U. S. Department of Agriculture
Soil Conservation Service
Engineering Division
Design Branch

January 19, 1973

DESIGN NOTE NO. 14*

Subject: Cavitation Potential at an Irregularity

Introduction

The purpose of this design note is to discuss the sizes of irregularities[1] at incipient cavitation and treatments for irregularities which exceed these sizes. The design note is based on the paper, "Construction Finishes and High-Velocity Flow," by Mr. James W. Ball, published in the Journal of the Construction Division, Proceedings of ASCE, September, 1963.

Irregularities in flow surfaces of hydraulic structures will cause erosion of these flow surfaces if the velocity is sufficiently high (Figure 1). The erosive damage inflicted on the flow surface is caused by a phenomenon known as "cavitation." During cavitation, small water vapor cavities (bubbles) form in a localized zone of negative pressure and are transported downstream by the water into a zone of higher pressure where each vapor cavity collapses (condenses). The collapsing of a cavity causes an extremely high localized pressure at the point of collapse. Those vapor cavities collapsing near or adjacent to the flow surface generate a rapidly fluctuating pressure on the surface which causes damage to that surface.

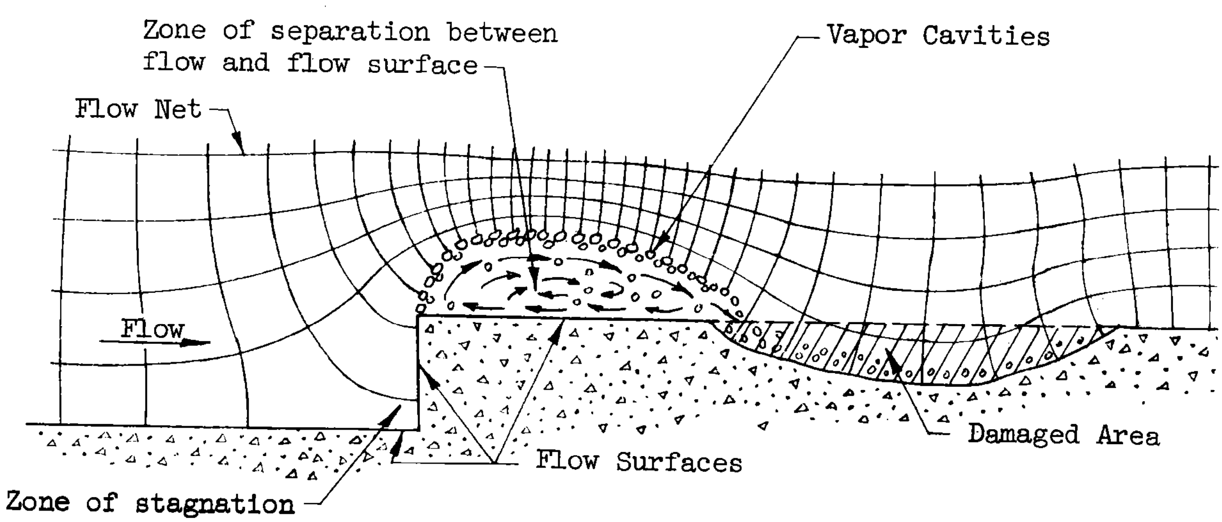

Figure 1. Definition Sketch

[1]The term "offset" is often used in literature to represent the irregularities shown in Figures 2 and 3. The term "offset" is not appropriate to describe other types of flow surface irregularities such as voids, transverse grooves, and roughened surfaces (Figure 4). This design note uses the term "irregularity" to represent all types of irregularities and offsets occurring in constructed flow surfaces.

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Cavitation is initiated when the localized pressure in the water is reduced to the vapor pressure[1] of the water. The reduction to vapor pressure can be caused by a flow surface irregularity when the flow velocity is sufficiently high. The irregularity causes separation of the flow from the flow surface. The greater the flow velocity, the larger the zone of separation between the flow and the flow surface. An increase in velocity will increase both the rate and the extent of damage. The condition of incipient cavitation caused by an irregularity is a relation of pressure, velocity, and the characteristics of the irregularity.

