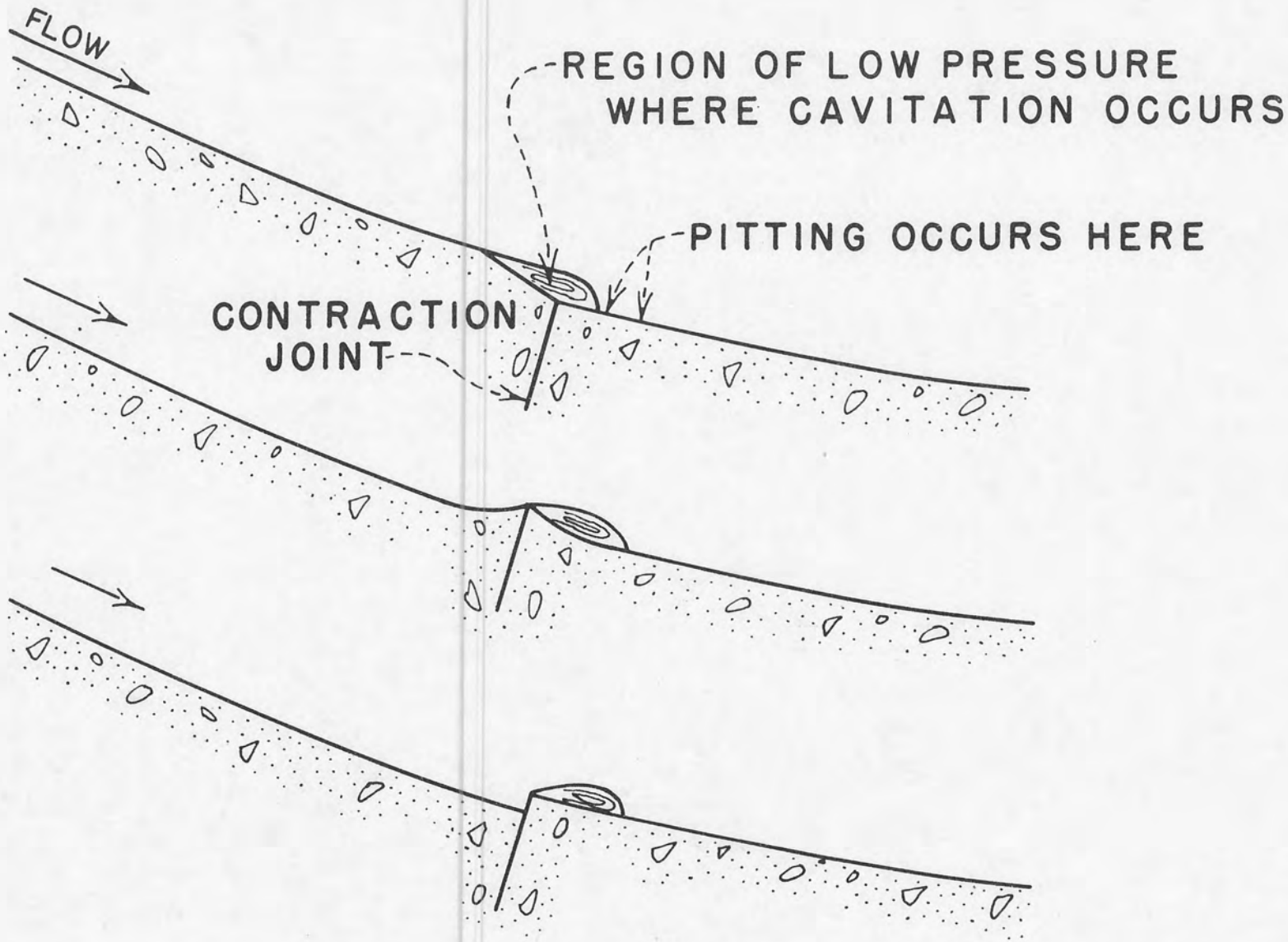


FIGURE 5 COMMON MISALIGNMENTS INDUCING CAVITATION

