PAP-43

CONSIDERATIONS AFFECTING UNITED STATES PRACTICE IN PROVIDING FREEBOARD FOR IRRIGATION WORKS

by

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INTRODUCTION

The practice of irrigation is necessary in many parts of the world to supplement natural precipitation in order that adequate water may be made available to the land to permit crop production. In such areas the entire economy may be dependent upon this artificial supply of water. The irrigation system must be planned and designed to provide water as needed. Failure to do so could cause total failure of the entire enterprise. Therefore, the correct design of the many features that collectively form the irrigation system is extremely important. One of the numerous design problems is proper freeboard allowances in each of the component parts of the system.

The term freeboard as used in the practice of irrigation hydraulics may be defined as the vertical distance that is left between the normal operating water level and the top of the sides of an open conduit, the crest of a dam, etc., to prevent overtopping due to contingencies in design and in operation. For purposes of design, freeboard is usually considered to be a band of constant width extending the length of the structure. In actual operation this band is generally variable in width over a wide range.

The precise amount of freeboard to allow cannot be determined by purely analytical methods. Rational solutions may establish a value within limits, but the optimum amount is governed primarily by the experience and judgment of the designer.

In general, freeboard allowances in irrigation works are influenced by two important and opposing factors. Of prime consideration is the fact that the initial and continued safety of the works must be assured. To fulfill this requirement a generous freeboard is indicated. On the other hand, consideration must be given to economy of construction. A minimum freeboard is thus inferred. A decrease in initial cost can generally be accomplished by minimizing freeboard allowances. However, caution must be exercised to prevent decreasing such allowances to the extent that operation and maintenance costs will be increased, resulting in greater over-all expenditures. Such practice is false economy and may also place the safety of the structure in jeopardy.

Since experience and judgment play such an important part in establishing proper freeboard allowances in design, this discussion of the subject includes principally the influencing considerations. In instances where an approximate rational solution may be obtained, the methods involved are described. Freeboard allowances in common usage are included where appropriate.

CONSIDERATIONS APPLYING IN GENERAL TO ALL TYPES OF IRRIGATION WORKS

With respect to optimum freeboard allowances, there are a number of considerations that apply generally to all types of irrigation works.

Design considerations. Probably the most important of these, and one that should receive early attention, is a careful review of all criteria considered in the design. If the values of all empirical coefficients may readily and accurately be determined and all hydraulic formulas involved are well defined, the normal water surface may be expected to follow that calculated. In such instances liberal freeboard allowances are not justified. On the other hand if all elements controlling the design are not precisely known or if there is reason to believe that some factors, such as friction coefficients, are not well defined or may change appreciably after operation has begun, more freeboard may be necessary. There are many factors that influence the design of freeboard as will be shown later.

Operational considerations. In addition to design considerations, the method of operation of the system must be anticipated. If it may reasonably be expected that operation will follow closely the pattern upon which the design was based, less freeboard will be needed. However, if for some reason radical departures may develop, freeboard should be judged accordingly. As an example, the system may be designed for normal operation at a stated discharge but with a peak maximum for short intervals only. If a probability exists that the peak flows will not be confined to short periods when operation of the entire system is accomplished, increased freeboard may be necessary to provide for this contingency.

Size. The size of the canal or structure will influence the freeboard. In general, the larger the structure the greater the freeboard. This may be due to uncertainties used in design. Increased disturbances in flow characteristics can be anticipated in works of greater magnitude. Probably the most dominant reason is the tendency to amply insure the safety of the larger works. In many instances failure of a major structure would jeopardize or possibly cause complete failure of the operation of the entire system with consequent destruction of valuable property and complete loss of crops. The role that the structure plays with respect to the operation of the whole should be considered and freeboard be allowed commensurate with its importance.

Location. The location of the works with relation to thickly populated and highly developed areas has a definite bearing on freeboard. A considerable amount of water overtopping a canal or small dam located in a remote area might result in very little damage, if the works were not otherwise endangered. The same amount of water might cause a major catastrophe if released into thickly settled or highly developed industrial zones.

Climate. Climate enters into freeboard calculations principally in regard to the formation of ice, whether in reservoirs, at diversion dams, or in conveyances and associated structures. Irrigation canals are normally not operated in freezing weather; but when power generation facilities are integrated into the system or when the channels and structures serve to fill off-stream storage, year-around operation may be required.

The effect of a complete ice cover on a canal is to practically double the wetted perimeter and, hence, for a given area to reduce the hydraulic radius one-half. There is also some increase in friction head due to the greater frictional effect of the underneath ice surface as compared with air surface.1/ Ice jams may form and cause the water surface to rise above normal. If the carrying capacity of the canal or structure is to be maintained the same throughout the year, ample allowance must be made for this reduced capacity when ice may be present. Additional freeboard may be required at storage and diversion dams, in all conveyance and other structures, and in other works throughout the system if the presence of ice is anticipated.

Safety devices. Another item to be included in the discussion of design factors is the adequacy of safety features,

1/ United States Geological Survey Water Supply Paper No. 187 pp 14-19.

other than freeboard, that are integral to the systems. The number, type, and location of spillways, wasteways, and other such outlets have an influencing effect on freeboard allowances. A storage dam having a spillway of ample capacity, that has an inlet which consists of a free overfall crest not susceptible to clogging easily by debris, may require less freeboard than if the spillway entrance were a narrow channel controlled by slow-operating gates or automatic gates, the dependability of which might be questioned. Similarly, a canal well protected by overflow sections might operate safely with a minimum of freeboard. Added freeboard or safety features are sometimes necessary to safeguard against the malfunction of an automatic device.

In addition to these general considerations, there are special considerations that are applicable to the various types of works found in irrigation systems.

CONVEYANCE AND DISTRIBUTION SYSTEMS

Conveyance and distribution systems, together with the structures included in them, constitute the major portion of the design problems of an irrigation system. A dam and its ancillary structures, to provide stored water, are generally a part of the over-all scheme. A drainage system and a levee system may be included in some developments. In each and every one of these features the proper freeboard must be determined by the designer.

<u>Canals and laterals</u>. First, consider the canals, laterals, and open distribution systems. These may be unlined

channels excavated in earth or they may be lined. Furthermore, they may be on slopes that cause flow to be above or below critical depth.

The optimum freeboard to allow in the design of channels, whether lined or unlined, where flow conditions are such that velocities are maintained below critical, can only be determined after a careful study of many influencing factors. Because local conditions vary widely, it is not possible to devise precise formulas that embody all factors in their true relationship. Each conveyance or reach of conveyance must be studied separately before final conclusions can be drawn.

Local conditions affecting freeboard. The local conditions affecting freeboard of either lined or unlined canals and laterals in which flow is above critical depth will be considered first.

The freeboard is normally governed by: the size of the conveyance, especially as regards depth of flow; the wind action; the likelihood of drainage or storm water entering the canal and raising the water level; the probability of excess water due to lack of regulation of flow; the location, whether in cut or fill; the location with respect to terrain, that is, the ground slope perpendicular to the center line; the alinement, whether relatively straight or containing many curves; the soil characteristics; percolation gradients; water surface fluctuations due to operations of check gates, turnouts, pumping or power plants, or other structures; and the possibility of changes in carrying capacity due to vegetable or animal growth.

Some comments regarding size of works in general have been made previously. When large quantities of water are being conveyed in open channels, freeboard allowances are usually greater than for small conveyances. As will be pointed out later, the depth of flow in canals is important when wind waves are considered.

Wind. There are a number of ways that wind may influence the flow in a canal. In many irrigated areas in the western United States strong winds blow sand into the canals, hold back the flow if blowing upstream, sometimes fill a canal with tumbleweeds of Russian-thistle or other plants, and create surface waves that may reach considerable magnitude.

When sand is blown into the canal the section is reduced. This reduction in section may not cause as much decrease in flow as the reduction in velocity caused by the increased roughness of the bottom due to the presence of the sand. This applies especially in lined canals. Fine sand drifts downstream in deep, irregular pockets and may entirely change the character of the bottom of a smoothly lined canal. On the other hand, water laden with very fine silt may flow more freely after the silt has deposited in a smooth coat over minor irregularities existing in a new canal. Blow sand may also slide down the inclined sides of concrete lined canals until it reaches the line where capillary water is effective, there becoming moist and accumulating in firm patches that are not removed even in reasonably high velocities. This is particularly true if the waters of the canal are silty, the effect then being to add sticky colloidal muds to the sharp sand deposits.

The prevailing wind direction must be given consideration. A study of vertical velocity curves shows a marked change in form with change in wind direction.2/ A downstream wind may aid the flow of surface water to the extent that it has the maximum velocity in the vertical, while an upstream wind so shapes the velocity curve that the surface velocity is as slow as that near the bottom.

Wind waves. The height of wind-generated waves has an important bearing on freeboard allowances in open channels. A number of formulas have been proposed for computing wave height. None may be said to give entirely reliable results. It is generally agreed that the size of the waves for any particular locality depends on the velocity of the wind, duration of the storm, depth of water, and the distance over which the wind can act, commonly called the fetch. Assuming a constant velocity and direction of wind parallel to the canal banks, the height of a wave will be greater for a wind whose direction is upstream than one whose direction is downstream due to the

2/ Scobey, Fred C., "Flow of Water in Irrigation and Similar Canals," Technical Bulletin No. 652, United States Department of Agriculture, February 1939.

greater difference in wind and water velocities. Winds whose directions are normal or oblique to the canal banks do not produce as large waves as those created by an upstream or downstream wind, since the fetch is not sufficient to allow formation of the maximum wave for the corresponding wind velocity. For the purpose of freeboard allowances, upstream wind directions are of most importance.

The fact that a canal is rarely straight must not be overlooked. An upstream wind may suddenly become a cross-wind or a downstream wind due to changes in direction of the canal. The water surface will rise, sometimes an appreciable amount, because of wind effect, at points where the canal is sheltered by the banks which immediately follow reaches subject to upstream or downstream winds.

The main source of information on wave heights is the observational data and empirical formulas based on the work of Thomas Stevenson.3/ This work was supplemented later by D. D. Gaillard 4/ and D. A. Molitor.5/ Their studies were directed toward the design of seawalls and breakwaters, but the results are applicable to some extent to the study of wave action in reservoirs and in

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3/ Stevenson, Thomas, "The Design and Construction of Harbours," A. C. Black, Edinburg, 1874.

4/ Gaillard, D. D., "Wave Action in Relation to Engineering Structures," Professional Paper No. 31, Corps of Engineers, United States Army, United States Government Printing Office, Washington, D.C., 1904.

5/ Molitor, David A., "Wave Pressures on Sea-Walls and Breakwaters," Transactions A.S.C.E., 1935, Vol 100, p 984.

canals. Canals are seldom straight, hence an estimation of fetch is difficult. Because of insufficient weather data, wind velocities and directions can rarely be determined accurately for a particular locality in which a canal will be constructed. However, if the best estimate possible is made of these variables and the estimated empirical relationships used, the height of the waves to be expected may be calculated with a fair degree of accuracy.