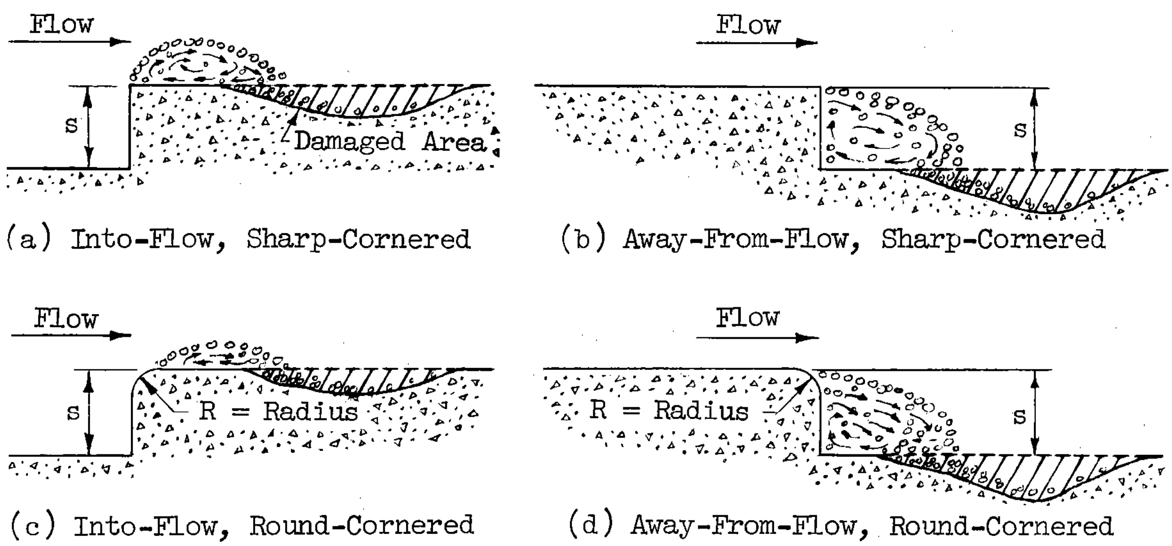


Figure 2. Sharp- and Round-Cornered Irregularities

Cavitation Potential (A relation of pressure, velocity, and irregularity)

Cavitation potential, i.e., the likelihood of cavitation occurring, increases as the size of an irregularity increases, the flow velocity increases, or the water pressure decreases. The water pressure is the pressure that would exist at the location of the irregularity if the irregularity were not present. The higher the water pressure, the higher the velocity required to reduce the localized pressure to vapor pressure. Cavitation potential also depends on the shape of the irregularity and the orientation of the irregularity to the direction of flow. Although an irregularity may be oriented at any angle with respect to the direction of flow, it has the greatest cavitation potential when perpendicular to flow.

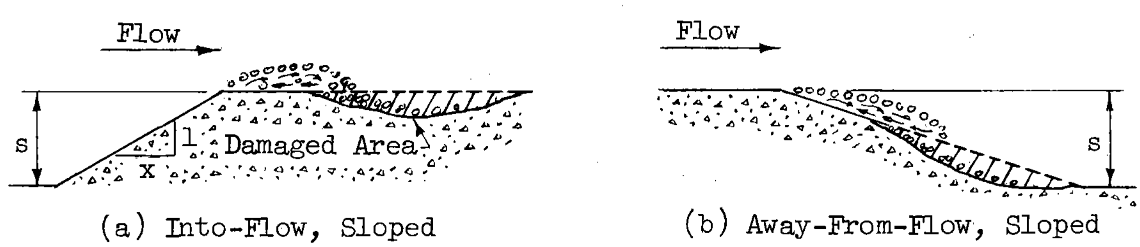


Figure 3. Sloped Irregularities

[1] See TR-4 and ES-110

Experimental incipient cavitation data is available for three shapes of irregularity, namely, sharp-cornered, round-cornered, and sloped. An irregularity either projects into the flow (Figure 2a) or recedes away from the flow (Figure 2b). The data, plotted in ES-196, is for into-flow irregularities which are oriented perpendicular to flow. The reference paper does not give definite data for voids, transverse grooves, roughened surfaces (Figure 4), or away-from-flow irregularities.

