Designed - in roughness can protect cavitation - prone surfaces

Designing Spillways to Prevent Cavitation Damage

by Kathleen H. Frizell and Brent W. Mefford

Twice, the steeply sloping tunnel spillways at the U.S. Bureau of Reclamation's Hoover Dam in Boulder City, Nevada, have experienced cavitation damage, once in 1941 and again in 1983. In the interim, many perceptions have changed about the causes of cavitation.

The first cavitation damage at Hoover Dam and experiences elsewhere prompted researchers to tighten flow-surface tolerance requirements. As a result, hydraulic structures have been built for years with the idea that high-velocity flow surfaces must be perfectly aligned, with only minimal offsets permitted. These cavitation-prevention requirements have made structures extremely difficult to construct and maintain.

Research advances in cavitation abatement, encouraged by Reclamation's need to reduce flow-surface construction and maintenance costs, have led to new concepts in both spillway design and concrete surface specifications.

These concepts include shifting analysis of a structure's cavitation potential, required surface tolerance, surface construction, and maintenance issues to the forefront of the design process. This assures that cavitation problems will be recognized early in the design process, thus prompting the use of aeration devices or consideration of alternative spillway designs.

In 1987, a study team was set up within Reclamation to review and revise concrete specifications for the construction and maintenance of hydraulic structures. The impetus was recurring problems in meeting and maintaining the strict surface-tolerance specifications on spillways and outlet works. Reclamation guidelines for concrete[1] required special stone finishes for flow surfaces subjected to velocities of 40 ft/s (12 m/s) or greater. The guidelines for a stone finish read:[1]

> The surface that is to receive the special finish should be thoroughly cleaned with high-velocity water jets to remove loose particles and foreign material and then brought to a surface-dry condition, as indicated by the absence of glistening-free water, by clean air jet. A plastic mortar consisting of 1 part cement and 1½ parts of sand, that will pass a No. 16 screen should be rubbed over the surface and handstoned with a No. 60 grit carborundum stone until the surface is evenly filled. Stoning should continue until the new material becomes rather hard. After curing for 7 days, the surface should be made smooth and even by use of a No. 50 or No. 60 grit carborundum stone or grinding wheel.

Special concrete tolerances for high-velocity flow surfaces, based on cavitation experience, were incorporated into construction specifications early in Reclamation's history. Cavitation damage to prototype structures was often attributed to isolated offsets or irregularities in the flow surface. Until the idea of aerating the flow to prevent cavitation damage was tested, the pri-

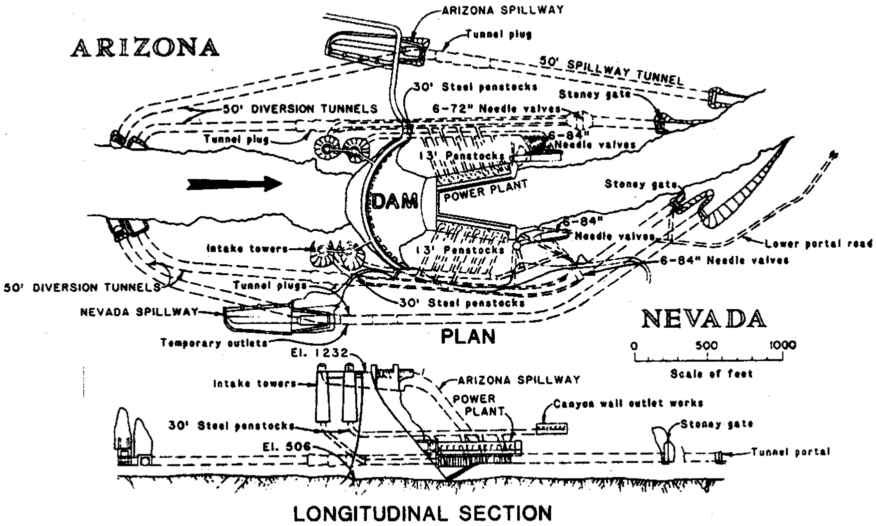

Fig. 1 — Overall schematic of Hoover Dam.