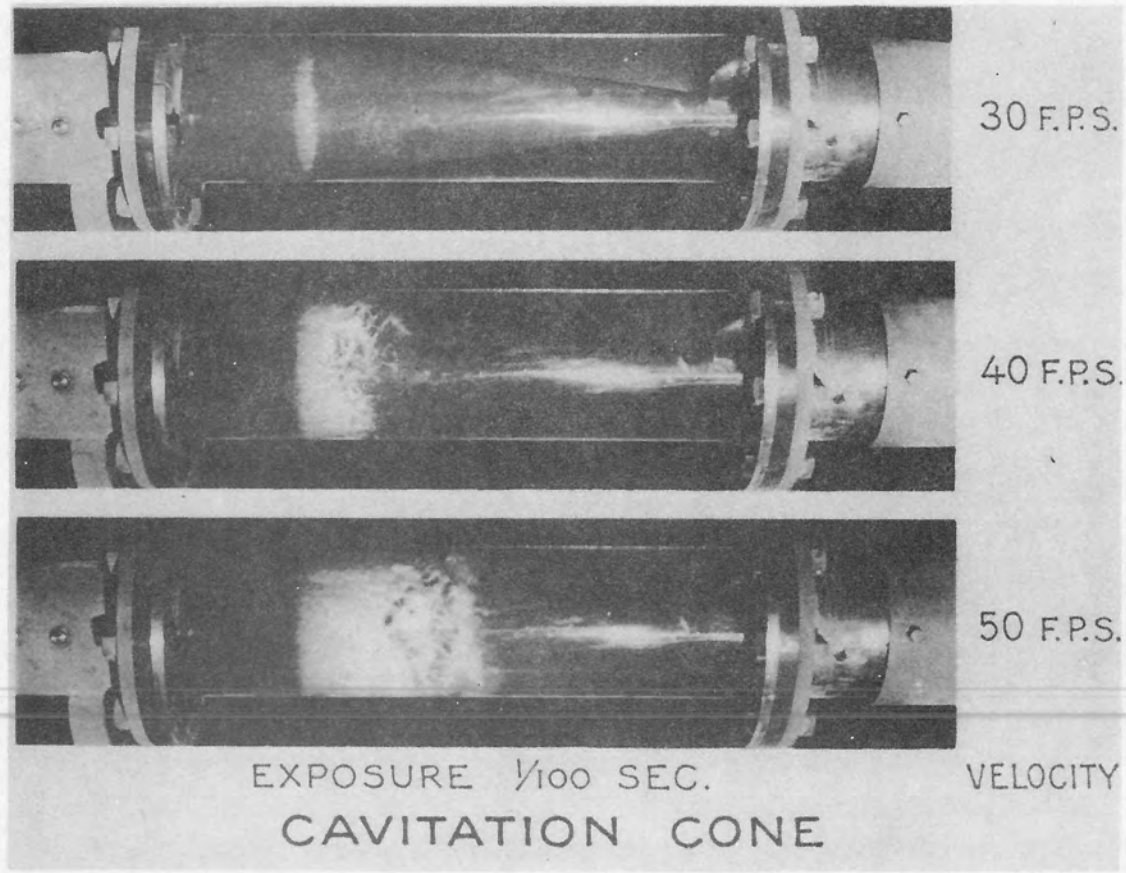


Figure 6. Appearance of Cavitation.

