NUMERICAL SIMULATION OF IMPACT OF BORES AGAINST INCLINED WALLS

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ABSTRACT: This work presents numerical simulations for the analysis of the impact of a bore against a wall. The 2D governing equations in the vertical plane are solved numerically using a variant of the simplified marker and cell method. Results are obtained for the maximum force and the runup height on the wall. Numerical results for the case of the vertical wall compare well with previous experimental data. A parametric study for the maximum force and the runup height on an inclined wall is presented.

INTRODUCTION

It is possible that structures located on the downstream side of a dam might be subjected to the impact of bores of a dambreak flow. Hence, considerations of such scenarios are important in the safety analysis of these structures. The primary quantities of interest in such studies would be the water surface elevation, maximum force, maximum runup height during the impact, and, perhaps, time evolution of the force against a wall. Fig. 1 shows the schematic of an idealized bore striking a wall, where \( h_b \) is the height of the bore, \( h_d \) is the depth of static water before the bore front, and \( v_b \) is the velocity of the approaching bore. In reality, the bore is not such a sharp discontinuity and has a length of three to four times the depth of water. In contrast, surge waves are even more gradual and have longer lengths. Stoker (1957) derived relations for the reflection of a constant bore from a rigid vertical wall. He also presented analytical equations for the force of the wall. Cumberbatch (1960) and Cross (1967) presented relationships for the impact of a water wedge on a vertical wall. All these analytical studies are based on the shallow water theory. Ramsden and Raichlen (1990) and Ramsden (1996) experimentally determined the forces and the overturning moments on a vertical wall due to the reflection of solitary waves, undular bores, turbulent bores, and surges on a dry bed. It was clearly demonstrated that the pressure distribution during impact is essentially nonhydrostatic and that the shallow water theory does not apply. Therefore, a numerical model, which does not make the hydrostatic assumption, would be a useful tool for the analysis of impact of bores on walls.

Navier-Stokes-type solvers (Harlow and Welch 1965; Hirt and Nichols 1981), which yield the pressure as part of the solution without making the hydrostatic assumption, are becoming popular for the analysis of hydraulic engineering problems (Lemos and Martins 1996; Bradford and Katopodes 1998). The approach is to numerically solve the 2D flow equations in a vertical plane without making the shallow water assumption. Recently, the authors (Mohapatra et al. 1999) have adapted a hybrid technique, which combined the generalized simple marker and cell (GENSMAC) Navier-Stokes solver (Tome and McKee 1994) with the Young’s volume of fluid (Y-VOF) technique for surface tracking (Rudman 1997), to study the effect of nonhydrostatic pressure distribution on the dam-break flow. In the present work, the same numerical model is applied to study the more difficult problem of the impact of a bore against a wall. The objective is to compute the maximum force and the runup height on the wall due to the impact of a bore. The numerical model is first verified by comparing the numerical results with the experimental data of Ramsden (1996) for a vertical wall, and then a parametric study is presented for the case of an inclined wall.

FORMULATION

 Governing Equations

The equations governing the 2D incompressible inviscid flows are the continuity and the momentum equations

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + g_x \tag{2}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + g_y \tag{3}
\]

In the above equations, \( u \) and \( v \) are the velocities in \( x \) and \( y \) directions, respectively; \( p \) is the pressure, and \( g_x \) and \( g_y \) are gravity components in \( x \) and \( y \) directions respectively; and \( \rho \) is the density. The coordinate axes \( x \) and \( y \) are in the horizontal and the vertical directions, respectively. The above equations have three unknowns, \( u, v, \) and \( p \). There are two explicit equa-

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Note. Discussion open until May 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on January 13, 1998. This technical note is part of the Journal of Hydraulic Engineering, Vol. 126, No. 12, December, 2000. ©ASCE. ISSN 0733-9429/00/0012-0942-0945/$8.00 + $.50 per page. Technical Note No. 17383.
tions for \( u \) and \( v \). While there is no explicit equation for \( p \), the pressure field is indirectly obtained through the imposition of continuity. Thus, no assumption, hydrostatic or otherwise, is made regarding the pressure field. Note that the above equations do not include turbulence effects, which are only of secondary importance compared to inertial effects in the current study.