For a given wind velocity, V, in miles per hour, and a fetch, F, in miles, the wave height, h, in feet, measured from trough to crest, may be estimated for any wave with the aid of the following formulas:

For values of F greater than 20 miles

$$h = 0.17 \sqrt{VF} \tag{1}$$

and for values of F less than 20 miles

$$h = 0.17 \sqrt{VF} + 2.5 - \sqrt[4]{F} \tag{2}$$

These are the empirical formulas developed from studies on inland waters by D. D. Gaillard with supplemental data by D. A. Molitor.

Measurements on the Belle Fourche reservoir by the Bureau of Reclamation resulted in the following empirical formula for wave height

$$h = 0.075 (V - 8.5) \tag{3}$$

Here the fetch was constant at 5 miles. This formula gives results comparable to the two above for wind velocities between 0 and 70 miles per hour.

Figure 1 based on Formulas (1) and (2) may be used to determine wave heights for any wind velocity from 20 to 70 miles per hour and for a fetch of from 2 to 40 miles. The equations upon which this chart is based are for nonflowing bodies of water; but since the velocity of flow at the water surface in a canal is only about 5 percent of the usual maximum wind velocity, their application to canals results in an error due to the motion of the water of about $\pm$ 5 percent or approximately 2 percent, being plus for a downstream wind and minus for an upstream wind.

In the computation of wave height, the maximum probable wind velocity and maximum fetch over which this wind will act must be estimated as closely as possible. Since velocity has from 3 to 15 times the influence on wave height as fetch, for the more violent storms, except in unusual cases, the maximum wave height will occur with the maximum wind velocity.

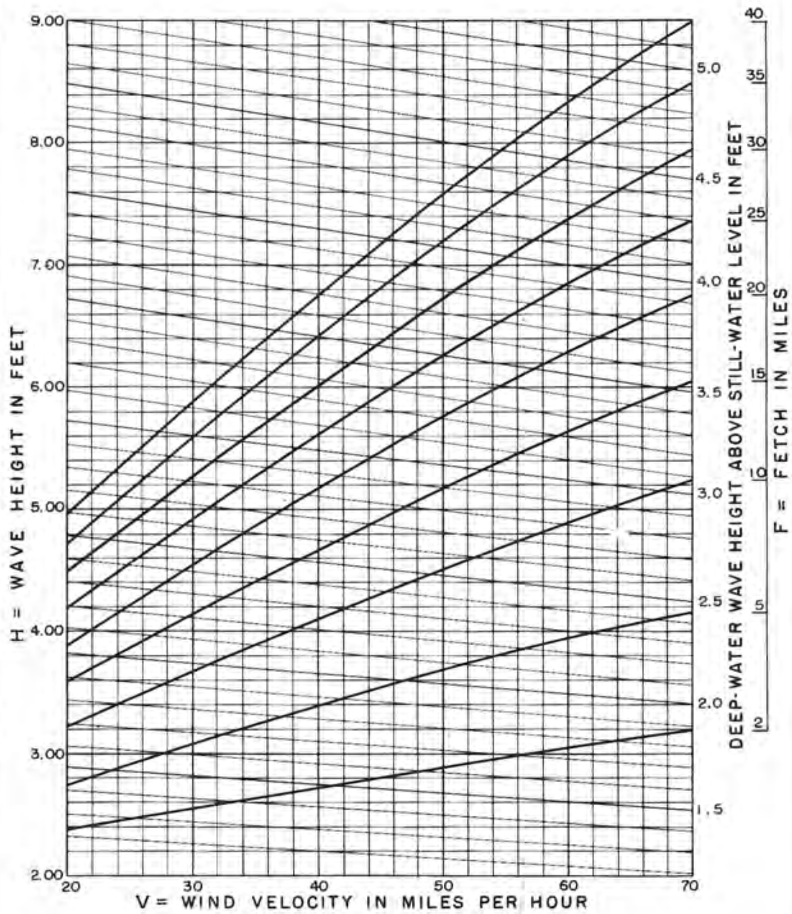
Many observations by various investigations show the crest of the wave to be about 2/3h above the stillwater level in deep water and rising still higher in shallow water. From the experiments of Gaillard and Molitor, it may be shown that for deep water waves, with $d > 1.84h$

$$a_d = \frac{h}{2} + \frac{hV}{840} \qquad (4)$$

and for shallow water waves, with $d < 1.84h$

$$a_s = \frac{h}{2} + \frac{hV}{420} \qquad (5)$$

FIGURE I



NOTE: For deep-water waves $d > 1.84\,h$.
For shallow-water waves $d < 1.84\,h$.
$a_s = a_d \left(1 + \frac{V}{420+V}\right)$.
where: a_d = Deep-water wave height above still-water level.
a_s = Shallow-water wave height above still-water level.

WAVE HEIGHTS FOR VARIABLE WIND VELOCITY AND FETCH

Figure 1--Curves for determining height of waves.

(Figure will ~~be~~ follow page 12 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

Figure 1.--Curves for determining height of waves.

where a_d and a_s are the average height of the wave, in feet, above stillwater for deep water and shallow water, respectively, and d is the depth of water, in feet.

Solution of these two equations results in the following:

$$a_s = a_d \left(1 + \frac{V}{420 + V}\right) \tag{6}$$

The quantity $\frac{V}{420 + V}$ is the increase of a_s over a_d.

To allow sufficient freeboard in canals, it is necessary to know the height above stillwater level to which a completely obstructed wave acts. When a wave is completely obstructed by striking normally on a vertical surface, the wave crest is raised a height to 2a above the stillwater level. The distance which a wave travels up a sloping bank is approximately 2a/s where s is the bank slope expressed as horizontal distance over vertical distance, and a is the normal height of the wave.

When the direction of propagation of the wave is parallel to the banks, the wave crest is raised to height, a, in feet, above stillwater level, and travels up a sloping bank a distance a/s. Due to bank resistance, waves adjacent to the banks strike obliquely when the direction of wind is parallel to the flow. Therefore, the height of wave above stillwater level and the travel distance up the banks are greater than for a parallel wave but less than for a wave striking normal. The theoretical values of height of wave above stillwater level, h_o, and travel distance up sloping banks, b_o, may be expressed as follows:

$$h_o = a\ (1 + \frac{\phi}{90}) \tag{7}$$

$$b_o = \frac{h_o}{s} \tag{8}$$

where h_o is the wave height above stillwater level, b_o is the travel distance up the sloping banks, and ϕ is the angle between the altered wave direction and the banks. The angle, ϕ, depends upon the dimensions and roughness of the canal and the characteristics of the original wave. The value of ϕ for a canal is small, so the height of wave above stillwater, h_o, and the travel distance up sloping banks, b_o, are essentially the same as for a parallel wave. Furthermore, since the value of a is smaller than given by Figure 1 for waves adjacent to the banks, the increase in height due to an oblique direction is approximately offset by the decrease in wave height due to bank resistance. For design purposes, the following formulas can be safely used:

$$h_o = a \tag{9}$$

$$b_o = \frac{a}{s} \tag{10}$$

where the value of a is taken from Figure 1.

As was stated at the beginning of this discussion, the formulas for calculating wave heights were developed empirically and are the ones generally used in this country. However, more recent relationships developed by Sverdrup and Munk 6/ and observations made at Clear Lake, California, and Abbots Lagoon, California, 7/ on relatively small bodies of water should be adopted soon. Studies by the Corps of Engineers, Department of the Army, United States, by means of instruments installed in the reservoirs created by Fort Peck (Montana) and Denison (Texas) dams and in Lake Okeechobee (Florida) to obtain reliable data on winds, waves, wind set-up, and wave runup, will undoubtedly add to current knowledge much factual data which can lead to a satisfactory solution of the behavior of waves.

Drainage or storm water. The possibility of drainage or storm water entering the canal has an important influence on freeboard allowances. It is rarely economically possible to protect the channel in such a way as to exclude all drainage or storm water run-off. Good design practice is to exclude from the canals as much of the storm water as is economically

6/ Sverdrup, H. U., and Munk, W. H., "Wind Waves and Swell Principles in Forecasting," Miscellaneous Publications No. 11275, United States Hydrographic Office, Washington, D.C., 1946.

7/ Mason, Martin A., "The Problem of Wave Action on Earth Slopes," discussion by C. L. Bretschneider and R. R. Putz of Paper No. 2472, Transactions A.S.C.E., 1951, Vol 116, p 1398.

feasible. This will prevent much costly maintenance. However, storm water may enter the system in various quantities. In this event, additional capacity must be provided to carry the increased flow to a point where it may be evacuated from the system. The amount of freeboard to be allowed is dependent upon the adequacy of the information available for estimating the probable intake of storm and drainage water and the practicability and economy of providing adequate waste passages.

Regulation. The likelihood of excess water levels due to lack of regulation of flow is a matter of judgment. In this respect dependable automatic regulation permits less freeboard allowance than unattended manually operated controls. This subject is further discussed under "Operation."

Location. If the canal is located on fill, more freeboard is indicated than if in cut for reasons of safety against overflow and also because of the possibility of settlement of the fill.

Alinement. Usually, in canals where the flow is above critical depth, alinement is not a major factor in freeboard allowances. However, in lined sections where velocities are greater than about 5 feet per second and sharp curves are contemplated, it may be necessary to investigate their effects on flow conditions and provide more freeboard. Several solutions have been offered for calculating losses induced by curvature in the alinement of the canal and consequent rise in water surface. Scobey 8/ has made many observations of existing channels containing bends and proposes a practical solution utilizing the total number of degrees of curvature per 100 feet of channel. Other formulas may be found for computing the losses due to curves. Figure 2 shows a lined canal where velocities are near critical and the lining is being overtopped at the design flow because of excessive curvature.

Figure 2.--Flow overtopping canal lining at curve.

Soil conditions. If soil conditions in unlined canals indicate the possibility of sloughing or excessive settling, increased freeboard may be indicated. In very stable soils minimum allowances may be ample. The use of excess freeboard, especially in unstable materials, may aggravate conditions. Where high percolation rates are anticipated, better practice is to increase the top width of the banks or the slope of the outside of the bank rather than freeboard.

Operation. Probably the most difficult factor to evaluate is the possible fluctuations in water surface that may be occasioned by the operation of check gates, large turnouts, pumping or power generating equipment, and other

8/ Scobey, F. C., "The Flow of Water in Flumes," Technical Bulletin No. 373, United States Department of Agriculture, p 61.


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Figure 2--Flow overtopping canal lining at curve.

(Figure to be incorporated in page 17 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

control features in the system. All contingencies cannot economically be guarded against, but a visualization of the results of many of the operations may indicate additional freeboard at some points if it is not practical to care for the excess water by removal through wasteways, siphon spillways, or similar structures.

