CASTOR: Simplified Dam-Break Wave Model

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Abstract: The five computation steps of CASTOR—a simplified dam-break, flood-wave model—are described. The first step uses a simple relation to determine peak discharge at the dam. Second, a dimensionless graph gives peak discharge at the distance x from the dam. Afterwards the uniform-flow equation is used to compute peak water elevation, peak velocity, and wave arrival time. The validation of these last three steps is obtained on a set of 15 dams and 440 channel cross sections by comparison to the results of the model RUBAR 3, which solves Saint Venant equations. The deviation is less than 30% for peak water depth and 50% for other results in more than 90% of the cross sections. Such statistically justified results might be used independently from CASTOR. The example of the Lawn Lake Dam failure is treated by CASTOR; except for a point where the topography changed during the flood, peak water depth shows a deviation less than 20%.

INTRODUCTION

Every year throughout the world several dams have such trouble that failure occurs and, without exceptional measures, a flood wave propagates along the downstream valley. In spite of the increasing safety of dams due to better construction and maintenance, complementary measures such as early detection of failures and flood-warning plans are also necessary.

To estimate the areas that might be inundated, various methods exist:

- Physical models, which are now limited to complicated cases when numerical computation cannot provide accurate flood warnings
- Mathematical models, whose complexity varies from simple one-dimensional (ID) to complex three-dimensional (3D) computations

Generally numerical methods include two steps: (1) the collapse of the dam (evolution of the breach) is simulated, or the outflow hydrograph at the dam is directly estimated by simple relations; and (2) the discharge hydrograph is propagated through the river valley.

For flood-wave propagation 1D computations are usually used (Benoist 1989). The more complete calculations solve Saint Venant equations, but simplified equations (kinetic wave, etc.) and dimensionless graphs also are used (Sakkas and Strelkoff 1976; Wu 1994). Sometimes two-dimensional shallow-water equations are used (Molinaro and Maione 1991); for instance, in the case of propagation over a wide floodplain (Paquier 1993).

In the simpler cases (which also constitute the majority)—for instance, routing a flood hydrograph from a small dam through a single valley with no city downstream—the more sophisticated methods are too expensive to be widely used. It is necessary to use simplified and less costly methods that still provide reliable results in the important points of the valley.

In two cases—Teton and Laurel Run—Wurbs (1987) showed that substantial differences may arise among the five simplified models tested. For six French dams we used the simplified dam break (SMPDBK) model (Wetmore and Fread 1983) of the U.S. National Weather Service [the "optimal" simplified model according to Wurbs (1987)] and the CTGREF method (Colin and Pochat 1978) that uses a dimensionless graph to obtain peak discharge from peak outflow at the dam. Compared to results obtained by solving the Saint Venant equations, propagation results given by SMPDBK may have errors of more than 100% for water depths (two dams out of six). Generally errors for the SMPDBK method increase more for the "difficult" cases (i.e., the cases with large errors) than the CTGREF method (Robin 1990).

It was clear that available simplified methods were not precise enough for engineering purposes and that models solving Saint Venant equations were too complex for general use, so we decided to improve the CTGREF method by:

- Extending the method to progressive failures
- Increasing the accuracy of the results
- Integrating the method in a modern software

DESCRIPTION OF METHOD

The corresponding software called CASTOR is now available for use on a personal computer with integrated pre- and postprocessing. Computation is based on the following five steps:

1. Estimate the peak discharge at the dam by using a simplified relation determined by the mode of failure (progressive or instantaneous).
2. Create a dimensionless graph providing the ratio of the peak discharge at a given section to peak discharge at the dam according to two values: S/n^2, where S is the bottom slope divided by the square of the Manning coefficient n; and $x/V^{1/3}$, where x is the distance to dam and V the volume of the reservoir. These ratios are determined on the reach between dam and section. For progressive failure of the dam, it is assumed that the discharge hydrograph at the dam corresponds to the discharge obtained by an instantaneous failure somewhere upstream from the dam. The dimensionless graph providing peak discharge has been obtained from previous experience on dam-break waves and from results of solving Saint Venant equations on triangular channels.
3. Compute the peak water depth at a given section from peak discharge and data concerning a cross section that assumes uniform flow conditions.
4. Compute the peak velocity from peak discharge and the cross-sectional area corresponding to the peak water level. A correction factor is necessary as peak velocity generally occurs before peak discharge.
5. Compute the propagation time using the distance from the dam and an average peak velocity at a section and peak velocity immediately downstream from the dam.