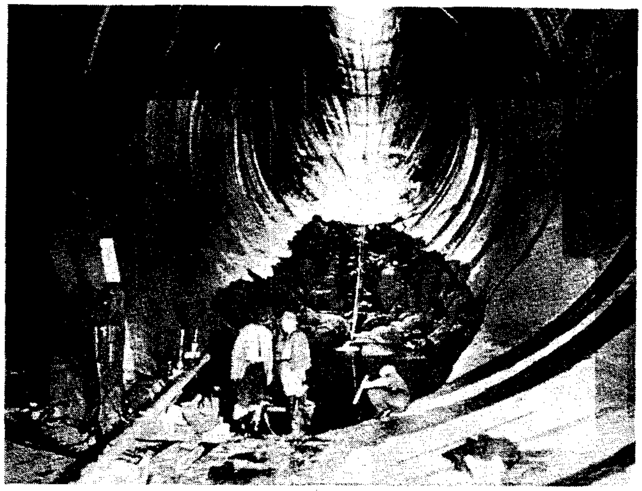

Fig. 2 — 1941 cavitation damage in the Arizona spillway tunnel at Hoover Dam.

Fig. 3 — 1983 cavitation damage in the Nevada spillway at Hoover Dam.

mary method of preventing cavitation damage was to eliminate the cause by decreasing the allowable size of surface irregularities.

Experience and time have since shown that efforts should not be geared to constructing smooth flow surfaces, but rather to improving spillway designs to prevent cavitation damage. Although there are many factors involved in choosing a spillway design, it is ironic that one solution to preventing cavitation problems may lie in designing large uniform roughnesses in the form of steps on a spillway face.

Cavitation at Hoover Dam

Hoover Dam, completed in 1935, has a hydraulic height of 576 ft (175.6 m) and 50 ft (15.24 m) diameter tunnels passing through each abutment, referred to as the Arizona and Nevada spillways (Fig. 1).

The Arizona spillway was first operated for four months in 1941 at an average discharge of 13,555 ft^3/s (383.8 m^3/s). Following operation, inspection revealed a hole, approximately 30 ft wide, 115 ft long and 45 ft deep (9.14 x 35 x 13.7 m), eroded through the concrete lining of the tunnel invert (Fig. 2).

The inspection revealed a misalignment of the tunnel invert in the form of a hump a few feet upstream of the damaged area. This misalignment was generally accepted as the source of the cavitation that initiated the damage. A subsequent Reclamation report[2] stated:

> It appears therefore, that the most effective means of preventing a recurrence of the 1941 incident would be to maintain the tunnel lining as smooth as possible. As an additional precaution Mr. J. L. Savage, Chief Design Engineer, suggested that some means be devised to introduce air into the spillway flow with the expectation that the air first, would act as a cushion between the high-velocity water and the tunnel lining, and secondly, that the same air would aid in relieving any subatmospheric pressures which may occur along the surface of the tunnel invert.

Although aeration would be studied, the immediate repair of the damage focused on reconstructing a smooth flow surface. The eroded areas were repaired with concrete.[3] After curing, the surface was stoned, then ground smooth with a small terrazzo machine.

During the repair, the entire tunnel invert was inspected to identify all misalignments and irregularities in the flow surface. Several additional misalignments, small rock pockets, and calcite buildups were identified between the tunnel entrance and the end of the vertical elbow. The invert surface was eroded downstream of the elbow, leaving a nearly uniformly rough surface. This section of tunnel was assumed to have been damaged prior to spillway operation when the tunnel section downstream of the elbow had also been used for diversion flows during dam construction. Surface erosion due to sediment in the flow and not cavitation was the probable cause for the uniformity of the damage.

Areas out of tolerance upstream of the elbow were repaired by patching, followed by grinding if low, or by chipping, bushing, then grinding if high. The first 200 ft (60.96 m) of the rough invert downstream of the elbow, was bushed, sand blasted, and stoned smooth with mortar. No repairs were made beyond 200 ft (60.96 m) downstream of the elbow. A similar inspection and repair of the invert surface was then carried out in the Nevada spillway.

A research study was conducted in 1945 to investigate the design of aeration devices for the Hoover spillway tunnels. Aerators were designed and tested at locations near the tunnel entrance and start of the vertical elbow. Air concentration was measured along the elbow invert to evaluate aerator performance. The study concluded that the air induced into the flow did not remain along the invert in sufficient quantities to ensure cavitation protection of the invert along its entire length.