Hydraulic bore. The sudden shut-down of pumping or power generating plants in a canal may produce bore waves which will overtop the banks for short periods of time unless adequate freeboard is allowed or ample means are provided to level off the wave. This type of wave may also be created by rapid changes in gate settings, sudden removal or insertion of stop logs, or a sudden inrush of water from an outside source. The preparation of adequate operating instructions will assist in reducing this hazard.

Hydraulic bore is a result of certain effects of volume, pressure, gravity, and momentum forces associated with sudden changes in flow conditions. It may be evidenced by a wave moving either upstream or downstream. Formulas for calculating the characteristics of the bore have been proposed, but their solution is usually rather difficult.9/ Specific problems have been studied extensively by means of hydraulic models. This may be the most reliable method of determining

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9/ Jurney, W. H., "Note on Flow in Canals," Brown University Quarterly Applied Math, January 1945, Vol 2, No. 4, pp 342-5.

the proper design of wasteways, siphons, etc., and the amount and extent of freeboard necessary to care adequately for the problem.

Aquatic growths. In the United States it has been found that canals carrying muddy waters the major portion of the time do not have extensive aquatic growth in the water prism and that canals carrying clear waters are seldom free of such growths throughout the irrigation season. Climatic conditions have some effect on the extent of growth but the degree of turbidity of the water appears to be the major factor. In concrete lined canals, silty water tends to form a coating on the concrete which may form a bed for aquatic growths and the resultant combination may present a very rough surface with a consequent loss in carrying capacity.

Muddy waters in earth channels may form deposits that encroach on the free passage from both sides. In the resulting shallow water and rich mud, dense vegetation usually appears and may further restrict the flow. Grasses and tules may hang beyond the bench into the flow. Scobey 2/8/ has developed some very useful values for calculating the reduced carrying capacity due to aquatic growths. If the carrying capacity is to be maintained, freeboard allowances must be increased or cleaning anticipated.

Aquatic insects. In some areas certain insects pass part of their life cycles in water. Caddis flies, for example, live in the air but have aquatic larvae. These wormlike aquatic larvae live in and carry around cylindrical cases or tubes covered with a down or fluff that excretes gelatinous material. This fuzzy, adhesive surface collects grains of sand, bits of straw, leaves, etc., and forms a tubular cell about 1 inch long and 1/4 inch in diameter. The collected material causes the cylinder to have a very rough exterior. The case is affixed to the side or bottom of lined canals, structures, and tunnels and serves as an abode for the larva during its lifetime and is abandoned in these locations when the larva is transformed. It may readily be seen that these abandoned cases present an extremely roughened surface in the water passage, and the coefficient of roughness of the channel is increased considerably. There may also be a slight decrease in the cross sectional area of the canal as the deposit builds out from the wall or bottom.

Serious examples of this infestation have occurred in southern California. In one instance the freeboard of the canal was increased. In another instance, studies showed that the best solution would be to cover the channel and deny entry to the flies.10/

Unlined channels. In the United States by far the greater number of canals, laterals, and farm ditches are

10/ Burzell, Linden R., "Low-Cost Irrigation Flume Cover," Engineering News-Record, May 13, 1948, p 75.

unlined and are simply excavated in earth. The slopes are flat so that velocities are below critical. In some instances channels excavated in rock or in coarse gravel are designed for velocities above critical.

Preliminary estimates of freeboard for channels in earth may be made by use of the empirical formula

$$F = \sqrt{Cd} \qquad (11)$$

where F = freeboard in feet

C = a coefficient

d = depth of water in feet

The coefficient, C, varies from 1.5 for a canal capacity of 20 cfs to 2.5 for a canal capacity of 3,000 cfs or more. This is an approximation method based upon Bureau of Reclamation practice 11/ and will not serve for all conditions. Greater freeboards and bank heights will normally be required after consideration of all of the factors previously mentioned.

Figure 3 gives relationships between water depth and base width and water depth and freeboard. The relationships shown in this figure represent averages of canals and laterals constructed by the Bureau of Reclamation. The base widths in relation to water depth give some choice in the section to fit local conditions. The freeboards given are the minimum ordinarily used and study of local conditions will determine additional needs.

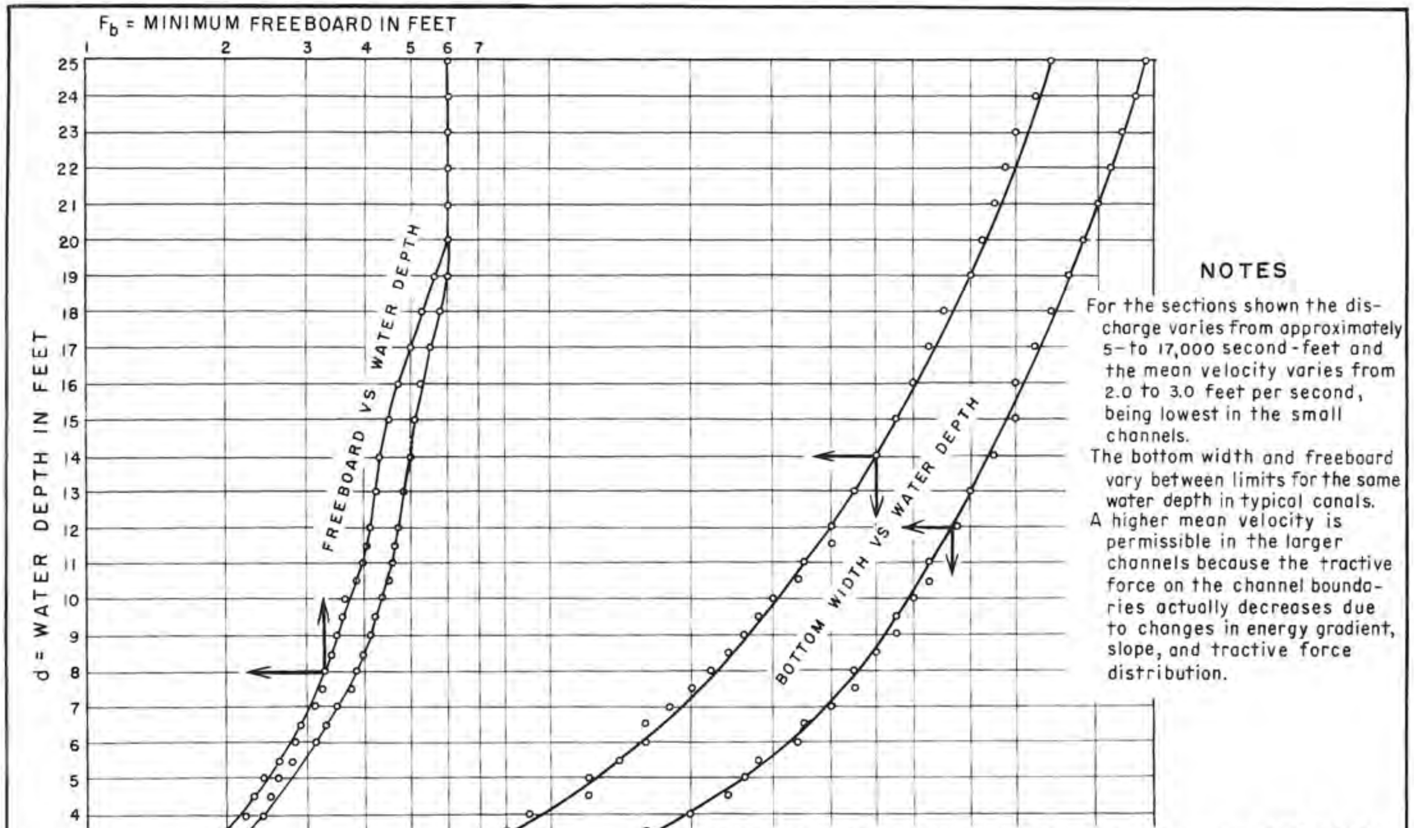
11/ Reclamation Manual, Vol. X, Chap. 1, Paragraph 1.8, Design Supplement No. 3 to Part 2.

Lined canals and laterals. Freeboard allowances for canals and laterals having hard surface linings, in which the flow is below critical velocity, require different analysis than for earth channels. The height of the lining above maximum water surface must first be considered and maintained at a minimum for reasons of economy. The additional freeboard necessary for extraordinary conditions is cared for by extending the height of the earthen bank above the top of the lining.

The general considerations stated previously will apply. Special consideration must be given to the possibility of water overtopping the lining for prolonged periods with a resultant saturation of the backfill. This may produce extensive leakage or possible bank sloughing, the water may react with materials that expand when wet, and hydrostatic pressures may cause rupture of the lining when the flow recedes.

Figure 3.--Minimum freeboard for unlined trapezoidal canals.

Velocity in the canal has a decided influence on the freeboard allowances in a lined canal since allowable velocities are usually much higher than for earth channels and there is an attendant increase in wave action. With higher velocities freeboard encroachment on curves becomes more acute and lateral wave action tends to build up below the curve. Observations have shown that the choppy water surface on the inside of the



BOTTOM WIDTH, WATER DEPTH AND MINIMUM FREEBOARD

UNLINED TRAPEZOIDAL CANALS WITH 1½:1 SIDE SLOPES

Curves plotted from information in Reclamation Manual Vol. X, Design Supplement No. 3 to Part 2.

Figure 3--Minimum freeboard for unlined trapezoidal canals.

(Figure to ~~be~~ follow page 22 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

curve causes the tops of the waves to be about the same elevation as the water surface on the outside caused by super elevation. Therefore, a freeboard equivalent to that on the outside is required on the inside of the curve.

