FLOOD CHARACTERISTICS AND SPILLWAY DESIGN

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SYNOPSIS.

Floods are of probabilistic character, while hydraulic structures for flood evacuation have deterministic properties. As floods are the primary factor for consideration, the design of spillways and other flood discharge structures should be adapted to the probabilistic phenomenon.

The concept of maximum probable flood of a river basin is defined in the Borel's sense.

The difficulties in determining reliable flood probability distributions from small samples of flow records do not justify a change from the probabilistic to the deterministic principle in spillway design.

Changes in flood probability distributions with time due to man-made changes in river basins should be allowed for in estimating the probability of rare floods. These probability estimates should also take account of the probability distribution of reservoir level at commencement of the flood.

The characteristics of flood phenomena suggest the spillway should be designed in such a way that the rate of change dQ/dH of the spillway capacity rating curve should increase with an increase of discharge. Spillways with the flow under pressure for the largest floods should be provided with safeguards of the free surface flow type.

RESUME

Les crues sont des évenements régis par les lois des probabilités. Les évacuateurs de crue, au contraire, ont des dimensions bien déterminées. Le calcul des évacuateurs étant surtout fait en fonction des crues, il doit tenir compte de leur caractère probabiliste.

La notion de crue maximum probable d'un bassin versant est définie au sens de Borel.

Les difficultés d'obtenir la loi des probabilités des crues à partir d'observations de débits sur des périodes relativement courtes, ne peuvent pas justifier l'abandon des principes probabilistes pour des considérations purement déterministes dans l'étude des évacuateurs de crue.

L'évolution dans le temps de la répartition des probabilités des crues, due aux changements apportés par l'homme au bassin versant, doit être prise en considération. Cette répartition doit aussi tenir compte de la probabilité du niveau des réservoirs au commencement des crues.

Les caractéristiques des crues suggèrent que la dérivée de la courbe des débits dQ/dH croit avec le débit maximum d'une crue. Les évacuateurs fonctionnant en charge lors de crues exceptionnelles deveraient être amenagés par des évacuateurs complémentaires de secours où l'écoulement serait à surface libre.

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INTRODUCTION

Flood events can be described by a set of random variables such as peak flow, peak level, and flood volume. These random variables are being determined currently by their probability distributions, with the probability usually expressed in practice by its reciprocal as the flood return period. Floods should be, therefore, treated from a probabilistic point of view in hydrologic design.

The hydraulic phenomenon of flood discharge at a dam has the property of a unique relationship of reservoir level to discharge, for given openings of gates and valves at spillways and outlets. Hydraulic design of flood discharge structures may be, therefore, considered from a deterministic point of view, because for given conditions the design outflow can be uniquely determined.

The integration of two phenomena, one of probabilistic and the other of deterministic character is usually a difficult engineering problem. Both approaches have been used in the hydrologic design of spillways in the past, the probabilistic by the concept of flood probability distributions, and the deterministic by the concepts of maximum possible flood, maximum probable flood, and maximum observed flood.

This paper discusses the question of whether the hydrologic design of spillways should be completely adapted to the probabilistic character of floods, or whether the difficulties in design resulting from this approach should impose a more deterministic standpoint with an assessment of the greatest possible or fixed probable flood event expected in the future.

FLOOD CHARACTERISTICS

Floods as random variables.

Any flood random variable depends on a large number of causes, but mainly on rainfall events.

As an example, the total water volume of 47 flood hydrographs from small watersheds (areas up to six square miles) in the U. S. A., was related to different variables in a stepwise multiple linear correlation analysis. The explained variance of the several correlations given by the multiple coefficient of determination R^2 (both biased and unbiased), is represented in fig. 1.* About 10 variables explain around 93% of variation, while all other twenty (by neglecting the loss of degrees of freedom, and using the biased R^2) increase the explained variance by around 4%. The most significant variables in these correlations are rainfall characteristics. As the rainfall is also described by several random variables depending on a large number of causes, the number of causes which affect floods is increased substantially. This explains the fact that floods are random variables.