Although aeration of the flow continued to be studied, these and other experiences with cavitation damage due to surface roughnesses formed the basis of concrete specifications for high-velocity flows. For nearly four decades after the repairs, there were no significant flows down either tunnel at Hoover. During this time, the ability to

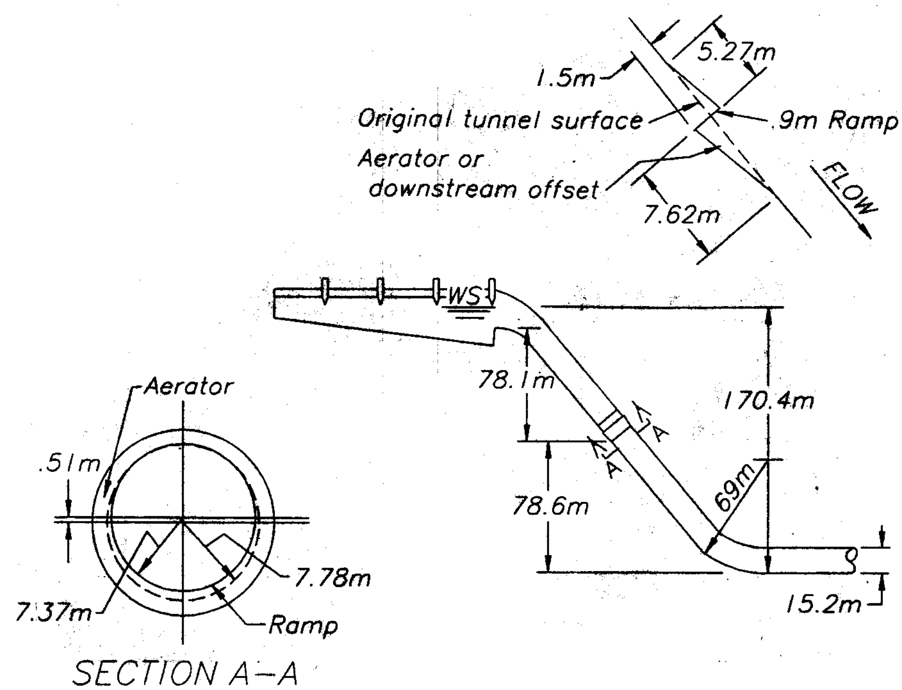

Fig. 4 — Aeration device for Hoover Dam tunnel spillways.

analyze, predict, and mitigate cavitation greatly increased through laboratory research and a growing prototype experience base.

Predicting cavitation damage

Developing analytic methods to predict cavitation in flow was of major importance. There is a critical combination of flow velocity, flow pressure, and vapor pressure of the water that determines the conditions for cavitation to begin. A relationship between pressure and velocity known as the cavitation index, or flow sigma, is widely used to predict cavitation:[4]

$$\sigma = \frac{P_o - P_v}{\frac{1}{2} \rho V^2}$$

where P_o = reference pressure; P_v = vapor pressure of liquid; ρ = fluid density; and V = flow velocity.

The cavitation index decreases as the velocity increases or the reference pressure approaches that of the vapor pressure of the fluid. Reclamation has developed PC-based computer programs for analyzing the cavitation potential of hydraulic structures.[4] Cavitation potential is determined by comparing the computed cavitation index at the boundary to available data. These flow-analysis programs enable new spillway alignments to be evaluated quickly for cavitation potential or required surface repairs to be determined for existing spillways.

Predicting cavitation inception is much easier than predicting cavitation damage. Laboratory tests provide data relating the cavitation index to the onset of cavitation. These values are very conservative in terms of predicting damage. The severity of damage that may be expected is related both to intensity of cavitation and time of exposure. By comparing these factors for many tunnel spillway structures, Falvey[4] found that if the flow cavitation index does not fall below 0.20, cavitation damage seldom occurs.

During the high-water years of the early 1980s in the Colorado River basin, Hoover Dam's spillways were reanalyzed for cavitation potential. Based on geometry and flow hydraulics, a minimum flow sigma of 0.11 was possible at a discharge of 15,000 ft^3/s (424.75 m^3/s). It was determined that without aeration the tunnels would likely experience some cavitation damage in spite of previous surface repairs. Also, the rough invert surface downstream of the elbow, which was not repaired in 1941, would probably cause cavitation at flows greater than 20,000 ft^3/s (566.3 m^3/s).