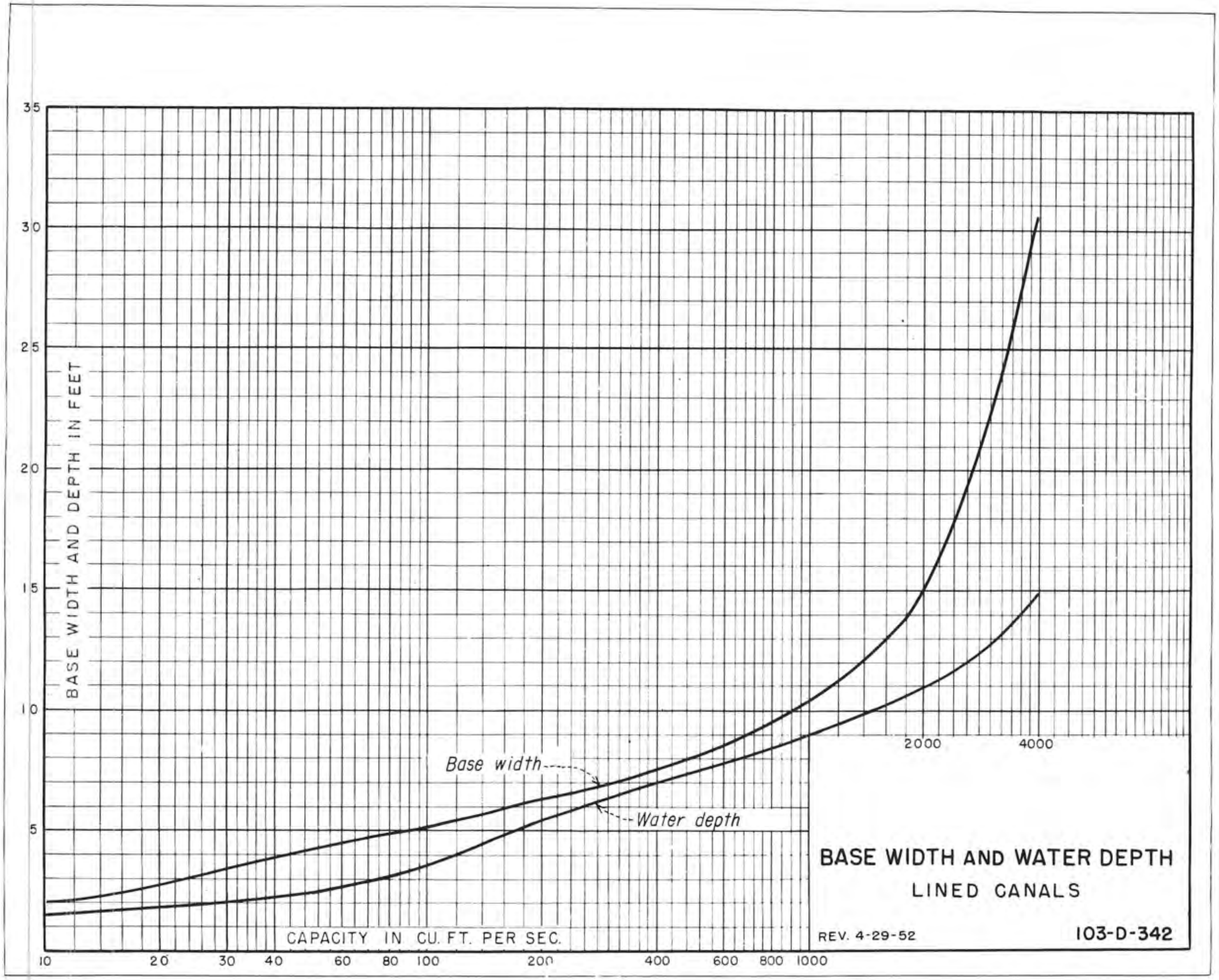
Figure 4 shows the relationship between base width and water depth and Figure 5 shows curves for freeboard and bank heights in relation to capacities for lined canals designed by the Bureau of Reclamation. These curves are intended to be used only as a guide.

Figure 4.--Dimensions of lined canals.

Figure 5.--Freeboard for lined canals.

FARM DITCHES

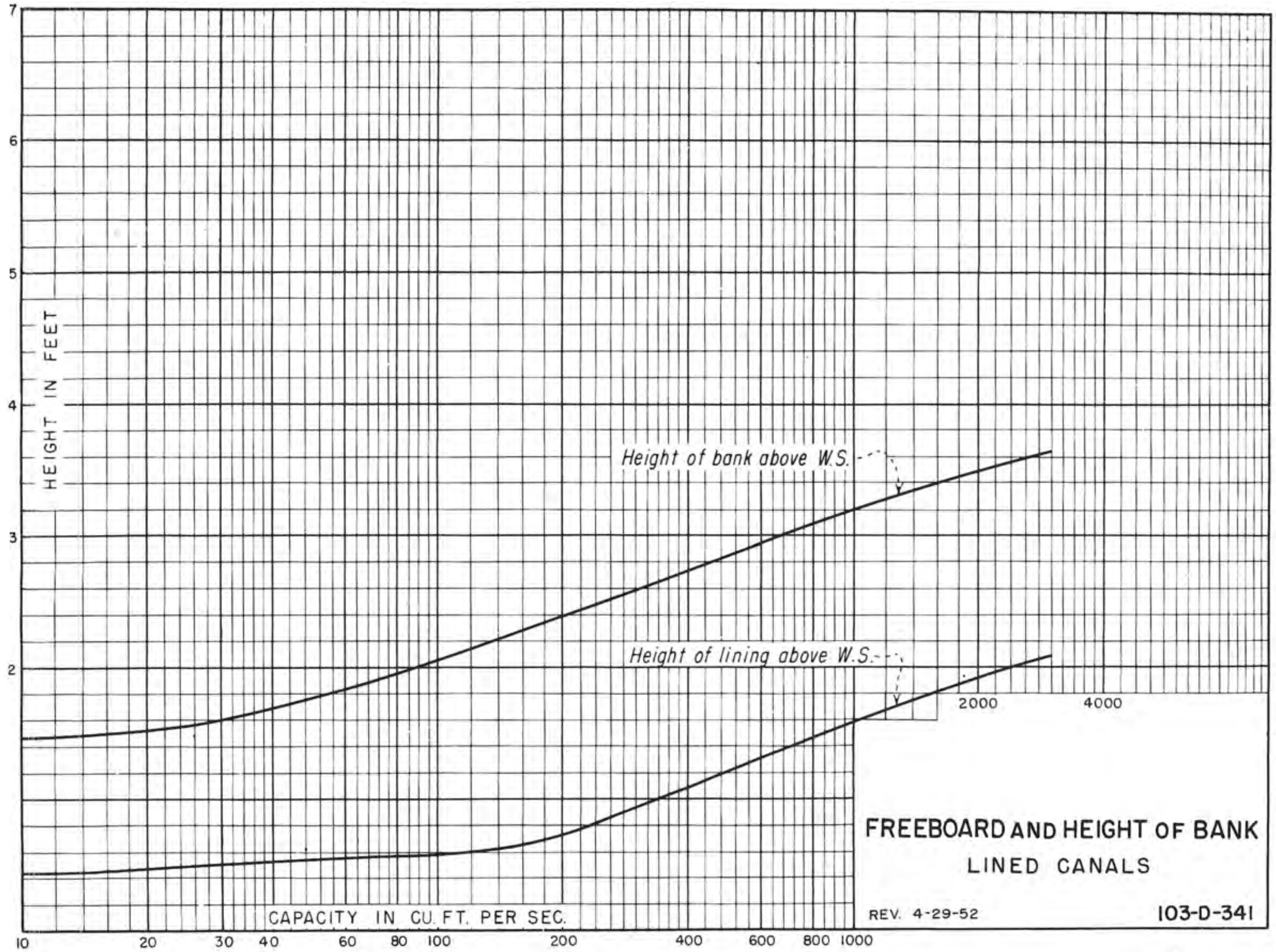
Freeboard is not an important consideration in small farm ditches especially when they are excavated in earth. Water overtopping the banks will normally be retained in the field. In larger farm ditches where the dimensions of laterals are approached, the considerations for freeboard allowances for laterals will apply. In modern irrigation practice many of the farm ditches are lined. Authorities differ on the amount of freeboard, but the majority recommend a minimum of 6 inches. Again local conditions should govern.



BASE WIDTH AND DEPTH IN FEET
35
30
25
20
15
10
5
Base width
Water depth
CAPACITY IN CU. FT. PER SEC.
10
20
30
40
60
80
100
200
400
600
800
1000
2000
4000
BASE WIDTH AND WATER DEPTH
LINED CANALS
REV. 4-29-52
103-D-342

Figure 4--Dimensions of lined canals.

(Figure to be incorporated in page 23 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)



7
6
5
4
3
2
HEIGHT IN FEET
Height of bank above W.S.
Height of lining above W.S.
2000
4000
CAPACITY IN CU. FT. PER SEC.
10
20
30
40
60
80
100
200
400
600
800
1000
FREEBOARD AND HEIGHT OF BANK
LINED CANALS
REV. 4-29-52
103-D-341

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Figure 5--Freeboard for lined canals.

(Figure to be incorporated in page 23 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

STRUCTURES

Structures are an integral part of all canal and lateral systems. These structures may be classified generally into four types: conveyance structures, regulating structures, protective structures, and others, such as bridges, pipe line crossings, etc.

It is important that the design include optimum freeboard allowances within each structure. An equally important design consideration is that the structures be so designed that they are not "bottlenecks" in the conveyances. All features that may contribute to head loss must be carefully reviewed to alleviate the possibility of the structure causing a loss in head that will seriously affect the freeboard allowances in the conveyance proper.

CONVEYANCE STRUCTURES

Conveyance structures may be defined as structures built in canals, laterals, or distribution systems to help provide general control and transmission of the irrigation water to a location of final control, usage, or disposal. For reasons of economy they may be built in combination with other structures. The most important in this classification of structures are: chutes, drops, inverted siphons, culverts, flumes, and tunnels. Short reaches of concrete lining in earth canals may also be included.

Conveyance structures form part of the passageway for the water in the system. Therefore, many of the freeboard considerations for channels are applicable.

These structures are usually fabricated of concrete, masonry, wood, or other durable materials. Water overtopping such stable substances will cause little direct damage to the structures but the foundations may become saturated resulting in settlement and possible disintegration of the works. The backfill may also be eroded away. Wind waves in the canals may rise to above average heights when striking structures normal to their path of advance. Water may be piled up at conveyance structures due to an upstream or downstream wind of long duration. Ample freeboard must be allowed to meet these conditions. The shape of the structure must be considered as well as the height of freeboard. In large canals wind waves have been observed to strike structures, ride up the face, and concentrate in stop-log slots and corners with resulting jets of water being thrown high in the air. This water may damage hoist equipment, saturate the backfill around the structure, or cause serious erosion of the banks.

Open transitions. Conveyance structures are nearly always preceded and followed by open transitions. These transitions serve to effect a smooth change from a cross section of one shape to a cross section of dissimilar shape or dimensions. The average velocity and velocity distribution in the flow are altered in passing through this change in section. If changes in shape are not abrupt and good design practice is followed a smooth water surface will probably result and hence a minimum freeboard may be tolerated. If velocities above about 0.8 critical velocity are encountered or if short or abrupt transitions are used for lower velocities, cross waves and undulating water surfaces may result while the changes in velocity are being developed (Figure 6). Freeboard must be allowed accordingly. The freeboard considerations for structures will usually govern the freeboard at the end of the transition adjoining the structure. Table 1 may be used as a guide for freeboard allowances in open transitions where the water depth does not exceed 12 feet.

Figure 6.--Waves forming downstream from transition section.

Chutes and drops. The principal hydraulic elements of a chute are: the inlet, chute channel, pool, and outlet. A drop has the same features as a chute, except drops are generally considered as having not more than 15-foot fall from water surface to water surface, with the chute section on a steep slope, say, not flatter than 3 horizontal to 1 vertical.

The inlet section is usually preceded by an open transition for which freeboard allowances have been discussed. The inlet to a chute or drop may be shaped to serve various


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Figure 6--Waves forming downstream from transition section.