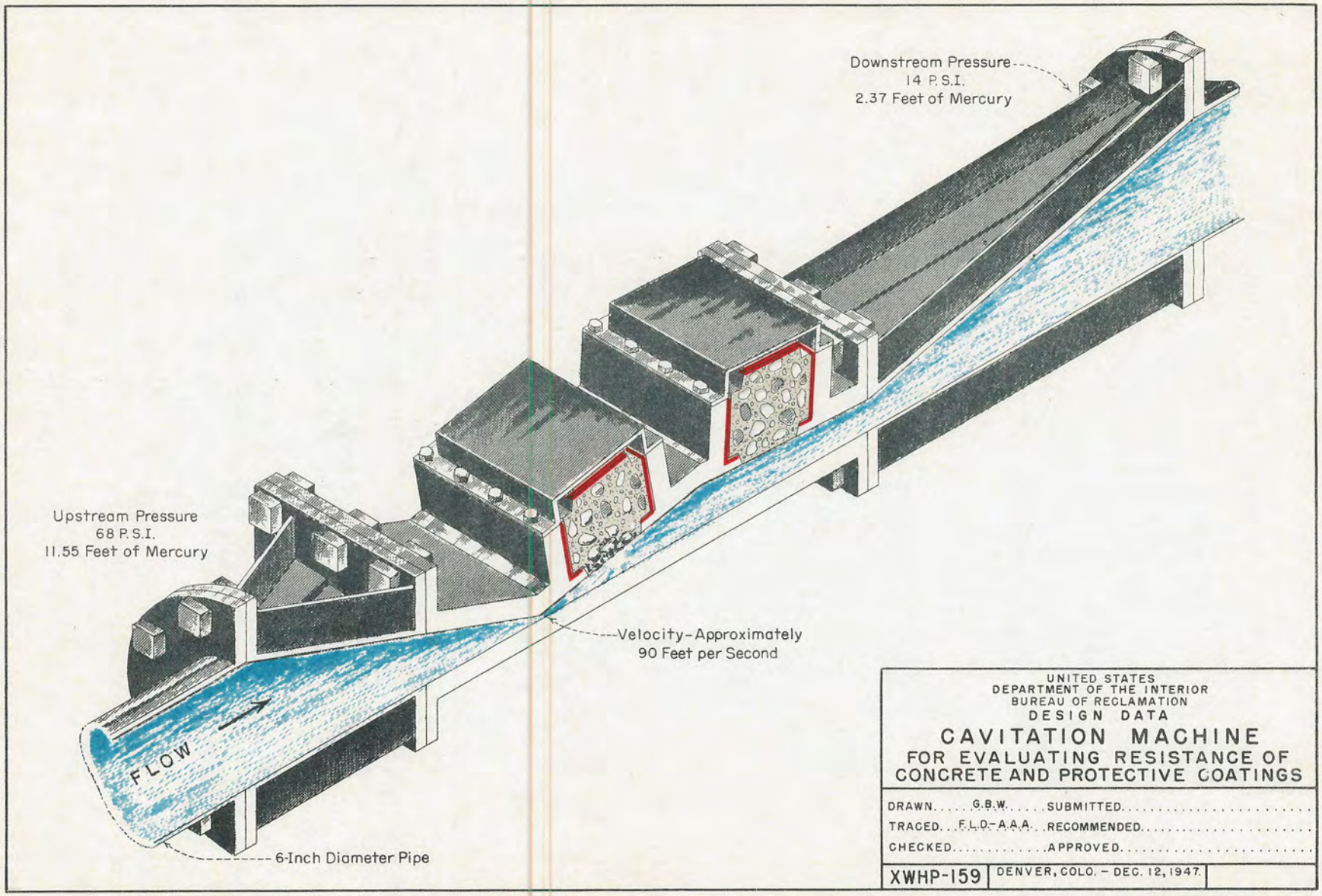

Downstream Pressure
14 P.S.I.
2.37 Feet of Mercury
Upstream Pressure
68 P.S.I.
11.55 Feet of Mercury
Velocity-Approximately
90 Feet per Second
FLOW
6-Inch Diameter Pipe
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DESIGN DATA
CAVITATION MACHINE
FOR EVALUATING RESISTANCE OF
CONCRETE AND PROTECTIVE COATINGS
DRAWN G.B.W. SUBMITTED
TRACED F.L.D.-A.A.A. RECOMMENDED
CHECKED APPROVED
XWHP-159
DENVER, COLO. - DEC. 12, 1947.