**Numerical Method**

Various numerical methods are available in literature for solving (1)–(3) for free surface conditions. The numerical method used in this study is a hybrid of the GENSMAC Navier-Stokes solution method (Tome and McKee 1994) and the Y-VOF surface tracking technique (Rudman 1997). The method uses a finite-difference approach to solve the equations on a staggered grid. Details of this technique are presented elsewhere (Mohapatra et al. 1999), and only a brief outline is given here. The velocity field, pressure field, and position of the free surface are known at any time level \( t \) (known either from a previous computation or as specified initial conditions). The following procedure is adopted to determine these quantities at the new time level \( t + \Delta t \):

1. An arbitrary pressure field for the new level is assumed ensuring that the pressure at the surface cells is atmospheric.
2. Velocity field at \( t + \Delta t \) is predicted by explicitly solving (2) and (3) using the velocity field at time \( t \) and the assumed pressure field at \( t + \Delta t \).
3. A Poisson equation is then solved to determine the corrections to be made to the pressure field, and the correct velocity field at \( t + \Delta t \), which satisfies the continuity equation. The conjugate gradient method is used for solving the pressure correction equation.
4. Location of the free surface at the new time level is obtained using the above velocity field. It is computed using the conservation equation for the fraction of the cell filled with fluid. The method of Youngs (Rudman 1997) is adopted for this purpose.

The cell variables are to be prescribed in the boundary cells on the wall. The normal velocity on a wall boundary cell is zero and the tangential velocity is approximated by a zero-derivative free slip condition. The boundary condition for pressure correction is a homogeneous Neuman condition on the wall bottom, and at the inlet and outlet, and a homogeneous Dirichlet condition at the free surface. The inclined straight wall at the downstream end is approximated as a staircase in the computational domain because the cells used in the computational grid are rectangular. In the numerical procedure, the pressure is computed at the cell centers while the boundaries fall on the cell edges. Therefore, a linear interpolation is used to determine the pressure on the boundaries. Numerical integration of the interpolated pressures gives the horizontal and vertical forces on the wall.

**RESULTS AND DISCUSSION**

The numerical model is used for the analysis of bores of height \( h_b \) moving with a velocity \( v_b \) into a static water depth \( h_d \). All the results are presented in terms of the following nondimensional parameters and variables used by Ramsden (1996):

- Nondimensional bore height, \( h^*_b = (h_b - h_d)/h_d \)
- Nondimensional time, \( t^* = t\sqrt{gh_d} \)
- Nondimensional bore velocity, \( v^*_b = v_b/\sqrt{gh_d} \)

- Nondimensional force per unit width, \( F^* = F/[0.5\rho g(2h_b - h_d)^2] \)
- Nondimensional runup, \( R^* = g(R - h_d)/v_b^2 \)

where \( F = \) force on the wall per unit width; and \( R = \) runup height on the wall. The angles of inclination \( \theta \), of the wall considered are 30°, 45°, 75°, and 90°.

**Bore Characteristics**

In Stoker’s solution (Stoker 1957), the bore moves downstream with a constant height and speed, whose value depends on the initial depths of water on both sides of the bore. In the numerical simulation, the bore velocity emerges from the solution of the governing equations. The nondimensional bore velocity versus nondimensional bore height for the present numerical and Stoker’s analytical solutions is shown in Fig. 2. The solutions match quite closely indicating that Stoker’s analytical solution is valid for the movement of a bore. The difference between the numerical and analytical bore velocities for \( h^*_b \geq 3.0 \) is due to the effect of the nonhydrostatic pressure distribution at the surge tip on a nearly dry bed (Mohapatra et al. 1999).