(Figure to be inserted in page 26 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

Table 1

GUIDE FOR FREEBOARD ALLOWANCES IN OPEN TRANSITIONS
Water Depths Up to 12.0 Feet 1/

Structure	Transition upstream from structure		Transition downstream from structure	
	Upstream end	Downstream end	Upstream end	Downstream end
FOR LINED CANALS				
Chutes and drops 2/	Same as for lining--Minimum 3/	Same as for lining--Minimum 3/	Same as for stilling pool	Same as for lining 4/--Minimum 3/
Inverted siphons and culverts	Same as for lining--Minimum 3/	Twice that at upstream end	Twice that at downstream end	Same as for lining--Minimum 3/
Flumes	Same as for lining--Minimum 3/	Same as for lining--Minimum 3/	Same as for lining--Minimum 3/	Same as for lining--Minimum 3/
Tunnels	Same as for lining--Minimum 3/	Same as for lining--Minimum 3/	Same as for lining 5/--Minimum 3/	Same as for lining--Minimum 3/
Checks (when standard transitions are used)	Same as for lining--Minimum 3/	Same as for check structure	Same as for check structure	Same as for lining--Minimum 3/
Measuring devices (when standard transitions are used)	Same as for lining--Minimum 3/	Same as for structure for measuring device	Same as for structure for measuring device	Same as for lining--Minimum 3/
FOR UNLINED CANALS				
Chutes and drops 2/	Minimum 3/	Same as for upstream end	Same as for stilling pool	Same as for stilling pool 4/
Inverted siphons and culverts	Minimum 3/	Twice that at upstream end	Twice that at downstream end	Minimum 3/
Flumes	Minimum 3/	Same as for flume	Same as for flume	Minimum 3/
Reaches of concrete lining	Minimum 3/	Same as for lining	Same as for lining	Minimum 3/
Tunnels	Minimum 3/	Twice that at upstream end	Twice that at downstream end	Minimum 3/
Checks (when standard transitions are used)	Minimum 3/	Same as for check structure	Same as for check structure	Minimum 3/
Measuring devices (when standard transitions are used)	Minimum 3/	Same as for structure for measuring device	Same as for structure for measuring device	Minimum 3/

1/ For water depths over 12.0 feet actual site conditions and design considerations will govern freeboard requirements.
2/ For discharges up to 100 cfs. Higher discharges require special considerations.
3/ Minimum allowances

Water depth (ft)	Freeboard
0 to 5.0	1.00
5.1 to 7.0	1.25
7.1 to 9.0	1.50
9.1 to 12.0	1.75

4/ The minimum freeboard where the outlet transition joins the canal should be as given in 3/, except that, on account of waves from the pool, for pool values of $\frac{Q\sqrt{d}}{A}$, Figure 9, from 200 to 3,000 the freeboard may be increased by amounts varying on a straight line between 0.125 times the pool freeboard for $\frac{Q\sqrt{d}}{A}$ equal to 200 to 0.25 times the pool freeboard for $\frac{Q\sqrt{d}}{A}$ equal to 3,000.

5/ The top of the transition should be level from junction with lining to tunnel portal except that if required it may have a uniform slope so that at the portal it will not be lower than the intrados of the portal arch.

Table based on information condensed from Reclamation Manual, Volume X, Design Supplement No. 3 to Part 2, Chapters 6 and 7.

Table 1--Guide for freeboard allowances in open transitions.

(Table to be page 27 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

purposes such as a critical depth control section, a check, a weir, or other measuring control. Freeboard allowances in these structures are important to insure that water does not overflow and by-pass the chute with resultant serious erosion. It is also important to insure that the structures do not cause encroachment on the freeboard in the channel above. In general, the freeboard will depend upon the local conditions and whether there is a combination of structures at the inlet to the chute channel.

The primary consideration for freeboard allowances in chute channels of either rectangular or trapezoidal section is the accuracy with which the water surface may be calculated. For velocities greater than about 30 feet per second, consideration must be given to possible bulking of the flow due to air entrainment. The additional section required for this air entrainment may exceed 50 percent in velocities above 50 feet per second.12/ In addition to air entrainment there is also a tendency for surges to form in very high velocites, Figure 7.

Figure 7.--Air entrainment and surges in high velocity flow.

Vertical curves must be calculated very carefully in high velocities and ample freeboard allowed at these points.

12/ Thomas, C. W., "Progress Report on Studies of the Flow of Water in Open Channels With High Gradients," Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-35.

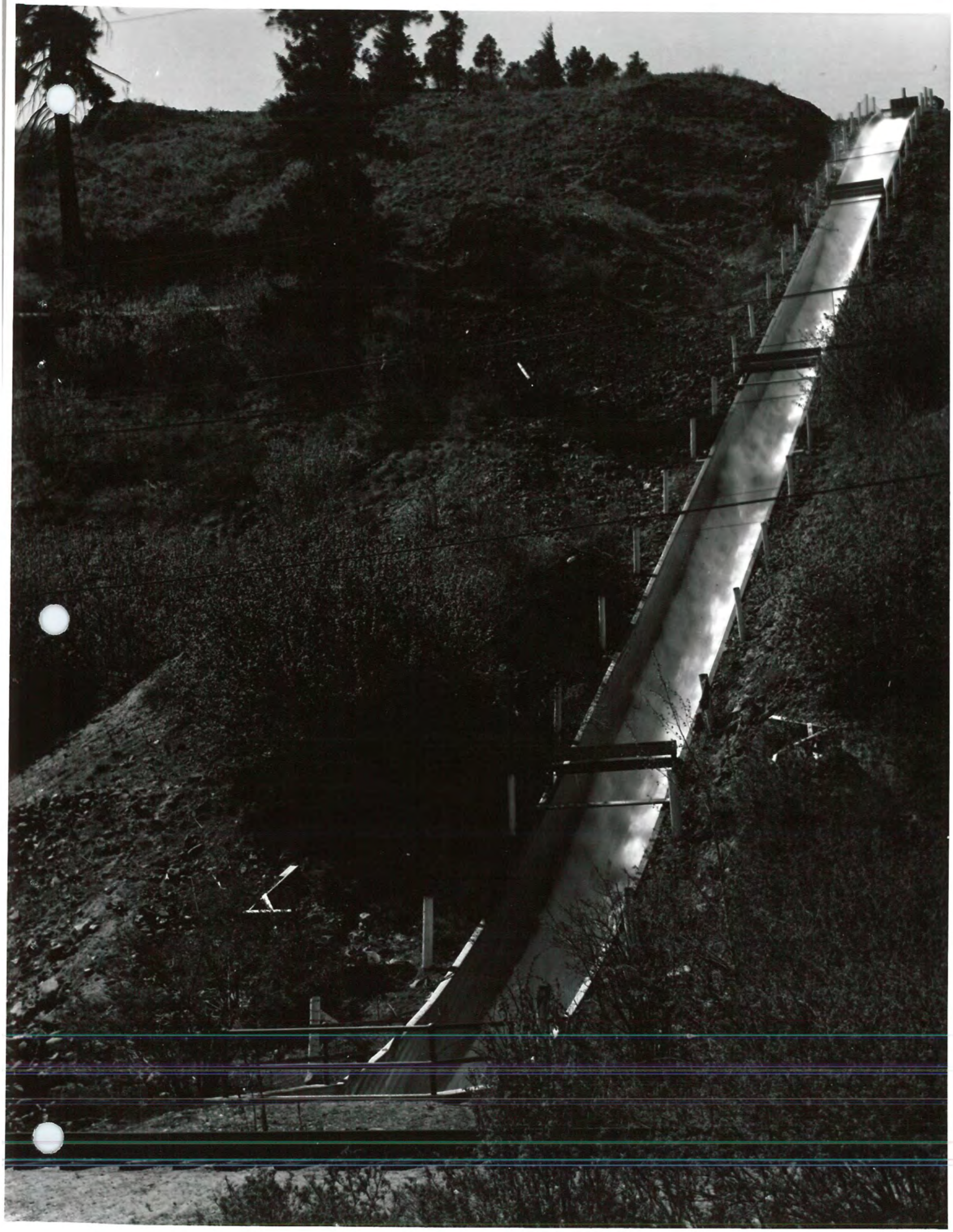


Figure 7--Air entrainment and surges in high velocity flow.

(Figure to be incorporated in page 28 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

Horizontal curves are to be avoided if possible in very high velocities. If used, adequate freeboard must be allowed because of the uncertainty of calculation of the exact water surface.

The entrance to chutes must be considered when making freeboard allowances. If flow conditions are not symmetrical at the entrance, diagonal waves may form, Figure 8. Hydraulic model studies may prove helpful in determining the amount of freeboard necessary and means of elimination or reduction of the waves.

Figure 8.--Waves in chute flow caused by entrance conditions.

Observations made on a high velocity chute 12/ show that the water surface is concave downward in cross section, being higher along the walls of the chute than in the center. As an example, with a discharge of 1,005 cfs in a rectangular chute of 8-foot width, at one station the water depth at the center was 2.48 feet while along the walls the depth was 2.84 feet and the mean depth was 2.65 feet. This would indicate a greater freeboard allowance than if mean depth were used in design.

The curves shown on Figure 9 may be used as a guide in designing freeboard in channels of rectangular or trapezoidal cross section for flows up to 100 second feet. On this curve

Q = discharge in cubic feet per second

Figure 8--Waves in chute flow caused by entrance conditions.