Envelopes of specific floods.

Experience shows that, on the average, the longer the period of flow observations in a large region, the greater is the largest observed flood event. Figure 2 demonstrates this simple fact by the properties of envelopes of specific peak flood flows (peak flow divided by river basin area) plotted against river basin area for observations in the period 1900-1920, 1900/1930, ..., and 1900-1960 of many river gaging stations in the Columbia River Basin, U. S. A. The envelope of largest floods, a hyperbolic function plotted as straight lines in log-log graph, shifts to greater values as the period of observation increases.

*Brian M. Reich, "Design hydrographs for very small watersheds from rainfall," Ph. D. dissertation, Colorado State University, July 1962.

A question can be rightfully posed. Can an envelope (line 6, fig. 2) be conceived above the envelopes of observed data of fig. 2, which could not be attained or exceeded in the future, assuming that the river basins, their flood producing characteristics, and climatic conditions do not change for a long period?

Different concepts of largest floods.

It is normal to expect that a small brook cannot have as high a flood event as a large river. On the other hand, there is no physical evidence that limiting factors exist in producing large storm events. Statistically speaking, there is no physical evidence that the tail of flood probability distributions is bounded on the side of the largest events. The tails of flood probability density functions converge fast or slow toward zero as the peak flow increases for small or large river basins, respectively.

The manner in which the concept of largest floods is defined in principle affects the main approach to the design of flood discharge. When the flood phenomenon is conceived with an unbounded tail of flood probability distributions, the approach to flood discharge may be the same as in the case of any practical problem involving the risk of given, but small, chances. For any selected peak flood flow Q with a given small probability of occurrence P, a greater flood peak $Q + dQ$ with a smaller probability $P - dP$ may occur. This leads to the Borel approach, which may be applied to largest floods, that risks with probability of the order of $1{:}10^5$ or $1{:}10^6$ should be accepted, as many risks of those probabilities are automatically accepted in everyday life.

A dilemma exists between a physical approach to support the concept of an upper boundary in the flood probability distribution, and a conventional approach to assume a threshold of accepted risks, on the unbounded tail of the probability distribution. Selection of the appropriate concept is being affected in practice by the availability of methods for the estimation of very large floods.

Difficulties in using small samples of data.

Samples of flood events are usually small, ranging in the order of several decades of observations. The probability distribution curves of floods, taking into account both the errors in computed flood variable and the sampling error, therefore, have very large confidence intervals for the standard levels of significance (10% or 5% level) in the region of the higher observed flood flows. The extreme parts, as well as the extrapolated parts, of flood probability distribution curves are, therefore, unreliable. The great difficulties in the application of, and the reservations about, flood probability distributions result from the use of small samples, and in the attempts to derive information on rare floods far beyond the potential of small samples.

A method of avoiding the danger of the small sample approach is the use, for design purposes, of the upper curve of the confidence interval on 5% or 10% level of significance computed around the flood probability distribution curve of small sample records.

Deterministic approach to flood analysis.

The above difficulties in the probabilistic approach to floods have induced practicing engineers to search for the solution of flood problems in the deterministic approach, through the concepts of maximum possible, maximum probable, and maximum observed floods, with these values considered as fixed for a river gaging station. The basis for this concept is the analysis of maximum intensity of rainfall events.

In order to avoid the difficulties of the small sample approach to flood probabilities, this second concept starts from the determination of maximum rainfall intensity, adding two other factors, the transposition of rainfall hyetographs from one observed position to another, and river basin response (infiltration rates, unit hydrograph, or distribution graph).

There is legitimate doubt about the validity of concepts underlying this approach, namely, the ideas of maximum possible rainfall intensity derived by meteorological analyses from small samples of meteorological data. There are no physical factors supporting the concept of boundaries in the tails of distributions of the several meteorological variables that affect the largest rainfall intensities. The transposition of the largest regional hyetographs to the position in a river basin which gives the maximum flood hydrographs poses the question of the probability that any new similar event would be located just in the most unfavorable position. There is a problem of geometric probability in flood hyetograph locations.