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The computation at a given section only depends on local data, distance from the dam, Manning roughness coefficient of the reach between the dam and the section, and some data concerning the dam and the reservoir. The data concerning the other sections are not used; this is one of the main features of the model.

COMPARISON OF CASTOR WITH MORE COMPLETE MODEL

As data concerning dam-break waves are scarce and often incomplete, we decide to start a more complete comparison with results of the model RUBAR 3, which solves (Paquier 1995) Saint Venant equations (subcritical and supercritical flows).

The same data were used for the two models. They included a set of 15 dams having a total of 500 km of valley and 440 cross sections from comparison of results. All the cases are for valleys for which safety downstream from dams had been studied. These cases constitute a representative sample of small to medium dams. The valley slope ranges from 0.01 to 10%, volume of the reservoir 730,000–48,000,000 m^3, height of the dam from 8 to 60 m, channel depth from 1 to 20 m, channel width from 50 to 300 m, and routed discharge from 300 to 23,000 m^3/s.

Every step of computation has been validated independently (i.e., supposing that the previous step gives the same result as Saint Venant equations) and globally (i.e., all the steps being computed by CASTOR).

THREE FINDINGS

In the following we insist only on three findings of our research, which concern peak water depth, peak water velocity, and wave arrival time. These conclusions can be used independently from our method if peak discharge is previously estimated using another method.

Uniform Flow Equation

The peak discharge and the peak water depth obtained by Saint Venant equations statistically verify the assumption of the uniform flow. We computed the ratio of the water depth obtained from peak discharge by using the uniform-flow equation to the peak water depth obtained by RUBAR 3. The average ratio is from 1.01 to 1.02, the standard deviation about 0.13, and 93% of the points have a deviation less than 20%. To obtain this result it is necessary to use a minimum bottom slope of 0.05% (the computation by the uniform-flow equation is, of course, not possible for a horizontal bottom).

In CASTOR it is possible to increase the model accuracy by adding one or two secondary sections to the main cross sections. With the use of this possibility for about 30 sections (out of 440), the standard deviation reduces to 0.11. A comparison of results is shown in Fig. 1.

The ordinate represents the ratio of the peak water depth computed by RUBAR 3 (Saint Venant equations) Y_{RUBAR3} to the water depth Y_{CASTOR} of the uniform-flow equation from peak discharge estimated by using RUBAR 3. The "average for sections" is the average giving the same weight to every cross section. The "average for dams" is the average giving the same weight to every dam (and the same weight for each section of one valley). One symbol is used for each dam.

Globally the first three computational steps of CASTOR lead to an acceptable estimate of peak water depth (average about 0.99, standard deviation 0.15), which is nearly as good as the results of the single third step shown in Fig. 1.

Peak Velocity

CASTOR computes the peak velocity by taking the velocity estimated by the uniform flow equation and multiplying it by 1.2. This factor takes into account the fact that the peak velocity is reached before peak water depth and peak discharge. The global comparison between the peak velocity computed by CASTOR and the results of peak velocity from RUBAR 3 (the value obtained for a depth greater than 10 cm) is shown in Fig. 2.

The average is close to 1.0 and the standard deviation is 0.34. About 2% of the sections give results greater than 2.0 but the ratio for more than 90% of the sections is situated between 0.5 and 1.5.