In 1983, major spring runoff down the Colorado River caused Hoover Dam to pass water through its spillways. With releases of about 14,000 ft^3/s (396.4 m^3/s) significant damage occurred in the elbow of the Nevada spillway tunnel (Fig. 3) and minor damage in the Arizona tunnel. Inspection of the tunnels after the damage revealed extensive calcite deposits, some 2 in. (50.8 mm) thick, and joint offsets within the tunnels. The concrete surface had obviously roughened significantly with age. No additional damage was noted downstream of the tunnel elbows where the rough invert had not been repaired in 1941.

Aeration device

Extensive hydraulic model studies were undertaken to investigate adding aeration devices to prevent further cavitation damage at Hoover and several other of Reclamation's tunnel spillways. As mentioned earlier, attempts had been made previously to protect structures from cavitation by providing air to the flow surfaces. Advances in technology now indicated a properly located and dimensioned aerator would significantly reduce the potential for cavitation damage at Hoover Dam.[5] The aerator designed for the Hoover Dam spillways is shown in Fig. 4.

The aerator was located in the tunnel based upon the point at which the cavitation index of the flow dropped to 0.2. The geometry was developed through a model study which determined the ramp or deflector size, size and shape of the aerator, and the geometry of the downstream offset.

Operation of the aerator at 20,000 ft^3/s (566.3 m^3/s) is shown in Fig. 5. The ramp lifts the jet from the invert of the tunnel. Air then is drawn from the free water surface around the jet through the air slot

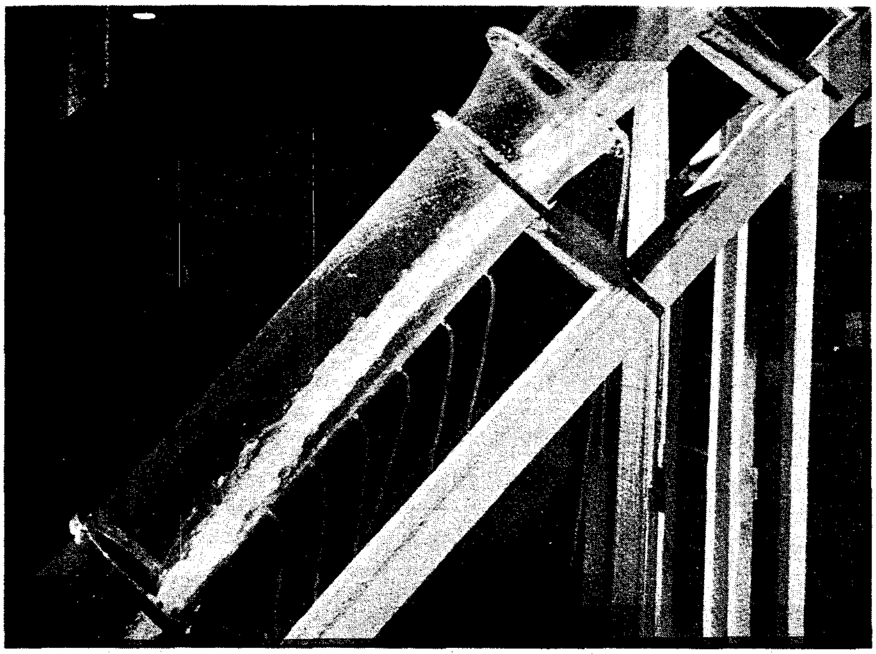

Fig. 5 — Aerator operating at 20,000 ft^3/s (566.3 m^3/s) in the hydraulic model of Hoover Dam.

or aerator. The offset downstream prevented water from filling the air groove during large free-flow discharges. It was determined that only one aerator was needed at Hoover Dam. Further details of aerator design are detailed in Reference 4.

A prototype test of the effectiveness of a similar air slot was conducted at Glen Canyon Dam just prior to installing the air slot at Hoover. An area of eroded concrete near the elbow of the Glen Canyon tunnel spillway was not repaired prior to the testing.[6] The successful outcome of these tests and other experiences with aerators provided a strong basis for relying on aeration of the Hoover spillway flow, instead of surface tolerance, as the main defense against cavitation damage.

For Hoover, the decision was made to relax surface tolerances and leave unrepaired many surface roughnesses that exceeded previous surface specifications. The lessons learned through years of experience and research with structures like Hoover demonstrated the need to update Reclamation's concrete surface specifications, standardize the design process for smooth spillways with high-velocity flow, and to develop innovative spillway designs that are less susceptible to damage by cavitation.