Though this approach has no theoretical background to claim that there is a fixed maximum flood, it gives an insight into the order of magnitude of the rare events.

Use of the term maximum probable flood, without stating what is the probability, conflicts with the objective definition of probability, which implies that the use of term probability must always be associated with a number from zero to unity, including the impossible event ($P = 0$) and the certain event ($P = 1$).

Nonstationary time series.

Time series of flood events at a river cross section are frequently nonstationary. The flood characteristics change with time because of man-made effects. The main causes are: (a) newly created reservoirs that modify the floods; (b) change in the operational practices of existing reservoirs or lakes; (c) sedimentation of reservoirs and lakes, with gradual loss of space for flood modification; (d) prevention of flood plain inundations.

Time series analysis of any flood variable, however, must be restricted to a time period in which such nonrandom factors affecting flood events remain unchanged. In cases where changes in these factors do occur, the computation of flood probability curves, or of flood events of a deterministic concept, becomes a problem of joint probabilities of natural flood events and modifications by the above factors.

Modified floods for spillway design.

The probability of the reservoir level at which the extreme flood events occur is a function of the inflow distribution, the release rule, and reservoir characteristics. Assuming a combination of cyclic walk (as it relates to the within-the-year flow fluctuation), and a random walk of both within-the-year and from-year-to-year fluctuation, for the inflow into, and a given outflow regime of the reservoir, then a joint probability distribution of reservoir level prior to flood and the flood event itself may be determined. This joint probability distribution would give a new flood probability distribution of the flood outflow characteristics by applying flood routing methods.

Application of stochastic processes to determine the probability of lake or reservoir level prior to the flood inflow promises a new approach from both theoretical and practical aspects of this problem, while synthetic hydrology may simplify the practical aspects.

Randomness of flood time series.

The fact is that annual maximum flood events are close to a random time series. Correlograms of annual floods of many stations show that from the practical point of view the time series of annual maximum peak flows is random in sequence, or that the members of the time series are independent of each other.

CHARACTERISTICS OF FLOOD DISCHARGE AT DAMS

Flood discharge structures are usually divided from the hydraulic point of view into two basic groups: (1) free surface flow for all flood events; (2) flow under pressure for largest floods.

Free surface flow.

The most general hydraulic relationships in the first case are given by expressions of the type

$$Q = MH^{3/2} \qquad (1)$$

with H = energy head above the spillway crest elevation, and M = factor which depends on the geometric characteristics of the structure, mostly on spillway crest length and shape, lateral or intermediate contractions, boundary conditions for the approach to the spillway, surface roughness of the crest, the submergence of the flow, etc. The power $3/2$ for H is an approximation. As some factors imply that M is related to H, the power of H differs from case to case. Figure 3, curve 1(B - H) represents this first case.

Flow under pressure.

The hydraulic relationship for pressure-type flow is given by the general expression:

$$Q = mAH^{1/2} \qquad (2)$$

with A = cross section area of the conveyance structure (or an equivalent, if A changes from one cross section to another), H = head difference on the energy line between the headrace and tailrace points, and m = a factor which is function of length, cross section shape, roughness, and singularities and other characteristics of the discharge structure. In general, the relationship of reservoir level to discharge capacity for all gates and valves open follows the rating curve of eq. (1) to a specific value Q_s, or a short range of Q-values, fig. 3, curve 2 $(A - S_1)$, then the structure becomes under pressure for $Q > Q_s$, and follows the rating curve of eq. (2), fig. 3, curve 2 $(S_1 - C)$.

Flood damage.

In general, the passage of a flood is associated with damage, usually only for rare events. The losses start with a high flood event, but then increase with an increase of either flood peak or duration. There is also either a specific value or a range of values for flood peak and flood duration, which may produce failure of the dam and/or of other structures.