Time for Wave Propagation

In order to estimate the arrival time of the flood wave, CASTOR first estimates the time for breaching (0 for instantaneous failure). Then it computes the time t for wave propagation that will be added to the time for breaching. This second computation uses the following relation:

$$t = \frac{2x}{V_0 + V_x}$$

in which V_0 = peak velocity immediately downstream from the dam; and V_x = peak velocity at the distance x from the dam.

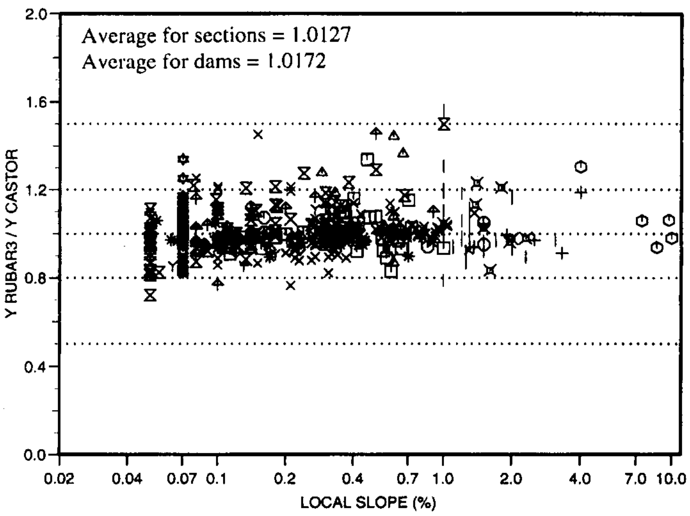

FIG. 1. Control of Uniform Flow Equation

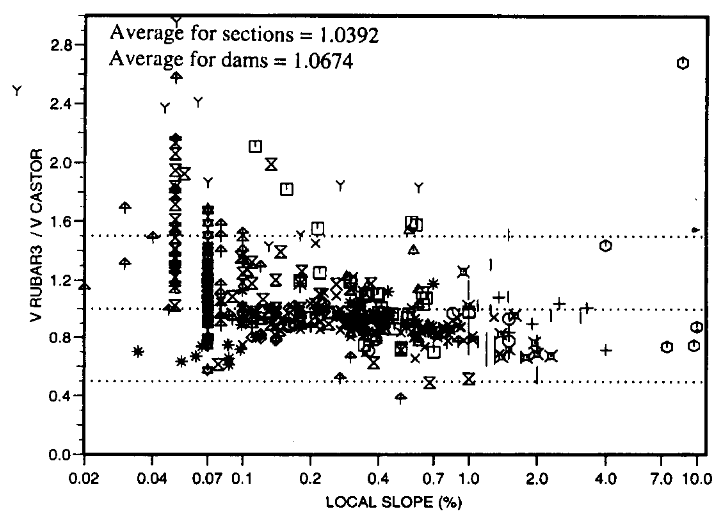

FIG. 2. Control of Peak Velocity Estimate

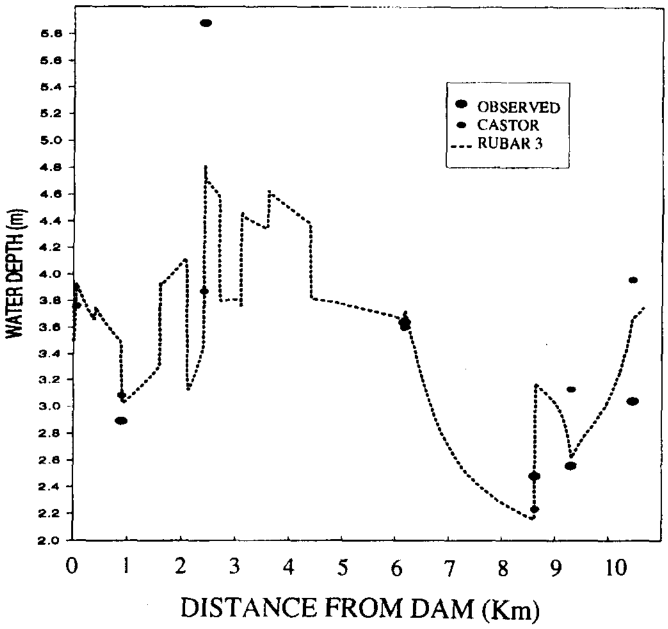

FIG. 3. Lawn Lake Dam—Peak Water Depths

The standard deviation of the corresponding ratio of T_{RUBAR3} to the time T_{CASTOR} computed by CASTOR reaches 0.34 whereas the average is close to 1.0. About 2% of sections give results greater than 2.0 but the ratio for more than 90% of the sections is situated between 0.5 and 1.5.

EXAMPLE OF COMPUTATION WITH CASTOR

From Jarrett and Costa (1986) we used data on the failure of the Lawn Lake Dam in Colorado, which occurred on July 15, 1982, and killed three people. This earthen dam was 8 m high and its reservoir capacity 830,000 m^3. Failure was probably due to piping. Cascade Lake Dam, a 5-m-high concrete gravity dam located 10.6 km downstream, also failed, toppling with 1.3 m of water flowing over its crest. But we only studied the reach upstream from the lower dam. As the flood was a very large one for these basins, channels were widened several meters and scoured from 1 to 5 m locally.

For computation a peak discharge of 510 m^3/s at the dam was used [assessment of Jarrett and Costa (1986)]. A constant Manning roughness coefficient of 0.1 was used; this globally corresponds to the actual conditions: a meandering stream, dense forest, and huge sediment discharge.

In Fig. 3, which gives the peak water depths, the backwater effect of Cascade Lake Dam may explain the difference at Km 10.4. At Km 2.4 the topography was deeply modified during the flood (erosion upstream and deposits downstream). We computed the change of bed level during the flood with a model coupling Saint Venant equations, a sediment mass balance equation, and the Meyer-Peter-Muller relation (Paquier 1994); the results showed that this was enough to explain the deviations. Except for these two points and despite the steep slope of 10%, for peak water depths CASTOR and RUBAR 3 give close results, ones that generally agree with the observations with a deviation less than 20%.