Surface tolerance specifications

Reclamation set up a team of engineers to review the design and concrete tolerance specification process for traditional smooth-surfaced hydraulic structures. This team recommended that flow surface tolerances (in the direction of flow) be treated separately from surface finishes and be limited to three levels, as presented in Table 1.

Surface roughnesses are treated differently by the tolerance specifications depending on whether they are abrupt or gradual in nature. The abrupt roughness tolerance specifies a surface offset dimension below which any type of roughness (abrupt or gradual) is acceptable. Roughnesses which exceed the abrupt tolerance limits are evaluated against the gradual roughness tolerances.

The gradual roughness tolerance is based on the maximum slope (height:length) of the roughness. An acceptable gradual roughness is defined as a roughness with a maximum slope that is less than specified by the gradual tolerance. The more gradually a flow surface varies, the less likely it is to cause cavitation of the flow. Therefore, the maximum height or depth of a gradual roughness is not important, only how quickly the flow must change direction. Structure tolerances (i.e., line, grade, etc.) control the maximum allowable offset of gradual roughnesses.

These surface tolerances have been incorporated into Reclamation's design process for hydraulic structures. A structure's required flow surface tolerance is determined by the minimum cavitation index of the flow, shown in Table 2. Experience has shown that cavitation damage may be prevented when these guidelines are followed. A minimum cavitation index of between 0.2 and 0.1 requires that special aeration devices, such as air slots, be included in the design. Any structure with a cavitation index of less than 0.1 must be redesigned to reduce its cavitation potential. Different spillway concepts or realignment of the preliminary design should be considered for any structure with a flow sigma less than 0.2. The search for better spillway designs for high-head dams often includes stepped spillways.

Stepped spillways

Stepped spillways have become a very popular method for such dam releases as those at Reclamation's Upper Stillwater Dam[7] because their compatibility with roller-compacted concrete construction techniques produces low additional cost for the spillway. Traditional types of smooth spillways with steep chutes and expensive energy dissipators are still being used with roller-compacted concrete dams,[8] but cavitation is still a concern with these structures. Designers have been reluctant to use stepped spillways because of the complex flow characteristics associated with them.

Several site-specific studies of steeply sloping stepped spillways have been conducted.[9] With each study, the upper limits of unit discharge have been extended — q = 154 ft^3/s (14.3 m^3/s) for Milltown Hill Dam[10] — and our knowledge of the flow hydraulics have increased. However, there is a lack of general design guidelines for their use.

Reclamation's initial experience with stepped spillways on high concrete dams came largely from hydraulic model studies conducted for Upper Stillwater Dam.[7] One objective of the model studies was to determine if cavitation would be a problem. Numerical analysis of a smooth spillway of similar geometry predicted a cavitation index of 0.2 would occur at high discharges. Extensive tests were conducted to observe the flow field and measure pressures and velocities. The research found no indication that cavitation would occur for the stepped geometry.

Reclamation is currently conducting extensive research on the hydraulic design of stepped spillways for high dams. The formation of cavitation due to the step geometry is still a concern. Although the complex flow that develops on a very rough surface such as steps prevents easy analysis of cavitation potential, research has shown that steps offer several positive aspects for preventing cavitation damage:

- Research results[11] suggest that a uniformly rough surface can have a lower cavitation potential than an isolated roughness of the same geometry due to reduced velocities and wake effects.
- Large surface roughnesses promote self aeration of the flow.
- Steps form large offsets away from the flow direction. This inhibits cavitation from residing on the boundary.
- Step geometries can be designed to prevent subatmospheric pressures on the surface.

Reclamation currently has an extensive research program underway to further study the characteristics and benefits of stepped spillways. The objective of the research is to develop design criteria to determine optimum step geometry based on hydraulic forces and energy dissipation. This research also will provide further data to improve the ability to predict the cavitation characteristics of uniform steps.

Test facility

The present laboratory facility consists of two sloping flumes. One flume is designed for studying 2H:1V sloped stepped spillways typical of high embankment dams. The second flume, sloping at 0.8H:1V, is used to study concrete dam stepped spillways. The flume facilities are used to study the flow hydraulics of different step geometries and the effects of increasing depth of flow on the steps.