(Figure to be incorporated in page 29 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

V = velocity in feet per second

d = mean depth in feet

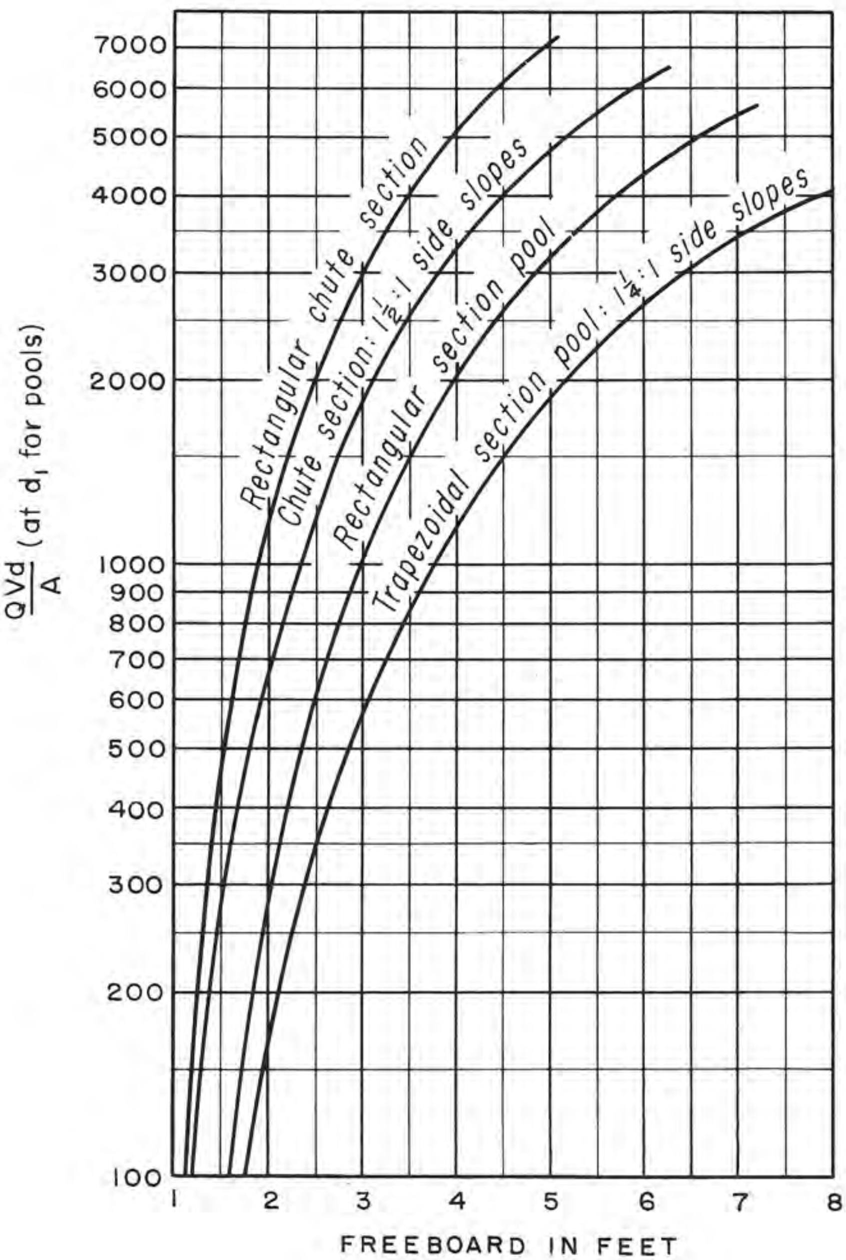
A = area of cross section of water in square feet

Large chutes beyond the range of these curves require special consideration in regard to possible damage to the structure and surrounding area. Minimum freeboard should be 1 foot, 1.25 feet, 1.5 feet for flows of from 0 to 10 cfs, 10.1 to 20 cfs, and 20.1 to 30 cfs, respectively. Freeboard should be measured normal to the bottom of the chute.

Figure 9.--Freeboard in chutes and stilling pools.

The freeboard for pools below drops and chutes is dependent upon the type of structure contemplated for energy dissipation and may vary widely. The primary consideration is the amount of turbulence and waves that may be formed. The hydraulic jump as a means of energy dissipation is very generally used in the United States. Freeboard for this type of pool may be calculated with a fair degree of accuracy because the laws governing this phenomena are fairly well known. Waves and turbulence are the unknown factors and are dependent upon the design of the entire structure. The probability of agradation or degradation of the channel downstream must also be considered.

The curves given in Figure 9 may be used as a guide for freeboard in small stilling pools. The water depth at the entrance of the pool is used for the value of "d." Minimum



$\frac{QVd}{A}$ (at d_1 for pools)
7000
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
1
2
3
4
5
6
7
8
FREEBOARD IN FEET
Rectangular chute section
Chute section: $1\frac{1}{2}$:1 side slopes
Rectangular section pool
Trapezoidal section pool: $1\frac{1}{4}$:1 side slopes

Figure 9--Freeboard in chutes and stilling pools.

(Figure to be incorporated in page 30 of paper "Considerations Affecting U. S. Practice in Providing Freeboard for Irrigation Works," Reeves and Thomas, U. S. Question No. 3.)

allowances should be 1, 1.25, 1.5, 1.75, and 2.0 feet for flows of from 0 to 5, 5.1 to 10, 10.1 to 20, 20.1 to 40, and 40.1 to 60 second feet, respectively.

Culverts and inverted siphons. These structures are, almost always, preceded and followed by transitions for which the freeboard allowances have been given. It is worthy of mention that unless ample capacity is allowed in the siphon barrel there may be an encroachment on the freeboard of the canal upstream. If the entrance and inlet leg of the siphon are designed in such a manner that air may be carried into the barrel, waves may be produced when this air is expelled at the downstream end and some additional freeboard may be necessary in the outlet transition. Air may also blow back at the entrance and cause disturbances. The freeboard at both the upstream and downstream head walls of these structures is important to prevent overtopping at these points and erosion of the backfill over the siphon or culvert barrel as well as the surrounding area. Considerable structural damage may result if water overflows the head walls and saturates the supports of siphon barrels laid above ground.

Flumes. For the purposes of this discussion a flume is defined as a complete, self-supporting artificial water conduit with a free water surface. It is used as part of the conveyance system to carry water along steep hillsides, across depressions, and through areas where lack of suitable material makes the construction of canal banks impractical.

The complete structure normally consists of an inlet, the flume proper, and an outlet. The inlet and outlet are transitions, except in rare cases, and the freeboard considerations stated previously apply. The flume proper may be of a number of shapes and design.

The general considerations and the considerations peculiar to lined canals previously stated apply to freeboard for flumes. In addition, particular attention must be given to design velocities. The velocities are usually high in flumes to reduce the section and cost. Ordinarily the velocities will be below critical. When critical velocities are approached, slight disturbances in the flow caused by minor changes in section, misalinement, or obstructions will cause an undulating water surface and freeboard allowances must be made for these waves. Extra freeboard is desirable for the first 20 to 30 feet of flume to care for rough water and lag in the surface drop while flume velocity is being developed.

Ample freeboard allowance is important in flumes because overtopping, even in relatively small amounts, may cause weakening of foundations and settlement. When settlement occurs additional water overtops the sides, and failure of the entire flume may result.

For semicircular metal flumes, the Bureau of Reclamation uses as a minimum freeboard, in feet, $0.1D\ (0.9 + h_v)$, where D is the diameter of the flume in feet and h_v is velocity head in feet. R. Hardesty Manufacturing Company recommends the use of a freeboard equal to 6 percent of the flume diameter for straight sections carrying water at velocities not greater than 80 percent of the critical velocity with a maximum of 8 feet per second.13/ If higher velocities are prevalent, freeboard must be increased because of possible wave formation.

Tunnels. Freeboard allowances for entrance and exit transitions for tunnels in canals and laterals have been discussed previously under open transitions. If the tunnel is designed to flow full, the primary consideration is proper design to insure that the desired quantity may be carried without causing encroachment on the freeboard of the canal upstream. If the tunnel is designed to operate as a free flow tube, freeboard is a consideration and must be ample to insure that if the tunnel fills the carrying capacity will not be diminished. Alinement, grade, and anticipated changes in roughness coefficients will affect freeboard. As a guide, the ratio of water depth to conduit diameter should not exceed about 0.83 to insure ample freeboard.

13/ Handbook of Water Control, R. Hardesty Manufacturing Company, Denver, Colorado, 1940.

REGULATING STRUCTURES

Regulating structures are defined as structures built in canals and laterals or distribution systems to provide specific control and measurement of water during transmission to a location of usage or disposal. Only the structures in most common use will be discussed.

Since these types of structures are usually preceded and followed by transitions, the same rules for freeboard allowances as given above, under "Transitions," will apply.

Checks. A check is a regulating structure placed across a canal or lateral to control the depth of water upstream or by operating in conjunction with a wasteway to control the quantity of water passing the check, or both. From this definition, it may be seen that the operation and relation of the check to other structures must be considered for freeboard allowances. The type of regulation provided, that is, whether gates or stop logs or a combination of both are employed, is important principally because of the time necessary to make changes. For instance, if stop logs only are employed some time may be necessary for manual removal and considerable freeboard may be necessary to prevent overtopping.

Adequate freeboard must be provided by the walls of the check structure. The walls are often carried to canal bank level to provide this freeboard. Little, if any, freeboard is necessary at the gates or stop logs since overflow will not harm the structure. The flow passing over the gate or stop logs will simply flow on down the stream. In fact, ample capacity over the gates or stop logs may tend to reduce the freeboard necessary for the walls of the structure.

Measuring devices. The more common types of measuring devices found in the canals and laterals are orifice structures, Parshall flumes, critical depth flumes, or some type of weir. When these types of measuring devices are placed in the conveyance systems, they may be preceded and followed by transitions for which the freeboard has been previously discussed. In general, the freeboard through the structure is added to the wall height, and the walls are usually carried to bank level or to top of lining in lined canals and laterals. The amount of freeboard is normally dependent upon the local conditions, and there are few general rules to be followed. In small orifice structures, it is well to consider the possibility of the orifice becoming clogged with debris coming down the stream. When a weir is placed across a canal or lateral there is danger of silting of the passage upstream from the weir. This silting may continue for some distance upstream and may seriously affect the freeboard allowed in this reach.

PROTECTIVE STRUCTURES

Protective structures are defined for the purpose of this discussion as structures which convey storm or drainage water over or under canals or provide controlled discharge of project water for purposes of safety, operation, or maintenance. Most commonly used of these structures are drain inlets, overchutes, spillways, and wasteways.

Drain inlets. Drain inlets are structures that carry water into a canal to prevent scouring of the banks. They are usually of small dimensions. Freeboard in such structures is normally of minor consequence.

Overchutes. An overchute may be defined as a flume type of structure that conveys drainage water across and above the canal prism. It disposes of drainage water and storm water debris which, if allowed to enter the canal, would decrease the canal freeboard and require additional protective structures.

The flume across the canal should have the same freeboard as discussed under the subject of "Flumes." The flume section is normally preceded and followed by inlet and outlet transitions which should have the same freeboard as discussed under "Transitions." In cases where the cross-drainage gradient is steep and where the flume slope selected gives high outlet velocities, the use of a chute or drop and a stilling pool may be required. Freeboard allowances should be similar to those discussed previously.

Spillways. Canal spillways are usually either of the side channel, overflow, or siphon type. Their normal function is to evacuate excess water from the conveyance system, thus permitting use of less freeboard in the channels. Siphon spillways present no particular problems concerning freeboard except that the discharge characteristics of the siphon must be known to design properly for freeboard in the conveyance.

For side channel and overflow spillways the freeboard must be adequate to protect the canal banks. The end structures are normally carried to the height of the banks or slightly above. A consideration other than flow characteristics is that spillways may be required to perform a secondary function of sluicing floating weeds, trash, or ice for the canal system.

Connecting channels between the spillway and point of disposal of the water, whether it be a drain or natural stream, may require freeboard considerations depending upon the type of channel employed.

Wasteways. Wasteways are provided in canal systems to dispose of excess water not removed by spillways. They should ordinarily be capable of discharging the entire flow, should an obstruction or break in the canal occur, or possibly a flow greater than the normal capacity, to include provision for unused irrigation water and flood water. The freeboard allowances will depend upon the type of channel used and, in general, follow the same rules as those given for canals or flumes, as discussed above.