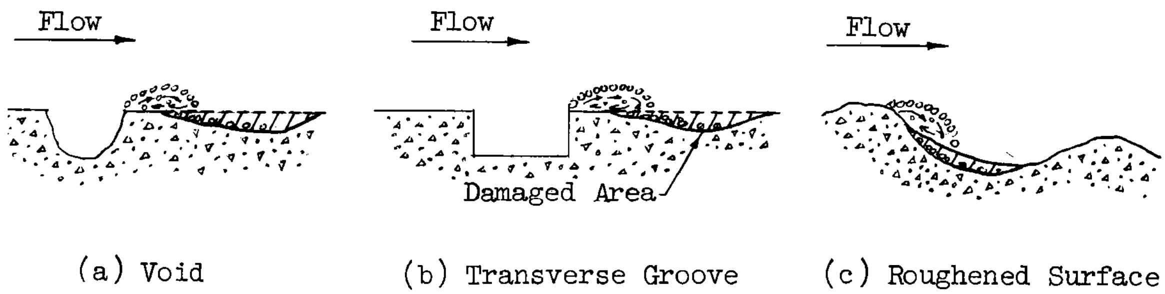


Figure 4. Flow Surface Irregularities

An away-from-flow, sharp-cornered irregularity has a smaller cavitation potential than an into-flow, sharp-cornered irregularity. Therefore, use Sheet 1 of ES-196 to investigate the cavitation potential of an into-flow or away-from-flow, sharp-cornered irregularity. Sheet 2 of ES-196 is for the investigation of the cavitation potential of an into-flow, round-cornered irregularity (Figure 2c). The reference paper is unclear concerning the relative cavitation potential of an away-from-flow, round-cornered irregularity versus an into-flow, round-cornered irregularity. Therefore, it is suggested that Sheet 1 of ES-196 be used to investigate the cavitation potential of an away-from-flow, round-cornered irregularity. The reference paper indicates that Sheet 3 of ES-196 can be used to investigate the cavitation potential of an away-from-flow or an into-flow sloped irregularity. Observe that the 90° line on Sheet 3 approximately corresponds to a sharp-cornered irregularity with a projection of 1/4 inch (see Sheet 1). Therefore, the suitability of the curves on Sheet 3 for projections larger than 1/4 inch is unknown.

Flow past transverse grooves results in a decrease in water pressure on the flow surface downstream from the groove. One of the variables related to this decrease in pressure is the ratio of width to depth of groove. Another variable is the flow surface geometry downstream from the groove. For information on cavitation potential of transverse grooves, refer to literature pertaining to cavitation caused by gate slots.

Treatments of Irregularities

ES-196 may be used to determine when cavitation may occur for a specific irregularity and set of velocity and pressure values. If an investigation indicates the cavitation potential must be reduced, then treatment of the irregularity is required.

The cavitation potential of an into-flow irregularity may be reduced by

1. rounding the corner or increasing the radius of rounding,
2. decreasing the projection, s, or
3. flattening the slope.

The cavitation potential of an away-from-flow irregularity may be reduced by

1. decreasing the depth of irregularity, s, or
2. flattening the slope.

A void can sometimes induce cavitation. Various authorities recommend that a void be filled to form a continuous smooth surface when the flow velocity exceeds about 30 to 50 ft/sec.

General

Repairing only the area damaged by cavitation does not remove the cause of the cavitation. The irregularity must also be corrected to prevent further damage.

A longitudinal groove with smooth surfaces which are parallel to the direction of flow is not considered as an irregularity.

The graphs of ES-196 are based on

1. the average velocity at the cross-section containing the irregularity, and
2. the pressure at the irregularity.

However, if the configuration of the hydraulic structure causes the velocity at a boundary containing an irregularity to be greater than the average velocity, the larger velocity should be used to determine the cavitation potential of the irregularity. If the water pressure at a boundary containing an irregularity is reduced because of the configuration of the hydraulic structure, the reduced water pressure should be used to determine the cavitation potential of the irregularity.

Example 1

Given: Drop Inlet Spillway with no submergence at outlet

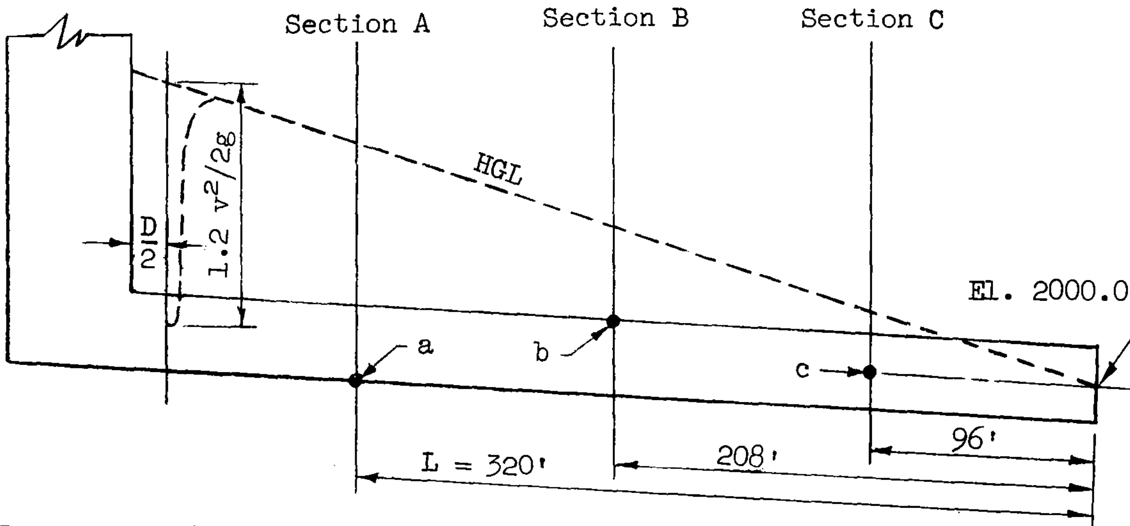
Discharge, $Q = 500$ cfs

Diameter, $D = 48$ in

Probable minimum atmospheric pressure, $h_a = 30.0$ ft (ES-110)

Roughness, $n = 0.013 \therefore K_p = 0.00493$ (ES-42, NEH-5)

Location	Elevation
a	2013.2
b	2010.5
c	2002.9



Determine: For locations a, b, and c

1. The maximum allowable projection of an into-flow, sharp-cornered irregularity.
2. The minimum allowable radius of rounding of an into-flow, round-cornered irregularity with a projection of $\frac{3}{8}$".
3. The maximum allowable slope of an away-from-flow, sloped irregularity with a depth of $\frac{1}{4}$".