Initial investigations — Initial investigations have concentrated on studying the hydraulics of step designs on the 2H:1V sloping flume. They have consisted of determining discharge capacity, flow depths, pressure profiles on the face of the steps, and velocity profiles, and documenting visual flow characteristics with increasing flow depth. Data are recorded for scaled overtopping heads (12:1 geometric scale) of 5, 10, 15, 20, 25, and 30 ft (1.52, 3.04, 4.56, 6.10, 7.62, and 9.14 m). The flow down the stepped face for 5 ft (1.52 m) of overtopping head is shown in an overall view in Fig. 6 and close up in Fig. 7.

Pressure measurements — Pressures were measured on both the vertical and horizontal faces of the steps. Three measurement stations are located along the flume slope for gathering pressure profiles on the face of the steps. The upper station (Steps 15 and 16) is located 30 ft (9.14 m) below the crest, the middle station (Steps 47 and 48) is 94 ft (28.65 m) down, and the lower station (Steps 79 and 80), near the toe, is 158 ft (48.16 m) down. At each station two steps are instrumented, each with 11 piezometer taps, for a total of 22 taps per station and 66 overall. The mean pressure from each piezometer tap was recorded with an IBM-compatible computer. The same computer was then used to plot the resulting pressure profiles over the steps at each station.

The pressure profiles indicate visual characteristics of the flow very well. The profiles are plotted over the two steps representing the upper, middle, and lower (toe) stations for the appropriate overtopping head (Fig. 8 and 9). Each piezometer tap location (No. 1 through 22) is indicated on the steps. The pressure profiles indicate the jet impact on the downstream end of the step tread (high pressure) and an area of reduced pressure in the offset below the pitch line of the steps. An eddy forms in the offset area. For the step geometry, if cavitation forms, it is most likely to occur in the fluid shear zone near the top of the eddy, well off the boundary.

Also on the graph is a plot of the approximate flow depth over the stepped spillway. The depth varied little down the stepped face and is shown as a single line regardless of measurement station. Comparison of this flow-depth measurement with the pressure profiles clearly shows the different pressure zones associated with the jet impact and the return eddy. The eddy rotation provides significant energy dissipation as the flow passes down the steps.

Conclusions and recommendations

The following conclusions can be drawn from these investigations:

- Constructing smooth concrete surfaces on high-velocity spillways has not prevented cavitation damage in many instances as natural roughening of surfaces with age is difficult to monitor and control.
- Concrete surface specifications for many existing high-velocity spillways do not sufficiently reflect construction and maintenance limitations.
- Research on stepped spillways suggests that they may be viable alternatives to cavitation-prone smooth spillways.

Based on these conclusions, the following recommendations can be made:

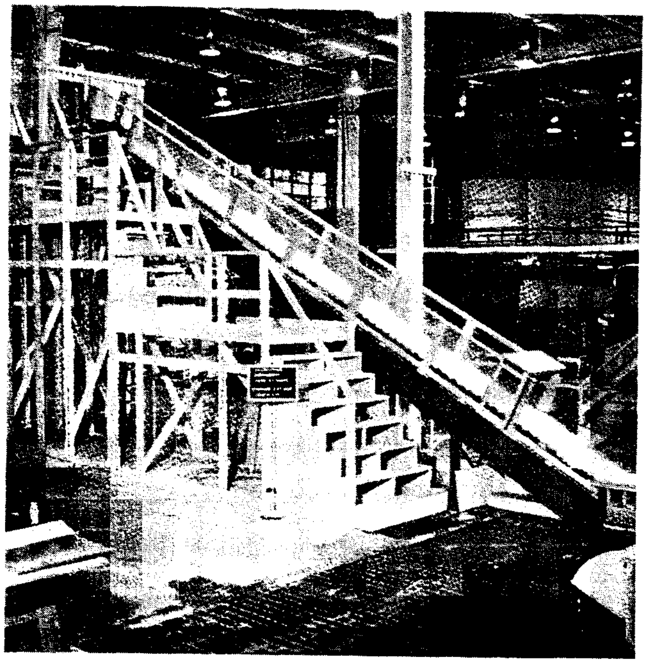

Fig. 6 — Overall view of overtopping embankment flume facility.

Fig. 7 — Close-up of flow down stepped spillway face near the crest: $H = 5$ ft (1.52 m); $q = 33.96$ ft³/s (3.15 m³/s).

