THE EFFECTS OF CULVERTS IN HYDRAULIC MODELING FOR FLOOD RISK MITIGATION

LES EFFETS DE PONCEAUX DANS LA MODELISATION HYDRAULIQUE POUR ATTENUATION DES RISQUES D'INONDATION

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ABSTRACT

The construction of road infrastructures has often affected floodplains next to waterways and the adopted technologies have frequently made use of road embankments designed by assigning an adequate freeboard to the road level with respect to the most severe floods (RT > 200 years). This technique has often led to the reduction of the detention capacity of the floodplain due to the partial exclusion of the area between the road embankments and the outer limits of the valley. Recent developments in Computational Fluid Dynamics (CFD) based on the Navier-Stokes equations or LBM algorithms, have reached a very high level of detail and computational accuracy, even though the presence of structural and hydraulic singularities (road, levees, bridges, ...) often weighs down the computational simulation. Thus the computation procedure can be simplified by means of: efflux laws for bridges; empirical formulas for banks overflow; laws for the synchronous filling of small extension floodplains without significant discontinuities. Aim of this work is to provide a numerical solution that can be easily implemented for engineering applications.

RÉSUMÉ

La construction des infrastructures routières a souvent touché les plaines inondables côté de cours d'eau et les technologies adoptées ont souvent fait usage de remblais routiers conçus par l'attribution d'un franc-bord adéquat au niveau de la route en ce qui concerne les inondations les plus graves (RT> 200 ans). Cette technique a souvent conduit à la réduction de la capacité de détention de la plaine inondable en raison de l'exclusion partielle de la zone entre les remblais routiers et les limites extérieures de la vallée. Les développements récents dans ComputationalFluid Dynamics (CFD) sur la base des équations de Navier-Stokes ou des algorithmes LBM, ont atteint un très haut niveau de détail et de précision de calcul, même si la présence de singularités structurelles et hydrauliques (digues, routes, ponts, .. .) pèse souvent en bas de la simulation numérique. Ainsi, la procédure de calcul peut être simplifiée par le biais de: lois efflux pour les ponts; formules empiriques pour les banques de débordement; lois pour le remplissage synchrone de petites plaines inondables de vulgarisation sans discontinuités importantes. Objectif de ce travail est de fournir une solution numérique qui peut être facilement mis en œuvre pour les applications d'ingénierie.

Keywords:culvert, floodplains, numerical method

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1. Introduction

Not always the computational techniques like finite difference solutions of the Navier-Stokes equations [1, 2] and the most innovative LBM models (Lattice Boltzmann Methods) [3, 4, 5, 6] for the hydraulic modeling of alluvial plains are easy to apply in extensive areas. Moreover, the presence of extended network infrastructures and by structural and hydraulic discontinuities (bridge, culvert and inline or lateral weir) [7, 8] heavily influence the computational process [9, 10]. Often, to overcome these difficulties, schematizations that simulate the flow through the combination of 1D and 2D steps depending on the calculation mesh and expressing with conceptual modules the singularities encountered are used. In literature, this kind of approaches also concern the modeling process of floodplains characterized by a lateral weir and by a synchronous filling law for the floodplain [11].At the moment there are no cases discussed featuring floodplain filling conditions controlled by an hydraulic interface such as a rectangular section culvert. This work is addressed to discuss this particular singularity which occurs very frequently in the simulation of the flooding of floodplains divided by road embankments parallel to the stream centerline as shown in Figure 1. The drainage of these areas is often accomplished through simple culvert without clapet crossing the road embankment below the road level.In this work, in particular, will be highlighted how the gradient of the flood hydrograph influences: i) the solution to the differences with the first order approximation (Euler); ii) the solution to the differences of the fourth order (RungeKutta, [12, 13]); iii) the length of the integration step (Δt). The discussion of the theoretical case has been exemplified in a particular case study represented by floodplain cut off by State Route 209 Val Nerina (Fiume Nera, Umbria, Italy).

FIGURE 1. Floodplainlimited by road embankment

2. Flow through culvert under unsteady conditions

The study of the hydraulic state upstream of the culvert during a flood was carried out under unsteady flow conditions simulating the amount of water stored by the floodplain. The problem rises a particular numerical difficulty since the flow rate through the culvert itself and the water depth in the depressed area are not known a priori. In fact, the flow through a culvert depends on the upstream or downstream conditions with different flow profiles and with different pressure losses in the inlet and the outlet. Conceptual difficulties were then amplified by the slowness of the change of the hydraulic head that required the use of very small integration steps. Once all previous computational difficulties have been overcome, the solution turned hydraulically correct and consistent with all the hydraulic and mass conservation constraints.

2.1 Setting of the Problem

In general terms, the equations describing the process are represented by the equation of motion through the culvert and the equation of the floodplain under conditions synchronous with the depression. The equation of motion, written in terms of energy, is as follows.