Solution: Conduit area, $a_b = 12.6 \text{ ft}^2$ (48" pipe)

Velocity, $v = \frac{Q}{a_b} = \frac{500}{12.6} = 39.7$ ft/sec

Velocity head, $\frac{v^2}{2g} = \frac{(39.7)^2}{64.4} = 24.5$ ft

Determination of the elevation of the hydraulic grade line, HGL, at Sections A, B, and C.

$$(HGL)_A = 2000.0 + \frac{v^2}{2g} (L\ K_p)$$

$$= 2000.0 + 24.5\ (320)\ 0.00493 = 2038.6 \text{ ft}$$

$$(HGL)_B = 2000.0 + \frac{v^2}{2g} (L\ K_p)$$

$$= 2000.0 + 24.5\ (208)\ 0.00493 = 2025.2 \text{ ft}$$

$$(HGL)_C = 2000.0 + \frac{v^2}{2g} (L\ K_p)$$

$$= 2000.0 + 24.5\ (96)\ 0.00493 = 2011.6 \text{ ft}$$

<u>Location a</u>

Evaluation of absolute pressure at location a, $(h_{ab})_a$

$$(h_{ab})_a = (HGL)_A - \text{Elev. of location a} + h_a$$

$$(h_{ab})_a = 2038.6 - 2013.2 + 30.0 = 55.4 \text{ ft abs}$$

For a velocity, v = 39.7 ft/sec, and $(h_{ab})_a$ = 55.4 ft abs, then:

1. Maximum allowable projection of an into-flow, sharp-cornered irregularity is $\frac{5}{16}$". (Sheet 1, ES-196)
2. Minimum allowable radius of rounding of an into-flow, round-cornered irregularity with a projection of $\frac{3}{8}$" is $\frac{1}{8}$". (Sheet 2, ES-196)
3. Maximum allowable slope of an away-from-flow, sloped irregularity with a projection of $\frac{1}{4}$" is 0 : 1, i.e., 90°. (Sheet 3, ES-196)

<u>Location b</u>

Evaluation of absolute pressure at location b, $(h_{ab})_b$

$$(h_{ab})_b = (HGL)_B - \text{Elev. of location b} + h_a$$

$$(h_{ab})_b = 2025.2 - 2010.5 + 30.0 = 44.7 \text{ ft abs}$$

For a velocity, v = 39.7 ft/sec, and $(h_{ab})_b$ = 44.7 ft abs, then:

1. Maximum allowable projection of an into-flow, sharp-cornered irregularity is $\frac{3}{16}$". (Sheet 1, ES-196)
2. Minimum allowable radius of rounding of an into-flow, round-cornered irregularity with a projection of $\frac{3}{8}$" is $\frac{3}{16}$". (Sheet 2, ES-196)

3. Maximum allowable slope of an away-from-flow, sloped irregularity with a projection of $\frac{1}{4}''$ is 1 : 1. (Sheet 3, ES-196)

Location c

Evaluation of absolute pressure at location c, $(h_{ab})_c$

$$(h_{ab})_c = (HGL)_C - \text{Elev. of location c} + h_a$$

$$(h_{ab})_c = 2011.6 - 2002.9 + 30.0 = 38.7 \text{ ft abs}$$

For a velocity, v = 39.7 ft/sec, and $(h_{ab})_c$ = 38.7 ft abs, then:

1. Maximum allowable projection of an into-flow, sharp-cornered irregularity is $\frac{5}{32}''$. (Sheet 1, ES-196)
2. Minimum allowable radius of rounding of an into-flow, round-cornered irregularity with a projection of $\frac{3}{8}''$ is $\frac{1}{4}''$. (Sheet 2, ES-196)
3. Maximum allowable slope of an away-from-flow, sloped irregularity with a projection of $\frac{1}{4}''$ is 1.5 : 1. (Sheet 3, ES-196)

Comments:

1. Observe the absolute pressure at the invert of the conduit decreases from Section A to Section C. Thus, the cavitation potential of the conduit invert is increasing towards the outlet.