The trend in design of spillways, dams and reservoirs for the past decades, as it concerns the flood discharge, has been to minimize the damage function. The damage would start at a great discharge and increase slowly as peak discharge increases. Thus the specific discharge of great destructive potential would be shifted to a high value on the rating curve by appropriate safeguards. This trend was justified in the past, and it will be more so in the future.

INTEGRATION OF FLOOD AND SPILLWAY CHARACTERISTICS IN DESIGN OF FLOOD DISCHARGE WORKS

Objective definition of maximum probable flood.

It is assumed here that the concept of maximum probable flood, as determined by meteorological analysis of rare rainfall intensities and from river basin response has an objective definition in the Borel's sense. Namely, the flood events greater than the maximum probable flood have a probability of occurrence of the order of $1:10^3$ to $1:10^5$. Thus, the subjective aspect of maximum probable flood is eliminated. The concept of maximum possible flood has no theoretical support.

Probabilistic approach.

The probabilistic approach to flood discharge at dams may be applied in such a way that a good integration of flood and spillway characteristics is obtained. This will be accomplished if the analytical, experimental, and structural hydraulic studies concentrate on obtaining discharge structures that are suitable for all flood events, especially those of unusually small probabilities, instead of achieving the best hydraulic performance for a given flood event (design flood).

There are thousands of dams already built in the world, and more and more will be constructed in different climatologic and hydrologic regions. The probability that a very rare flood (i. e., greater than the maximum probable or design flood) would occur at one or several dams among these thousands in a year is sufficiently large in order not to be neglected. Though each dam may be considered individually as safe, if the flood evacuation structures are determined for large design floods, all dams taken together would have non-negligible probability of occurrence of extremely large flood events at some of them in a time unit. This is a disadvantage of the deterministic approach to flood evacuation design, if no special attention is given to the problem of discharge of larger floods than the maximum design floods.

Flood-spillway design integration.

The slopes of the spillway rating curves of eqs. (1) and (2) are respectively

$$\frac{dQ}{dH} = \frac{dM}{dH} H^{3/2} + \frac{3M}{2} H^{1/2} = \frac{Q}{M}\frac{dM}{dH} + \frac{3M}{2}\sqrt[3]{\frac{Q}{M}} \tag{3}$$

$$\frac{dQ}{dH} = \frac{mA}{2} H^{-1/2} = \frac{m^2A^2}{2Q} \tag{4}$$

with M dependent on H, and m and A considered as independent of H.

One way of measuring how the flood probability characteristics are integrated into spillway design may be obtained by relating the rate dQ/dH to a characteristic of flood probability distribution. This characteristic may be the probability of flood exceedence $P(Q)$, the probability density $p(Q)$, the return period $1/P(Q)$, or similar.

Assuming the return period $1/P(Q)$ as this characteristic, and taking the flood probability distribution in the form of the double exponential function of largest values

$$P(Q) = \exp\left[-e^{-\alpha(Q - Q_m)}\right] \tag{5}$$

with Q = any peak flood flow, Q_m = mode flow, and α = shape parameter, then the curve $dQ/dH = F[1/P(Q)]$ may serve as integration measure.

In the case eqs. (3) and (5) are applied, then the curve obtained is

$$\frac{Q}{M}\frac{dM}{dH} + \frac{3M}{2}\sqrt[3]{\frac{Q}{M}} = F\left\{\exp\left[e^{-\alpha(Q - Q_m)}\right]\right\} \tag{6}$$

in which both dQ/dH and $1/P(Q)$ increase with an increase of Q. This curve changes from one design to another, and may be used as the measure of flood-spillway integration.

Safeguards for spillway design.

The rate of change of spillway capacity rating curve increases faster than linearly with the discharge for free surface flow, while the rate dQ/dH for flow under pressure decreases with an increase of discharge. Any hydraulic design of flood discharge with the submergence effect (i. e., lateral collectors on spillways), which decreases M with H for very large Q, or any closed conveyance structure which comes under pressure for large values of Q must be considered as a potential source of future trouble, if safeguards are not provided.