CONCLUSION

We studied a simplified method for dam-break wave computation. For the first time we have shown that from the peak discharge at a given section, it is simple to determine good estimates for

- Peak water depth, using the uniform-flow equation
- Peak velocity, using the value obtained by the uniform-flow equation and a constant correction factor of 1.2
- Time for wave propagation, using a propagation velocity obtained as an average of the peak velocities at the dam and at the section

This simplified method gives 90% of the results having a difference less than 30% for peak water depths and less than 50% for peak discharge, peak velocity, and arrival time, when compared to the results of a computation by Saint Venant equations.

Such a method requires minimal data: general data about the dam and the reservoir, a description of the cross section where results are required, and Manning's coefficient for the reach between the dam and this cross section. Its use is limited to "regular valleys" (no storage areas nor control structures that might strongly modify the flow) and more generally to the same situations where Saint Venant equations are used.

With uncertain data several computations with CASTOR (each one requiring a few seconds on a personal computer) will give lower and higher limits for peak water level at a given section and thus will provide a good way to assess the risk at a given point to houses, bridges, etc. In such a case, time necessary to prepare the data for CASTOR (a few minutes) is several times less than for a dynamic routing model.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

n = Manning roughness coefficient;

S = bottom slope;
t = time;
T_{CASTOR} = wave propagation time computed by CASTOR;
T_{RUBAR3} = propagation time computed by RUBAR 3;
V = volume of reservoir;
V_{CASTOR} = peak velocity computed by CASTOR;
V_{RUBAR3} = peak velocity computed by RUBAR 3;
V_x = peak velocity at distance x from the dam;
V_0 = peak velocity at dam;
x = distance from dam along waterway;
Y_{CASTOR} = peak water depth computed by CASTOR; and
Y_{RUBAR3} = peak water depth computed by RUBAR 3.