2. Cavitation may be caused by reasons other than surface irregularities.

Example 2

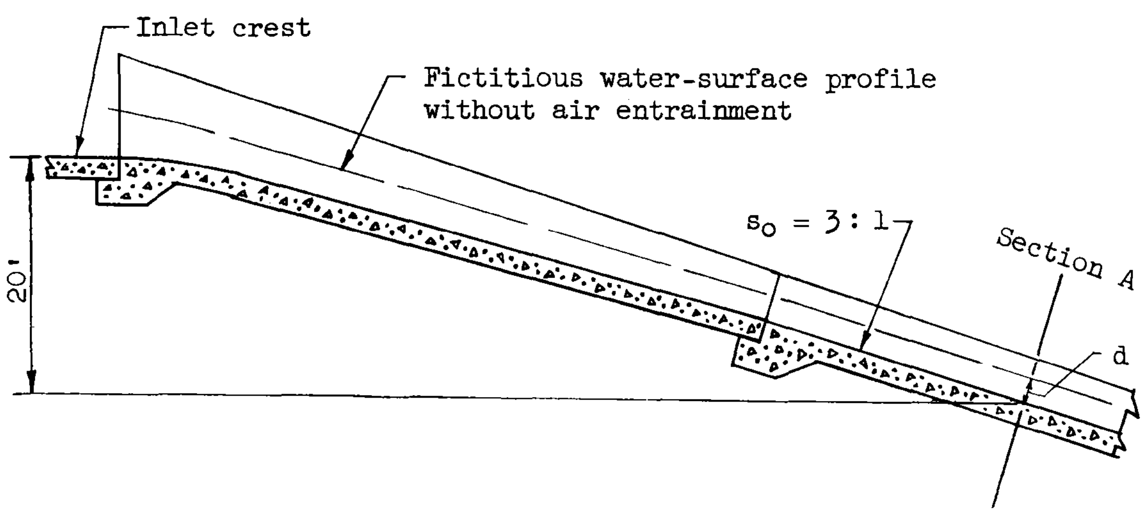
Given: A rectangular prismatic channel chute spillway.
The channel bottom of Section A is 20 ft below the crest of the control section.

Discharge, $Q = 375$ cfs

Probable minimum atmospheric pressure, $h_a = 29.5$ ft

Channel width, $W = 15$ ft

Channel slope, $s_o = 3:1$



Determine: For the bottom of channel at Section A

1. The maximum allowable projection of an into-flow, round-cornered irregularity with a radius of rounding of $\frac{1}{4}$".
2. The maximum allowable depth of an away-from-flow, sharp-cornered irregularity.
3. The maximum allowable slope of an into-flow, sloped irregularity with a projection of $\frac{3}{16}$".

Solution: $q = \frac{Q}{W} = \frac{375}{15} = 25$ cfs/ft

$d \equiv$ Fictitious depth of flow, assuming no air entrainment

$d = 0.68$ ft (Sheet 13, ES-78, NEH-14)

$v = \frac{q}{d} = \frac{25}{0.68} = 36.8$ ft/sec

Disregarding any local deviation, the hydraulic grade line, HGL, for open channel flow is at the water surface obtained without correction for air entrainment.

The absolute pressure at the bottom of the channel of Section A is h_{ab} = HGL − Elevation of channel bottom of Section A + h_a.

$$h_{ab} = d + h_a = 0.68 + 29.5 = 30.18 \text{ ft abs}$$

For a velocity, v = 36.8 ft/sec, and h_{ab} = 30.18 ft abs, then:

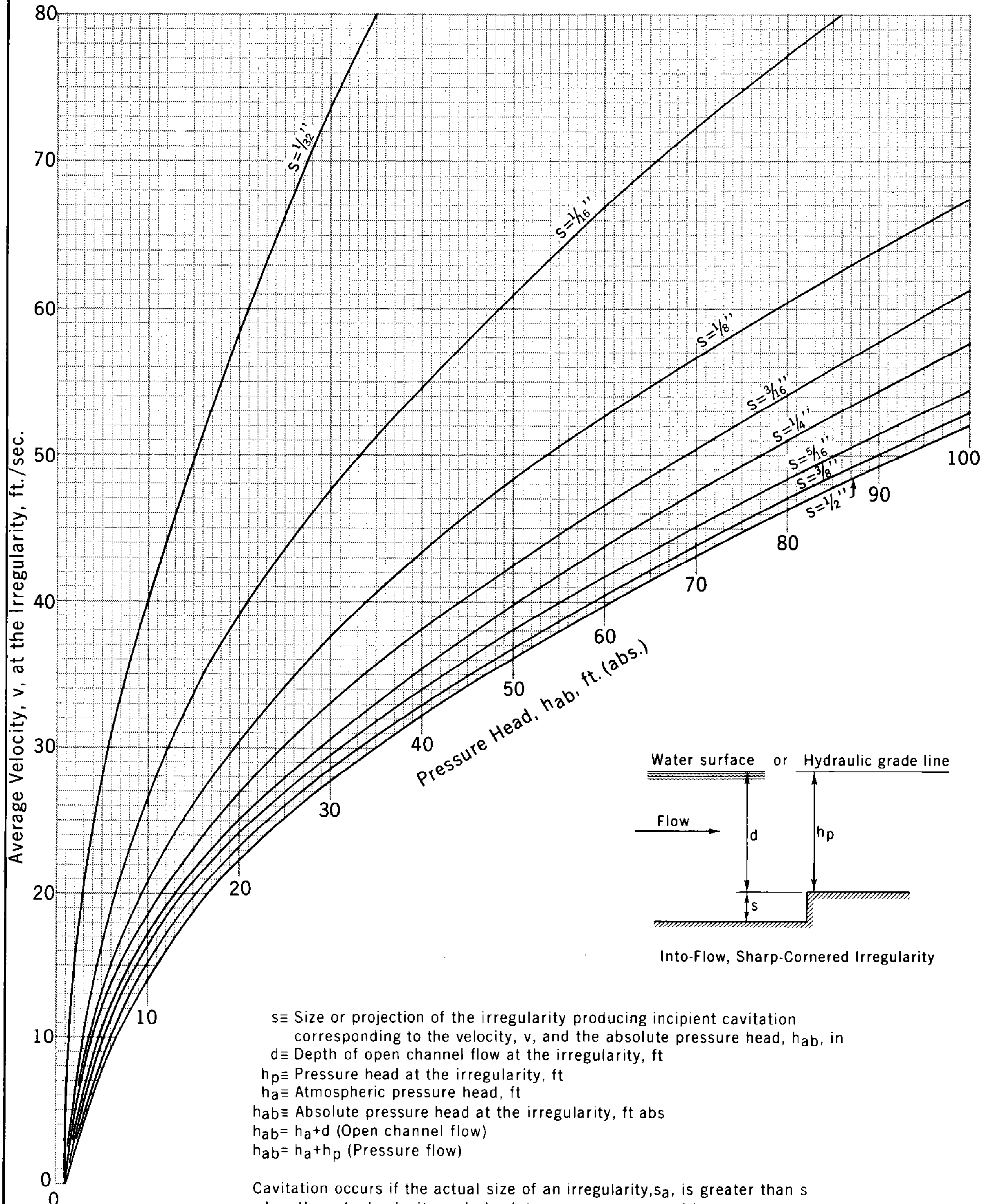
1. The maximum allowable projection of an into-flow, round-cornered irregularity with a radius of rounding of $\frac{1}{4}$" is $\frac{3}{8}$". (Sheet 2, ES-196)

2. The maximum allowable depth of an away-from-flow, sharp-cornered irregularity is $\frac{1}{8}$". (Sheet 1, ES-196)

3. The maximum allowable slope of an into-flow, sloped irregularity with a projection of $\frac{3}{16}$" is 1.5 : 1. (Sheet 3, ES-196)

Comment: Observe, as in Example 1, the cavitation potential also increases in a downstream direction for accelerating flows in chutes.

HYDRAULICS: Pressure-Velocity-Size Relation For Incipient Cavitation Into-Flow, Sharp-Cornered Irregularities



Into-Flow, Sharp-Cornered Irregularity

s≡ Size or projection of the irregularity producing incipient cavitation corresponding to the velocity, v, and the absolute pressure head, h_{ab}, in

d≡ Depth of open channel flow at the irregularity, ft

h_p≡ Pressure head at the irregularity, ft

h_a≡ Atmospheric pressure head, ft

h_{ab}≡ Absolute pressure head at the irregularity, ft abs

$h_{ab} = h_a + d$ (Open channel flow)

$h_{ab} = h_a + h_p$ (Pressure flow)

Cavitation occurs if the actual size of an irregularity, s_a, is greater than s when the actual velocity and absolute pressure are v and h_{ab}

REFERENCE
"Construction Finishes and High-Velocity Flow"
by James W. Ball
Construction Division, Proceedings of ASCE
September, 1963