$$Hm - Hv = \overline{J} \cdot L + \Delta H_i + \Delta H_u$$

in which H_m, H_ν are respectively the total load upstream and downstream of the culvert; J is the friction slope; ΔH_i, ΔH_ulosses at the inlet and outlet. The conditions for the filling of the depression are expressed by the following equation

$$\frac{dV}{dt} = Q$$

where V is the volume floodplain filled and Q is the water flow through the culvert. Flow chart for outlet control computations are represented in HECRAS®, Hydraulic Reference, chapter 6/13, Fig. 6.9. Frequently, it is assumed that the reservoir at the back of the culvert is at the same level of the outlet, due to the partial filling of the depression due to the flow coming from the hill. Therefore, when the outlet is not submerged and its bed has no slope, the flow inside the culvert is calculated as gradually changing flow. Once the inflow conditions imposed by the flood hydrograph of the main stream are known is then possible to calculate the flow rate Q in respect of the continuity equation. In the case of a submerged outlet, the flow rate is calculated as a pressurized conduit flow, evaluating any losses in the input and output with the typical formulas of phoronomy. Assuming, to a good approximation, that the losses at the inlet and outlet are calculable proportionally to the kinetic high of the flow, the equation of motion can be written as follows:

$$Hm - Hv = Q^2\left[\frac{4L}{(km - kv)^2} + \frac{1}{2g}\left(\frac{\alpha_m}{Am^2} + \frac{\alpha_v}{Av^2}\right)\right] = \beta Q^2$$

where L is the length of the culvert; *Q* is the flow rate of the culvert; km, kv are the conveyance upstream and downstream; *Am, Av* is the hydraulic sections upstream and downstream, αm, αv are inlet and outlet coefficients of the flow. The equation of the reservoir is as follows:

$$\Omega\frac{dHv}{dt} = Q$$

where Ω is the horizontal surface of the basin volume. Combining the two previous equations, we obtain the following differential equation:

$$\frac{d[hm(t), Hv]}{dt} = \frac{1}{\Omega(Hv)}\sqrt{\frac{Hm(t) - Hv}{\beta[Hm(t), Hv]}} = f[Hm(t), hv]$$

that can be numerically solved at the differences as follows

$$Hv_{i+1} = Hv_i + \Delta Hv_i$$

The ΔHvi difference can be evaluated, with Eulero first order approximation:

$$Hv_{i+1} = Hv_i + f[Hm(t), hv]_i \Delta\mathrm{t}$$

In order to have a more accurate solution and a quicker convergence, the integration process can be conducted with an approximation of the fourth order (RungeKutta). Assumed that:

$$\Delta_1 Hv_i = f(t_i; Hv_i)\ ,\ \ \Delta_2 Hv_i = f\left(t_i + \frac{\Delta t}{2}; Hv_i + \frac{\Delta_1 Hv_1}{2}\right), \Delta_3 Hv_i = f\left(t_i + \frac{\Delta t}{2}; Hv_i + \frac{\Delta_2 Hv_1}{2}\right),\ \ \Delta_4 Hv_i = f(t_i + \Delta t; Hv_i + \Delta_3 Hv_1)$$

the final increment is evaluated with the following equation:

$$\Delta Hv_i = \frac{1}{6}(\Delta_1 Hv_1 + 2\Delta_2 Hv_1 + 2\Delta_3 Hv_1 + \Delta_4 Hv_1)\cdot\Delta t$$

At each integration step, once the value of Hv_i+1 has been estimated, it was possible to calculate the flow rate *Q* and the volume *V* contained in depression with inverse formulas.

3. Outcomes and conclusions

In order to achieve a numerical solution, the first-order Euler method and the fourth-order Runge Kuttaanalysis have been implemented as aforementioned in paragraph 2. However the convergence of the Euler methodrequired an ad hoc calculationproceduresothat longer integrationsteps, withlighter data output, couldbechosen. The adoptedintegrationstepsdependent on the Return Time (RT) of the flood wave passing through the main riverbed are as follows: Δt: i) Δt = 0.5 sec for RT = 500 y; ii) Δt = 0.2 s for RT = 200 y; iii) Δt = 0.1 s for RT = 50 y. For the sake of brevity, only the values of flow rate Q calculated for a flood with RT = 500 yearsparametrized over the width of the culvert are reported. It isobservedthat the laminatedflowsreach the maximum value at the initial part of the flood hydrograph; while in the vicinity of the flow peaks, the withdrawnflows are practically close to zero and thatwe have an almostlineardependencywith the width of the culvert (Figure 2).

This procedure has allowed to evaluate the influence of the dimensions of the culvert on the withdrawn flow. This influence ishighlighted in figure 2 that shows the withdrawnflows for threedifferentculvert dimensions (0,5m - 1,0m -3,0 m). This studyalsoshowedthat the effectiveness of the culvertdepends on the volume thatisavailable in the floodplain. The proposed model and its solution isalso a robusttool to verifyboth the influence of culvert dimensions and the volume of fringe areas for the mitigation of hydraulicrisk..

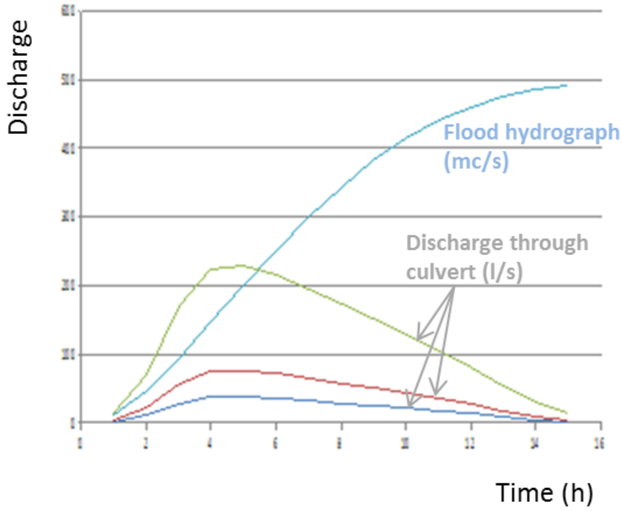

FIGURE 2. Simulation output RT=500 yearsparametrized over the width of the culvert.

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