In economic studies, it may be well to consider wasteways at frequent intervals instead of allowing extra freeboard in the canal proper. Cost of structures, cost of freeboard, and possible wastage of water and the value of this water must be considered. In the location of the wasteways, the possibility of salvaging the wasted water should not be overlooked. In regard to spillways from canals, long spills into pasture or well vegetated areas may not cause damage; in fact, it may be beneficial. These types of protective structures may be provided instead of additional freeboard in canals and laterals.

OTHER STRUCTURES

There are numerous other structures that do not require freeboard consideration in themselves, but which will affect the amount of freeboard calculated for the conveyance systems. Such structures as bridges, pipe line crossings, farm ditch crossings, and similar crossings that may obstruct the flow in the channel should be considered when freeboard allowances are being calculated for the channels.

DRAINAGE CHANNELS

For the purpose of this discussion, drainage channels will be divided into two general classes: those which are employed to remove excess subsurface water, and those which carry excess surface water away from the land. Those channels carrying surface run-off which originates above the irrigation areas, as well as those carrying excess water from the cultivated areas, are included in the latter category.

Drains for subsurface water. Open drainage channels that serve to remove the excess subsurface water from irrigated areas are located in the lowest parts of the topography. By virtue of this location, the surface flow is toward the channel; hence, no freeboard problems are involved.

Drains for surface water removal. This type of drain may be a natural water course, with or without artificial improvements, or an entirely new artificially created channel. In the first instance, the natural water course is situated in low parts of the topography and freeboard is not a problem. However, the improvements may include artificial channels that require freeboard considerations. Artificially created channels may be designed to carry considerable amounts of storm water originating in areas above the irrigated sections. For this condition, freeboard considerations may be an important factor to prevent flooding of adjacent improved lands. Freeboard generally will be small for these channels and will depend upon the type of construction used; that is, whether an earth or lined channel, or a lined chute. Unless there are particular circumstances that indicate more generous allowances, the minimum freeboard prescribed for canals will be quite adequate. If these channels become quite large, they may be contained by levees or dikes, the freeboard for which is discussed in the following section.

LEVEES AND DIKES

Considerations that govern freeboard allowances for levees and dikes are: the probable wave action inherent in the flow or caused by winds; the contemplated growth of vegetation in the channel; and the degree of protection desired against actual flood water levels rising above that calculated for the maximum flood.

The rise in the flood plane may be a general rise due to actual floods exceeding that assumed in the computations or local rises due to local physical changes in the channel, or unavoidable inaccuracies in the computations.

Computations for waves caused by winds on wide channels have been covered in other sections of this paper. The height of the waves caused by disturbances in the flow is a matter of judgment, and the freeboard requirements will include protection against these waves.

Allowances may be made in the computations for the design of the channel to care for the increased friction caused by vegetation growing in the channel and along the levees. If this increased roughness is contained in the calculations for the flood plane, additional freeboard may not be necessary. However, if this condition is not considered in the design of the cross section of the channel, then additional freeboard will normally be required.

The freeboard allowances for this type of construction will range from a minimum of 2 feet for levees or dikes along channels of small or moderate width protecting farm lands, the flooding of which would cause no great disaster, to 5 feet or more for similar structures on wide channels protecting property of high value or thickly populated areas. The freeboard should be applied to the flood water levels corresponding to the maximum flood against which protection is desired.

To protect the irrigated areas along the Sacramento River in California, a freeboard of 3 feet is allowed on the main river channels and 5 to 6 feet on the by-passes. This freeboard is applied to the flood planes computed for maximum flood flows having a probable frequency of about once in 25 years. The greater freeboard for the by-passes was adopted because of the greater wave wash in these wide channels whose widths range from about 1/2 to 3 miles and the desirability of providing surplus capacity for floods of greater intensity than those assumed in the flood plane computations.

Definition of freeboard. Freeboard is the vertical distance between the maximum reservoir water surface level that would be attained for the inflow design flood and the top of the nonoverflow section of the dam.

General considerations. The spillway capacity at the dam and the freeboard are so closely interconnected that a few remarks in regard to spillway capacity are in order. Adequate capacity must be provided in the structures to accommodate the inflow design flood by the most economical combination of storage, as provided by freeboard, and spillway capacity. In cases where auxiliary spillways may be used, the frequency, magnitude, and probable effect of flows in excess of the moderate frequency flood should be considered in adjusting the economic merits of that type of spillway against the increased freeboard necessary on the dam. As an auxiliary means of providing additional storage, a parapet, provided it is designed as a water barrier, is considered as part of the nonoverflow section of the dam in computing the freeboard. In the design of freeboard allowances for the dam, a conscientious effort should be made to avoid providing for maximum probable floods in conjunction with improbable simultaneous combinations of such factors as strong winds, earthquakes, and initially full, or nearly full, reservoirs.

Of first importance in considering the relation between spillway capacity and flood discharge is the accuracy of the estimate of anticipated maximum flood run-off and the time period or peaking characteristics of the run-off in relation to the depth of flow over the spillway and the corresponding storage capacity in the reservoir. The proper correlation of these factors applied to the critical condition of full reservoir at the time of contribution of flood inflow will determine the increment of freeboard that will be required by the rise of the reservoir water level. In the case of a controlled spillway crest, consideration must be given to the possibility of the failure of automatic gates to operate or human failure, if reliance is placed on manual control of gates and outlets. This consideration demands that the required freeboard provision be applied above the top of the gate.

The most critical condition, that for which the minimum safe freeboard is computed, is that due to the occurrence of the maximum anticipated flood at a time when the reservoir is at normal water surface elevation. The rise in the reservoir due to the flood is dependent on the quantity and duration of the flow, storage capacity at various elevations, and discharge capacity of the spillway and outlet works for the period considered. In other words, the flood rise will be the increase in water surface resulting from the net difference between the flood inflow and the discharge outflow.

Another factor to be considered in establishing total normal freeboard is the possible rise in water surface during the maximum anticipated flood. If it is determined that the maximum flood flow will cause a rise in water surface above a level corresponding to an elevation of one-half the distance of the normal freeboard, the total normal freeboard is increased accordingly. Current procedure in establishing freeboard in relation to storage may be summed up as follows:

(1) The reservoir water surface elevation during the infrequent flood should not exceed that used in computing the normal freeboard.

(2) The reservoir water surface elevation during the maximum anticipated flood should not encroach on more than one-half the normal freeboard.

The importance of adequate freeboard cannot be overstressed. The provision of ample freeboard in relation to the designed spillway and outlet capacity is therefore fundamental to the safety of the structure. While, in many cases, the amount of freeboard appears to be determined largely by custom, there are a number of general factors that must be considered in determining the minimum requirements. In addition to the relationship of the spillway discharge capacity to flood runoff and reservoir storage, which is mentioned above, the effect of winds on the reservoir must be considered. The freeboard allowance at a dam must guard against overtopping of the dam by waves on the surface of the impounded water. The wind effects upon the water may result in wind waves or wind tides, otherwise known as set-up. Either will cause a rising water surface at the dam somewhat higher than stillwater level. Such other factors as steepness and type of material affording protection of the upstream slope, size, location, and importance of the dam are also to be considered.

The total normal freeboard requirement is computed by adding the flood water rise, height of waves, wave set-up (if considered important), and runup of the waves on the slope. Each of these factors should include a proper margin of safety.

Effects of wind. As stated above, freeboard must be adequate to prevent overtopping of the structure by waves on the surface of the impounded water. The height of the waves will depend on the reservoir fetch, wind velocity, and, to some extent as affecting freeboard requirement, on the steepness of the upstream slope and the type of protective material.

In determining the required freeboard of the dam, the effect of seiches, wind set-up, wave height, and wave runup are to be considered. Seiche is the oscillation or undulation of the lake surface. The period may vary from a few minutes to several hours. Wind set-up is the actual displacement of water in a lake due to very strong or continued winds. Water from the windward end of the lake or reservoir is actually moved toward the leeward end. Wave runup is the height above stillwater level to which the waves will follow up the face of the dam. It has been customary to ignore seiche effects, except where experience has shown such phenomena to exist. This information is available for large bodies of water, such as the Great Lakes, but any allowance for seiche effect in an artificial body of water would be arbitrary.

Wind set-up can be computed by the Zuider Zee formula: 14/

$$S = \frac{V^2F}{1400D} \cos A \qquad (12)$$

in which:

S is the set-up in feet above stillwater level

V is the wind velocity, in miles per hour

F is the fetch, in miles

D is the average depth of water in the reservoir in feet

A is the angle of incidence of the waves

It has been customary to take D as two-thirds of the maximum depth of the reservoir at the heel of the dam.

More recent work on wind set-up on inland waters 15/16/ provides additional information on this subject that may be

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14/ "Review of Slope Protection Methods," Report of the Subcommittee on Slope Protection of the Committee on Earth Dams of the Soil Mechanics and Foundations Division, Proceedings of the A.S.C.E., June 1948, Vol 74, No. 6, p 845.

15/ Keulegan, Garbis H., "Hydrodynamic Effects of Gales on Lake Erie," Journal of Research of the National Bureau of Standards, February 1953, Vol 50, No. 2, p 99.

16/ "Wind Set-up and Waves in Shallow Water," Technical Memorandum No. 27, Beach Erosion Board, Corps of Engineers, June 1952.

made use of if extensive study appears necessary or desirable.

The formulas for computing wave height generated by winds have been given previously under the subject of canals. Factors which limit their accuracy are the influence of the topography surrounding the reservoir basin, direction of the prevailing winds, and the shape of the reservoir. In general, accurate data relative to the height of wave on the impounded water are not yet available, except in a few isolated cases.

The effective fetch is usually considered as the normal distance from the windward shore of the reservoir to the structure being designed. The effective fetch may have a curved path, as in the case of a wind sweeping down a slightly curved valley between high land ridges. The probability that the effective fetch may be determined by a curved path, rather than by a straight one, may explain some of the exceptionally high waves sometimes observed in long winding reservoirs.

Although the Stevenson-Molitor formulas are still in general use, experience has proved that the results do not assure reliable indications of critical wave heights, occasions having been reported in which wave heights have exceeded those given by the formulas. Accordingly, wave heights computed from the formulas should be considered as approximate and more representative of average occurrences than the usual events involved in structural design. Further research and study of this problem are important to the engineering profession. Until such time as additional information is available, the use of the Stevenson-Molitor or other empirical methods must be tempered with judgment.

Wave ride-up may be an important consideration in some instances. The previous discussion on rise of wave crest above stillwater level when the wave strikes an obstruction, under the subject of canals, will also apply to dams. The slope of the upstream face is the major factor.