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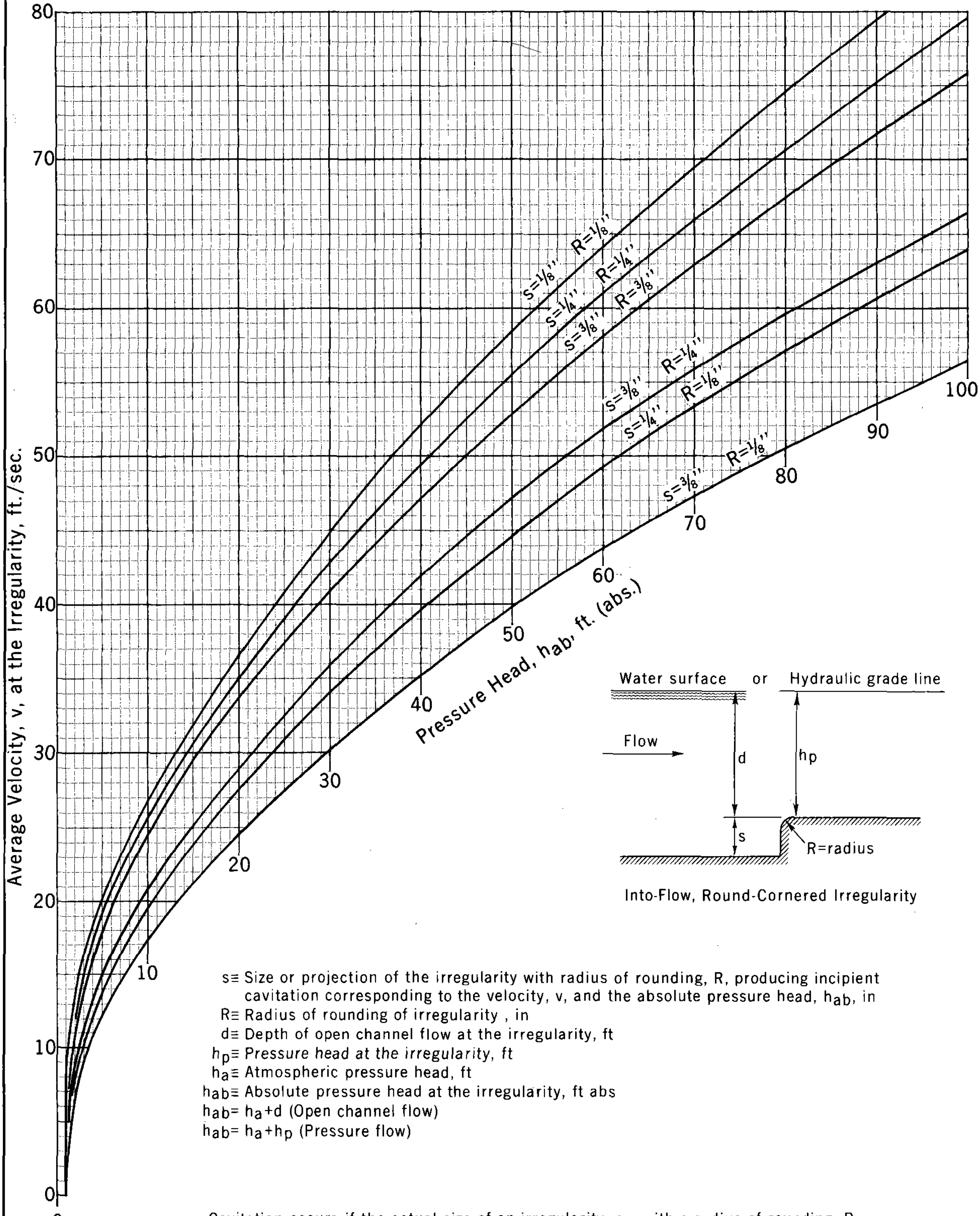
HYDRAULICS: Pressure-Velocity-Size Relation For Incipient Cavitation Into-Flow, Round-Cornered Irregularities



s ≡ Size or projection of the irregularity with radius of rounding, R, producing incipient cavitation corresponding to the velocity, v, and the absolute pressure head, h_{ab}, in

R ≡ Radius of rounding of irregularity, in

d ≡ Depth of open channel flow at the irregularity, ft

h_p ≡ *Pressure head at the irregularity, ft*

h_a ≡ Atmospheric pressure head, ft

h_{ab} ≡ Absolute pressure head at the irregularity, ft abs

$h_{ab} = h_a + d$ (Open channel flow)

$h_{ab} = h_a + h_p$ (Pressure flow)