Figure 7.

Figure 8. Cavitation-erosion of concrete specimens.

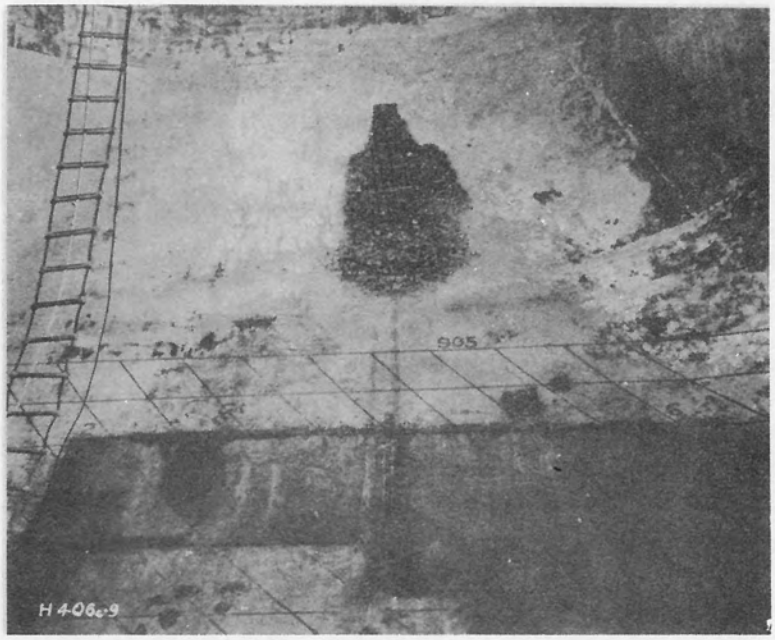


Figure 9. Erosion caused by operation of temporary needle valve in draft tube--Grand Coulee Dam.