These safeguards are of different types, and some will be described here briefly.

The factor M in eq. (1) may be maximized for given topographic characteristics of a dam site by a proper selection of spillway crest length, shape, and other design elements. This determines the position of curve 1 of the graph, fig. 3, as well as the rate of change dQ/dH. If the crest is shaped in such a way that M increases with an increase of H, even with a pressure drop on the crest until pressure approaches zero permitting cavitation to take place for large flood events, the rating curve may be substantially improved, as shown in fig. 3, curve 1a(B - I).

A safeguard in spillway design is to reverse the slope of the rating curve at the point S_2, or S_3, fig. 3, in order to counteract the inflection of the rating curve, which occurs at the point where free surface flow passes to flow under pressure, thus avoiding a rapid increase of reservoir level for a small increase of the flood peak (fig. 3, curve 2, point S_1). The reversal may be obtained by two main design approaches: (a) an emergency facility to discharge flood excess by surface flow over the dam, the part of dam, or by a side arrangement, which is unaccounted for the regular spillway capacities; and (b) any structure designed to be destroyed at a point S_3 (such as a fuse-plug dam), and to be reconstructed after the flood event.

While the number of earth and rockfill dams constantly increases, both because the sites that favor concrete dams become exhausted with time, and because of constant improvements in the design and construction of filled dams, the hydraulic and structural problems of shaping these dams to allow safe water overflow on rare emergency occasions remain unsolved. Solution of these problems, or, alternatively, the use of side emergency spillways would result in a rating curve of the slope given by curve 2-3, fig. 3 (A - S_1 - S_2 - D). Some small dams in soil conservation work have spillways of two types combined, one of closed type and the other of emergency free surface flow, thus resulting in a total capacity rating curve similar to the curve 2-3 of fig. 3.

The "fuse-plug dams" are convenient safeguard solutions at many dam sites. They are usually designed as temporary structures to be destroyed during exceptional floods, but to be reconstructed after the flood event. They increase the capacity and safety for flood discharge. A negative wave created by sudden removal of the fuse-plug results in a complex rating curve with two branches, one for the rising flood limb, as curve 2-4a-4 (A-S_1-S_3-S_4-E), fig. 3, and the other for the falling flood limb, as curve 4-4b-2, (E-S_4-F-A), fig. 3, with the top of the fuse-plug dam at the level of point S_3, and the bottom at the level of point F. This safeguard solution produces an increase in flood peak ΔQ_{max}, curve 4a, because of the sudden wash-out of the fuse-plug dam. The new peak $Q + \Delta Q_{max}$ may be greater in some cases than the inflow maximum flood peak Q_{max}.

The fuse-plug usually is conceived as a transient solution in order to increase the safety of flood discharge until upstream river basin development, especially the construction of large reservoirs, makes operation of the fuse-plug dam a remote possibility.

As the curves 1a, 3, and 4 of fig. 3 show, the increase in water level ΔH in the reservoir for a given increase in discharge ΔQ is decreased. Thus the requirement of safe discharge of floods much larger than the design flood is satisfied with a small risk of loss. In this way, the uncertainties of flood events resulting from the probabilistic character of flood phenomena are allowed for in the design of spillways by a slow growth of reservoir level with a substantial increase of flood discharge.