Concrete dams. Freeboard allowances for concrete dams, whether they be gravity, arch, or buttress type, should be calculated in accordance with the general considerations enumerated above. Usually, no additional special considerations are involved in the calculations for freeboard for these types of dams. Since the upstream face of a concrete dam may be vertical, or nearly so, it must be borne in mind that waves striking normal on such an obstruction will cause the crest to rise to double its ordinary height above stillwater. The general practice is to make the freeboard in even feet, although occasionally 1/2-foot increments of freeboard are used. Table 2 gives the freeboard allowances for selected concrete and masonry dams constructed by the Bureau of Reclamation.

Earth dams. Adequate freeboard for earth dams is very important. Most earth dam failures have resulted from overtopping during flood conditions caused by inadequate freeboard or spillway capacity. In addition to the general considerations outlined above, the steepness of the upstream slope of the dam and the depth of frost penetration probably represent the major special considerations in determining minimum requirements.

Dynamic forces exerted by wave action are ordinarily negligible with respect to an earth dam. Concern is chiefly with the effects of erosion and saturation. Waves overtopping the crest will produce destructive erosion, and spray will saturate the embankment between normal water surface and the crest. The result will be sloughing of the upstream face, unstable embankment conditions, and opportunity for destructive frost action in cold climates.

The steepness of the upstream slope and the material with which it is surfaced will have some effect on the extent of the wave travel. Waves will mount higher on a flat than on a steep slope, and, in excess of their own height, on comparatively flat slopes. More of their energy will be destroyed in travel over a rough surface, such as dumped rock or riprap, than over a smooth surface such as a concrete pavement. There is no exact information on these phenomena; and the freeboard provision is, therefore, a matter of experience, judgment, and consideration of local factors. One rule for wave runup is to take 1.5 times the wave height, measured vertically from the stillwater level, and consider this the maximum height to which the wave will ride up on the sloping face of the dam.

Table 2

FREEBOARD ALLOWANCES ON CONCRETE AND MASONRY STORAGE DAMS

Name of dam	Type of construction	Height in feet	Freeboard to top of dam in feet	Height of parapet in feet
Concrete Dams				
Hoover (Boulder)	Arch gravity	726	10.6	4.0
Shasta	Curved gravity	602	12.5	—
Grand Coulee	Gravity	550	23.0	4.0
Owyhee	Arch gravity	417	5.0	3.67
Arrowrock	Arch gravity	349.5	6.0	3.75
Friant	Gravity	319	3.25	3.75
Elephant Butte	Gravity	301.2	7.0	5.0
Marshall Ford	Gravity	278	36.0	4.0
East Park	Gravity	137	3.5	—
Altus 1/	Arch gravity	110	5.0	3.0
Buffalo Bill (Shoshone)	Arch	325	10.0	4.0
Parker	Arch	2/ 320	5.0	4.0
Seminoe	Arch	295	4.0	3.5
Gibson	Arch	198.5	1.5	3.5
Deadwood	Arch	165	6.0	3.5
Gerber	Arch	88	6.5	3.5
Bartlett	Multiple arch	287	4.0	—
Stoney Gorge	Slab buttress	139	6.0	3.5
Thief Valley	Slab buttress	73	10.0	3.0
Cyclopean Masonry Dams				
Roosevelt	Arch gravity	280	8.0	4.0
Pathfinder	Arch	214	8.0	4.0

1/ Concrete, masonry faced
2/ Seventy-five feet above stream bed level

For small earth dams and reservoirs less than 1/4-mile long, The National Resources Committee 17/ recommends a minimum freeboard allowance of 2 feet in warm climates and 3 feet in the northern United States.

Table 3 gives freeboard allowances for selected earth dams constructed by the Bureau of Reclamation.

Diversion dams. Diversion dams do not ordinarily impound large amounts of water. There are occasions when a diversion dam also serves to reregulate the flow in the stream, and considerable water may be stored. In the calculation of freeboard for a diversion dam, the size of the pool upstream from the structure, its importance, and the possibility of debris clogging the overflow section must be considered. A rule that may be used for the calculation of freeboard for the nonoverflow portions of a diversion dam is to allow a minimum of 3 feet. The practice in the Bureau of Reclamation is to calculate the pool water surface elevation with flow over the overflow section for the 50-year flood, then to calculate the water surface elevation for a 100-year flood. If the water surface elevation for the 100-year flood is over 3 feet, the higher figure is used. More important diversion dams now being designed will have a freeboard in excess of that indicated above.

17/ "Low Dams," A Manual of Design for Small Water Storage Projects, National Resources Committee, United States Government Printing Office, Washington, D.C., 1938.

Table 3

FREEBOARD ALLOWANCES ON EARTH DAMS

Name of dam	Height above foundation in feet	Freeboard to top of dam in feet	Height of parapet in feet
Green Mountain	309	10	3.0
Alcova	265	10	3.67
Deer Creek	235	8	3.5
Tieton	235	9	2.0
Taylor Park	206	14	3.75
McKay 1/	180	8	2.5
Vallecito	162	8	3.0
Cle Elum	160	10	3.0
Echo	158	10	3.0
Alamogordo	148	10	3.0
Guernsey	135	10	3.0
Belle Fourche	122	15	2.0
Lahontan 2/	122	12	--
Grassy Lake	118	8	1.9
Hyrum	116	8	3.0
Boca	116	7	2.0
Caballo	112	6.5	3.0
Fresno	111	22	--
Agency Valley	110	8	3.0
Pine View	103	7	3.5
Moon Lake	101	8	3.0
Kachess 2/	92	5	--
Minidoka 3/	86	5	3.0
Deer Flat	70	7.5	3.0
Avalon	58	16.6	--

Notes:
1/ Gravel fill
2/ Earth fill and gravel fill
3/ Earth fill and rock fill

Table 4 gives freeboard allowances for selected diversion dams constructed by the Bureau of Reclamation.

SPILLWAYS FOR DAMS

For calculating freeboard allowances for training walls for spillways, it is necessary to consider the accuracy of the depth of flow determinations; the amount of air entrained in the flow; the probability of the formation of diagonal wave patterns induced by piers, contractions or expansions of the water prism, unsymmetrical flow created by approach conditions, control gates, curves, or irregularities in the structure; and the damage that might result to power or other installations if water overflows the training walls. Some of these considerations have been covered previously in the discussion of chute flow.

Model studies are of considerable help in determining the possibility of wave patterns forming in the spillways. Air entrainment problems cannot as yet be solved by model studies.

One rule that is used for calculating the freeboard for training walls on spillways is to allow 100 percent of the computed entrained air, plus 5 feet, in structures of major importance.18/

In many instances, spray caused by wave patterns and disturbances in the flow can overtop a normal training wall.

18/ Gumensky, D. B., "Air Entrained in Fast Water Affects Design of Training Walls and Stilling Basins," Civil Engineering, December 1949, p 35.

Table 4

FREEBOARD ALLOWANCES--DIVERSION DAMS

Name of diversion dam	Diversion in second-feet 1/	Height in feet 2/	Freeboard in feet 3/
Easton	1,320	51.0	4.2
Willwood	320	41.0	5.5
Roza	2,200	34.0	4.4
Lost River	1,200	26.0	5.0
Imperial	17,160	23.0	6.0
Harper	660	21.0	7.0
Wind River	2,200	19.0	5.0
Percha Arroyo	30,000	19.0	5.8
Cross Cut Canal	590	14.5	3.5
Grand Valley	1,425	14.0	4.0
Lower Lost River	810	12.0	2.7
Murdock	550	10.5	3.0
Fort Sumner	100	10.0	3.0
Laguna (completed 1908)	1,950	10.0	1.7
Superior Courtland	890	9.5	5.0
Power Canal	220	8.0	2.0
Sweetwater	77	8.0	2.0
Webb Creek	20	8.0	2.0
Dunlap	220	7.5	3.0
Fire Mountain	180	5.0	2.0
Cambridge	325	3.0	4.0
North Poudre	250	2.5	2.3

1/ Diversion provided by canal headworks at dam

2/ Height is given between original stream bed and highest controlled water surface

3/ Distance from maximum operating water surface level to top of nonoverflow sections. For dams equipped with gates, the distance from top of gate

This spray can be very destructive to power installations, and, in some instances, additional curtain walls have been added above the normal training wall to curtail the spread of this spray into areas containing electrical equipment.

STILLING POOLS FOR SPILLWAYS AND OUTLET WORKS AT DAMS

The general rules previously given will apply to freeboard allowances for small stilling pools for spillways and outlet works at dams. However, in most instances, these structures attain sizable proportions and require special consideration. Each must be considered on the basis of prevailing local conditions. Hydraulic model studies are often required to fix the height and length of the training walls.

CONCLUSION

The authors believe that proper freeboard allowance in all irrigation works is an extremely important design consideration. Economy dictates conservative freeboard, but the fact that the safety and continued operation of the works must be assured if the primary purpose, namely, that of delivering water for irrigation of crops, is to be fulfilled. Failure of the system and loss of these crops could be an economic disaster to a developed area. Therefore, it may be false economy to provide minimum freeboard allowances.

If due consideration is given to all the influencing factors set forth in this paper and the conditions existing in the field are carefully analyzed, adequate freeboard should result.

SUMMARY

This paper deals chiefly with the considerations that influence freeboard allowances in irrigation works. In instances where approximate solutions may be obtained by rational methods, the methods involved are described.

Rules in common usage in the United States are included where appropriate.

Because hydraulics is not an exact science, the precise amount of freeboard to allow cannot be determined by purely analytical methods. Therefore, the experience and judgment of the designer combined with careful analysis of the conditions prevailing at each particular locality are important factors in establishing proper freeboard allowances. Since the Bureau of Reclamation has built a large number of complete irrigation systems, considerable experience has been gained. This experience has made possible the development of guides for use in designing freeboard. A number of these guides are included in the paper.

First, there is a brief discussion of the considerations affecting freeboard that apply generally to all irrigation works. Among these are: safety, economy of design, critical evaluation of all design criteria, manner of operation of the completed works, size and importance, location, climate, and the adequacy of other safety devices included in the works. This discussion is followed by a review of the factors that

influence freeboard allowances in canals, laterals, and farm ditches, with and without hard surface linings. Flows above and below critical velocity are examined. The influence on freeboard of depth of flow, wind action, entrance of storm water, regulations due to operation, location, alinement, soil characteristics, sudden fluctuations of water surface, and possible changes in carrying capacity of the system from extraneous causes, are evaluated. There is a section devoted to waves, since they have an important bearing on freeboard both in canals and at dams.

The factors that must be considered when making freeboard allowances in the various types of structures in the irrigation system are enumerated and their influence evaluated. This is followed by a coverage of the freeboard considerations for drainage channels and levees on flood channels.

The paper closes with a discussion of the different effects of winds on reservoirs, such as seiche, wind waves and set-up, and runup of waves and their influence on freeboard for dams. Tables are given showing the amount of freeboard allowed at selected concrete, masonry and earth storage dams, and diversion dams. Conditions affecting freeboard in spillways and outlet works for dams are explained.

The authors believe the more important considerations are set forth, and if each is given proper attention in relation to existing field conditions, adequate freeboard should result.