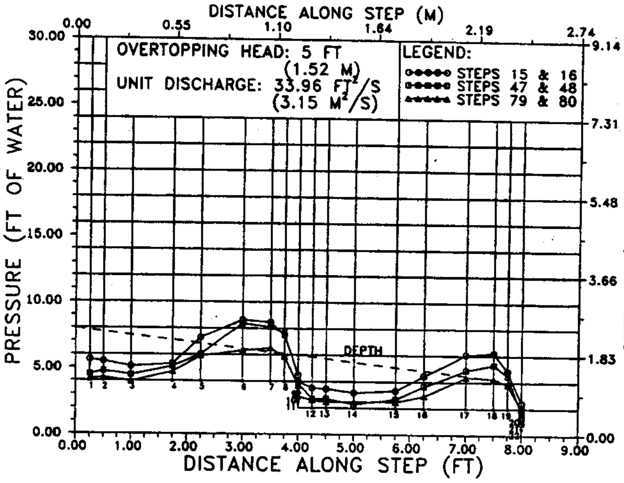

Fig. 8 — Pressure profiles of stepped spillway face at three stations along slope: $H = 5$ ft (1.52 m); $q = 33.96$ ft³/s (3.15 m³/s).

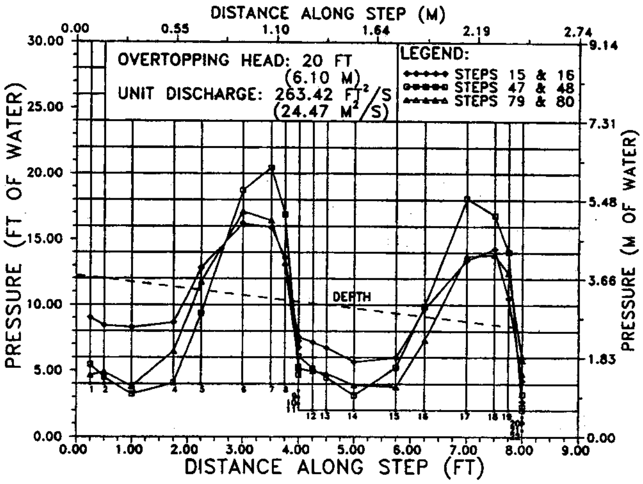

Fig. 9 — Pressure profiles of stepped spillway face at three stations along slope: $H = 20$ ft (6.1 m); $q = 263.42$ ft³/s (24.5 m³/s).

Table 1 — Concrete surface tolerances

Tolerance	Roughness type	
	Abrupt offset, in.	Gradual slope
T1	1.0 (25 mm)	1:4
T2	0.5 (12 mm)	1:8
T3	0.25 (6 mm)	1:16

Table 2 — Specification of flow surface tolerance

Cavitation index of flow	Tolerance without aeration	Tolerance with aeration
>0.60	T1	T1
0.40 to 0.60	T2	T1
0.20 to 0.40	T3	T1
0.10 to 0.20	revise the design	T2
<0.10	revise the design	revise the design

• Surface tolerances alone should not be relied upon to prevent cavitation damage to a spillway structure.

• Consideration must be given to the cavitation potential of a structure early in the design process. Preliminary designs must be analyzed using current spillway-flow computer models which compute flow-cavitation indices as a function of stationing and discharge.

• Design alternatives, including stepped spillways, should be considered when the cavitation indices are less than 0.2.

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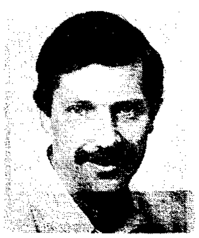

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Cover

ACI's 68th president is I. Leon Glassgold who assumed the post at the recent convention in Boston, Mass. In this photo, Glassgold, president of Masonry Resurfacing and Construction Co., Inc., poses at the firm's storage yard in Baltimore, Md. A concrete pump and other construction equipment can be seen in the background. (See article starting on page 13.)

(Photo by Don Willett, Baltimore, Md.)

Discussion is welcomed for all material published in this issue. To facilitate expeditious handling of committee reports and standards, observe dates found with those items. Discussion of other items will appear in the December 1991 issue if received by August 1, 1991. Discussion of all material received after specified dates will be considered individually for publication or private response.

Features

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Annual Index is published in each February issue.