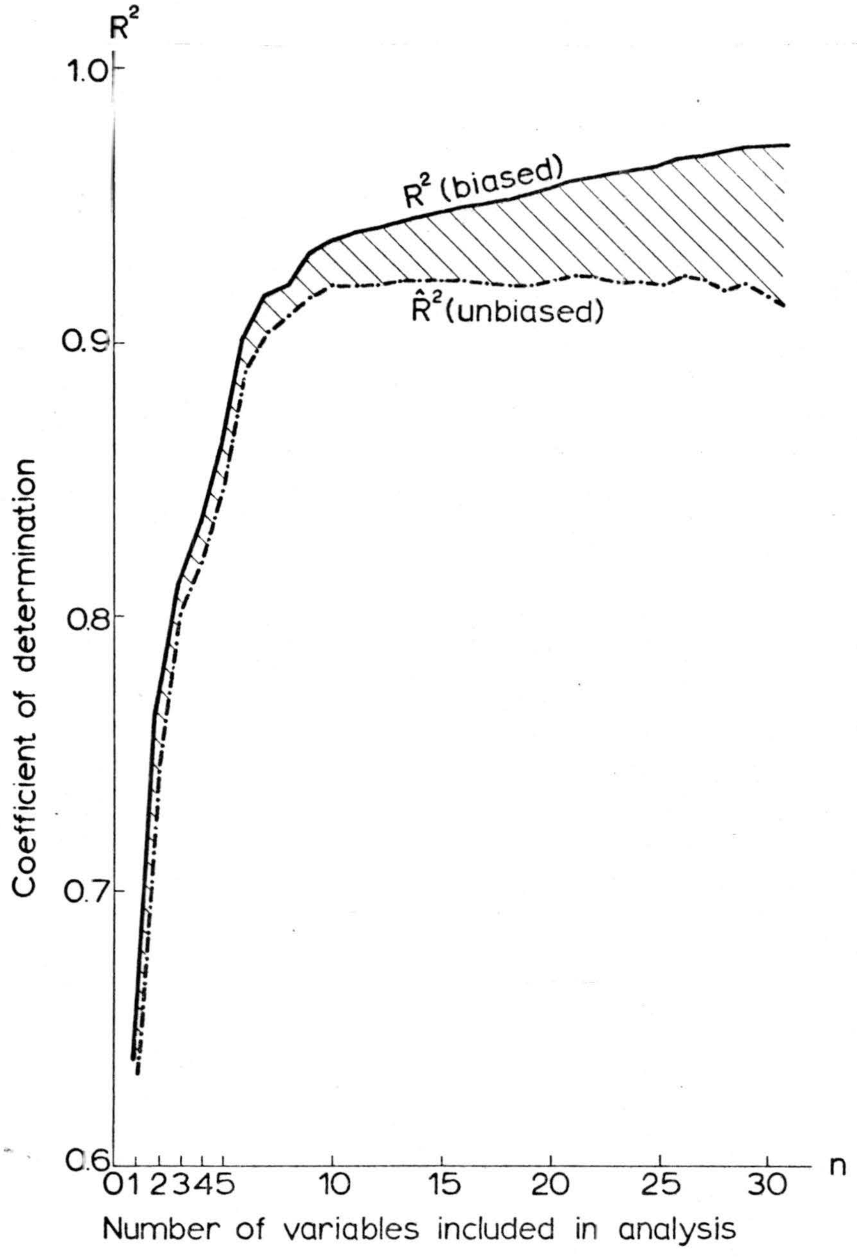

Fig. 1. Explained variance, given by the coefficient of determination in the multiple linear stepwise correlation and regression analyses of the total water volume of 47 flood hydrographs plotted against the number of parameters of rainfall and river basin, used in the analysis.