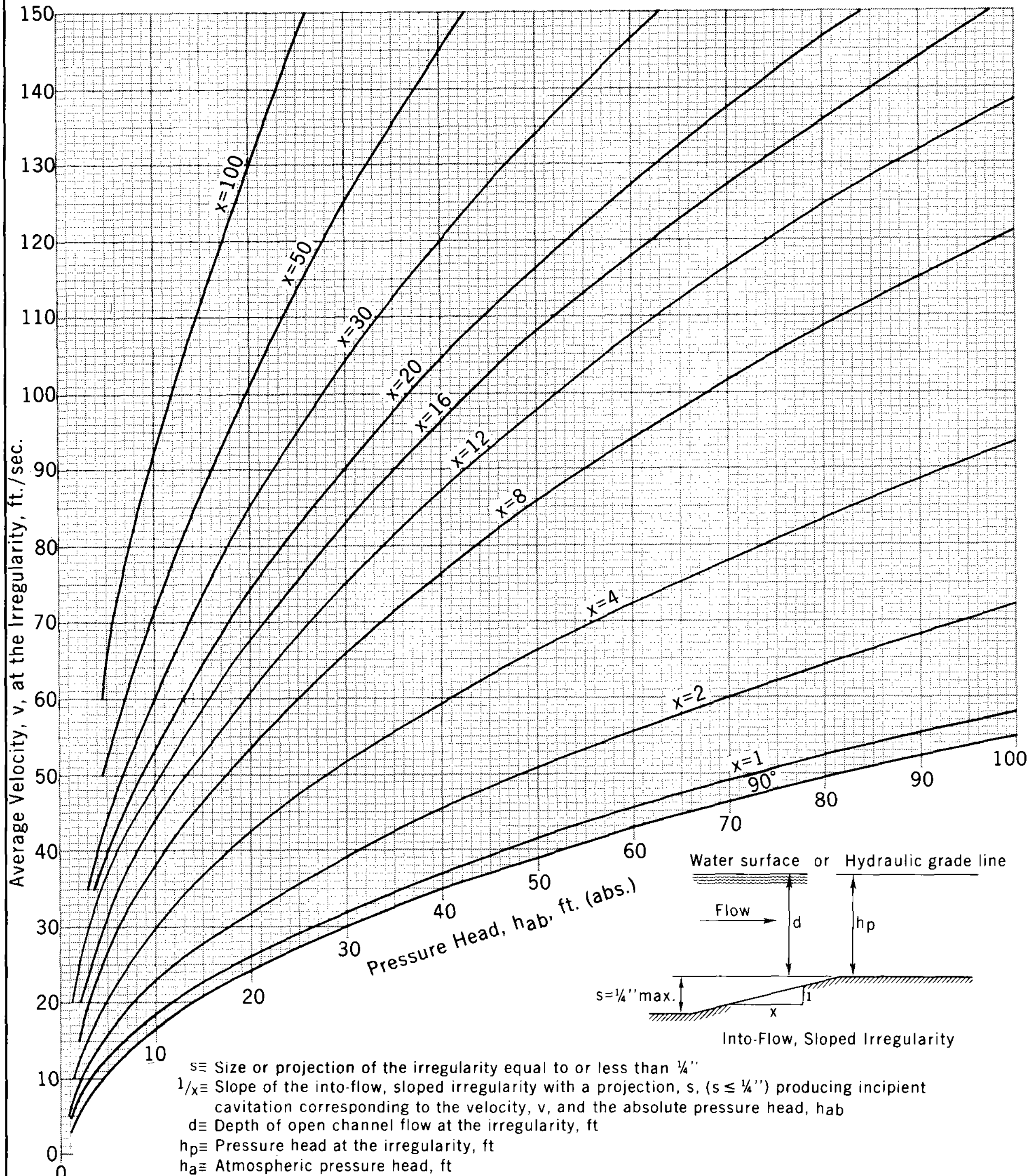
Cavitation occurs if the actual size of an irregularity, s_a, with a radius of rounding, R, is greater than s when the actual velocity and absolute pressure are v and h_{ab}

REFERENCE **"Construction Finishes and High-Velocity Flow"** **by James W. Ball** **Construction Division, Proceedings of ASCE** **September, 1963**	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES-196 SHEET 2 OF 3 DATE 1-73

HYDRAULICS: Pressure-Velocity-Size Relation For Incipient Cavitation Into-Flow, Sloped Irregularities

$s \leq 1/4$" *

*The 90° line is for an into-flow, sharp-cornered irregularity with a projection of approximately ¼". The use of this chart for projections larger than ¼" is probably unsafe.



$s \equiv$ Size or projection of the irregularity equal to or less than ¼"
$1/x \equiv$ Slope of the into-flow, sloped irregularity with a projection, s, ($s \leq$ ¼") producing incipient cavitation corresponding to the velocity, v, and the absolute pressure head, h_{ab}
$d \equiv$ Depth of open channel flow at the irregularity, ft
$h_p \equiv$ Pressure head at the irregularity, ft
$h_a \equiv$ Atmospheric pressure head, ft
$h_{ab} \equiv$ Absolute pressure head at the irregularity, ft abs
$h_{ab} = h_a + d$ (Open channel flow)
$h_{ab} = h_a + h_p$ (Pressure flow)

Cavitation occurs if the actual slope, $1/x_a$, is greater than the slope, $1/x$, (i.e., if $x_a < x$), when the actual velocity and absolute pressure are v and h_{ab}

REFERENCE "Construction Finishes and High-Velocity Flow" by James W. Ball, Construction Division, Proceedings of ASCE, September, 1963	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - DESIGN UNIT	STANDARD DWG. NO. ES-196 SHEET 3 OF 3 DATE 1-73

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