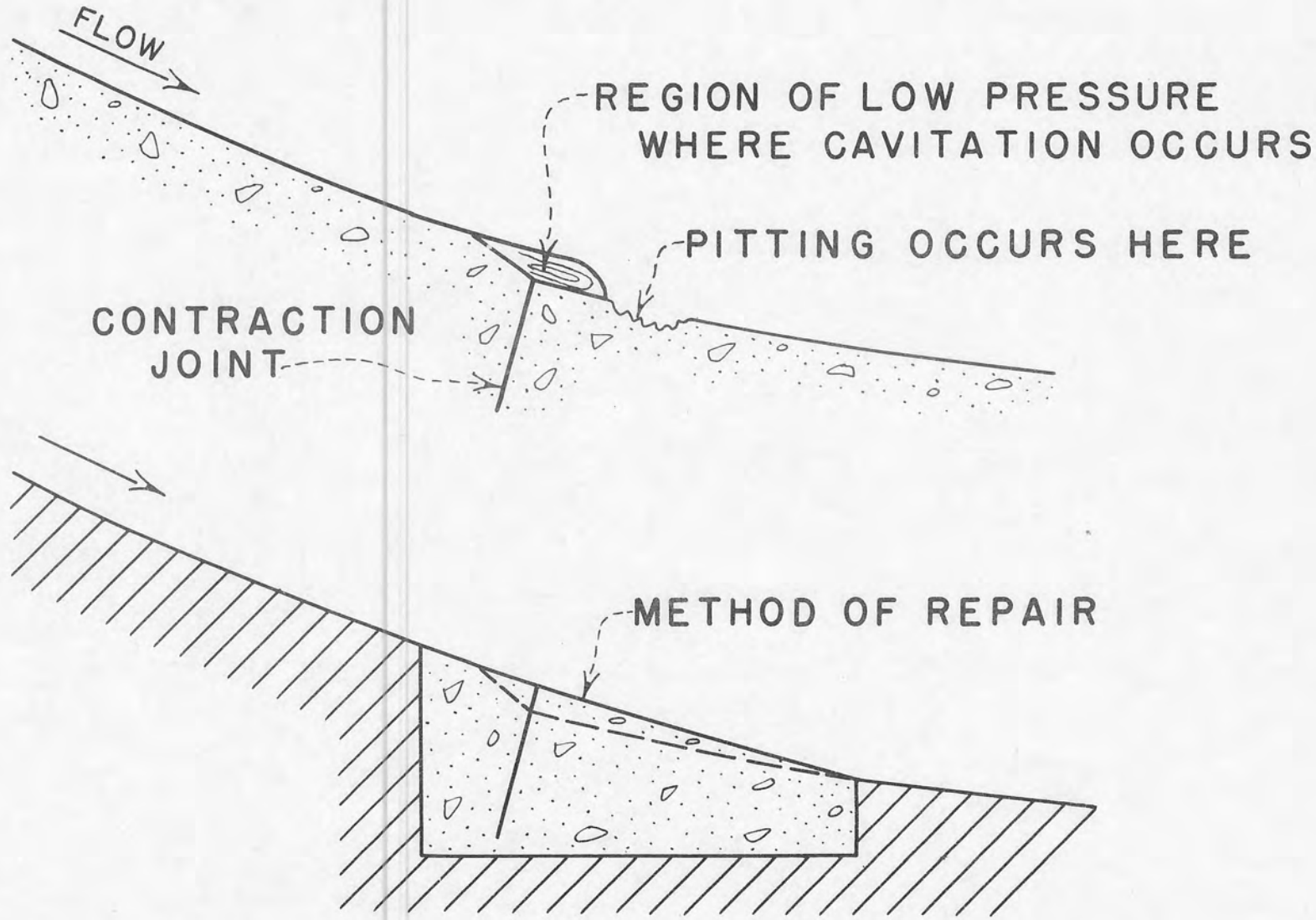


FIGURE 10 JOINT MISALIGNMENT AND REPAIR METHOD OF DRAFT TUBE AT GRAND COULEE DAM

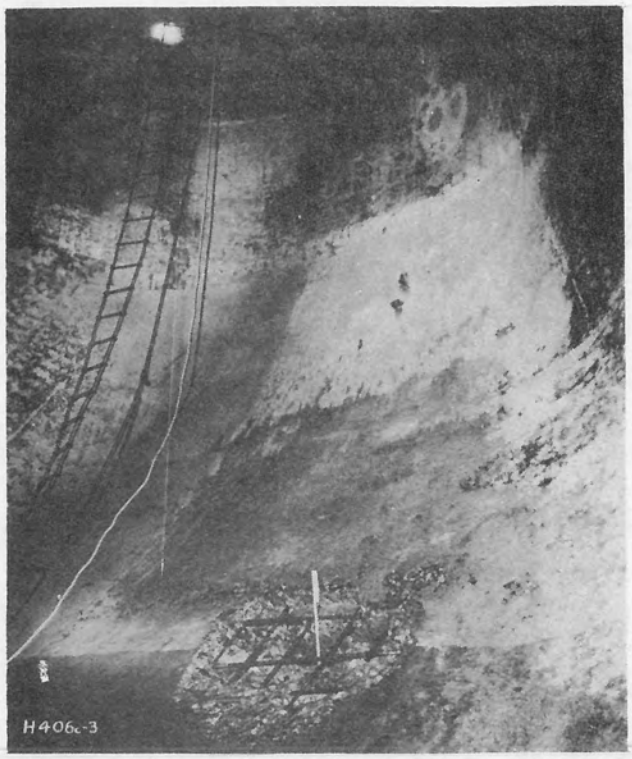


Figure 11. Repaired area (~~lower~~ upper portion of photograph) shows no damage by subsequent operations. Loss of patch (upper portion of photograph) caused new erosion. lower