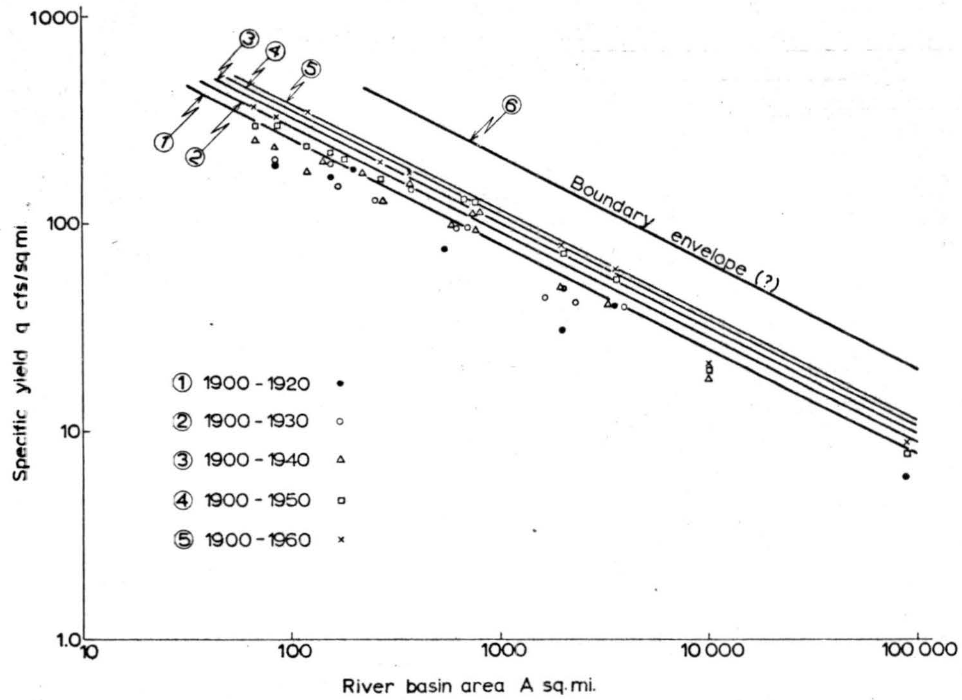

Fig. 2. Largest specific flood peak as related to river basin area, for many river gaging stations in Columbia River Basin (U. S. A.), for periods of 20 years (1900-1920), 30 years (1900-1930), ..., and 60 years (1900-1960).

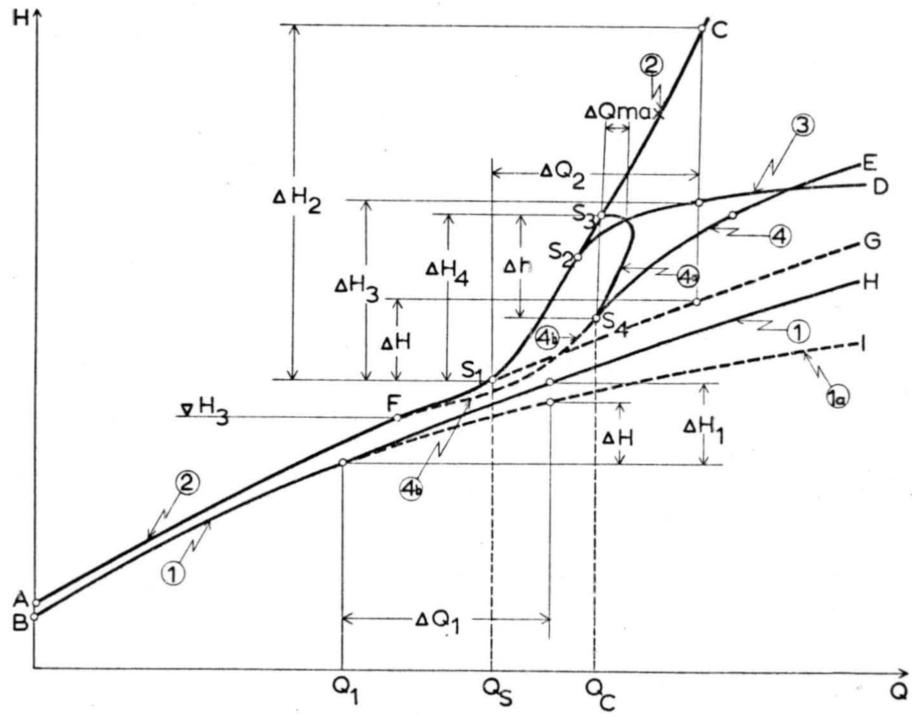

Fig. 3. Different capacity rating curves for flood discharge: (1) Spillways with free surface flow; (1a) Improved spillways with free surface flow; (2) Conveyance spillway structure with a transition from free surface flow to flow under pressure; (3) Emergency spillway with free surface flow added to case (2); (4a)-(4)-(4b) "Fuse-plug dam" spillway for emergency flood discharge.