**Model Verification**

Results for the maximum nondimensional force, \( F^*_m \), and the maximum nondimensional runup, \( R^*_m \), on a vertical wall (\( \theta = 90^\circ \)) for bores of different nondimensional heights are

![Image](320x261 to 564x440)

**FIG. 2. Variation of Bore Velocity with Bore Height**

![Image](322x55 to 563x233)

**FIG. 3. Variation of Maximum Force with Bore Height, \( \theta = 90^\circ \)**
presented in Figs. 3 and 4, respectively. In these figures, the
current numerical results are compared with those obtained
experimentally by Ramsden (1996), and with the analytical
results of Stoker (1957). The empirical equations proposed by
Ramsden are used to plot the experimental data in these figures. It can be seen in Figs. 3 and 4 that the current numerical
results match well with the experimental data. The numerically
computed value of $\frac{H}{H_0} = 0.724$, for the case of a dry bed,
matches quite closely with the experimental value of 0.75–
0.9. The time evolution of the runup is presented in Fig. 5 for
the case of surge on a dry bed. The numerically simulated
maximum runup, time to attain this maximum value, and con-
stant runup attained thereafter match closely with the experi-
mental data of Ramsden (1996). The analytical solution of
Stoker (1957) does not consider the flow dynamics during the
impact of the bore on the wall; the solution is valid only after
the bore is fully reflected. Since this is not a constraint in the
current numerical model, the current numerical results match
more closely with the experimental data.

**Parametric Study for an Inclined Wall**

The force per unit width on an inclined wall due to the
impact of the bore is a function of the velocity, height of the
bore, and wall inclination. The maximum nondimensional total
force on the wall versus nondimensional bore height for dif-
ferent inclinations of the wall is plotted in Fig. 6. It can be
seen in Fig. 6 that the total force on an inclined wall is higher
than that on a vertical wall. This is because of the weight of the
water above an inclined wall. However, as expected, the
force in the horizontal direction decreases with the angle of
inclination as indicated in Fig. 7.

The nondimensional maximum runup versus nondimen-

**FIG. 4. Variation of Maximum Runup with Bore Height, $\theta = 90^\circ$**

**FIG. 5. Time Evolution of Runup of Dry-Bed Surge, $\theta = 90^\circ$**

**FIG. 6. Variation of Maximum Total Force on Inclined Wall with Bore Height**

**FIG. 7. Variation of Maximum Horizontal Force on Inclined Wall with Bore Height**

**FIG. 8. Variation of Maximum Runup on Inclined Wall with Bore Height**
sional bore height for different angles of inclination is presented in Fig. 8. As expected, the maximum runup increases with the angle of inclination. Figs. 6 and 8 may be useful while designing structures located in the path of a dam-break wave.

SUMMARY

In this paper, the impact of a bore on an inclined wall is studied numerically by solving 2D flow equations that allow for nonhydrostatic pressure distribution, and yield the complete 2D velocity and pressure fields. For a vertical wall, the maximum force and runup computed numerically match well with the experimental data of Ramsden (1996). For the case of a surge on a dry bed, the numerically predicted time evolution of the runup matches closely with the experimental data. Comparison of numerical and analytical results clearly shows the breakdown of shallow water assumption during the impact. The maximum force and runup are parameterized for different angles of inclination of the wall and different nondimensional bore heights.

APPENDIX I. REFERENCES


APPENDIX II. NOTATION

The following symbols are used in this paper:

- $F$ = force on wall per unit width;
- $g_x$ = gravity component in $x$ direction;
- $g_y$ = gravity component in $y$ direction;
- $h_b$ = height of bore;
- $h_d$ = depth of static water before bore;
- $p$ = pressure;
- $R$ = runup height;
- $u$ = velocity in $x$ direction;
- $v$ = velocity in $y$ direction;
- $v_b$ = velocity of bore;
- $x$ = horizontal distance;
- $y$ = vertical distance; and
- $t$ = time.

Subscripts

* = nondimensional variable.