Journal of Hydraulic Research Vol. 59, No. 2 (2021), pp. 351–354
https://doi.org/10.1080/00221686.2020.1780504

Discussion

Comparison between hydrostatic and total pressure simulations of dam-break flows

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The Authors presented an interesting comparison of 3D Navier–Stokes solvers for dam-break-like flows using two different modules for the pressure, one that calculates a total pressure solving a Poisson equation, and another one based on a hydrostatic pressure distribution. They concluded that hydrostatic consideration could not represent dam-break flow phenomenon with accuracy. The Discussers agree with the Authors on this point, but we believe that a fair account of what the Authors call "shallow water equations" (SWE) was not given in the introduction to the problem. In fact, the SWE quoted in the paper are the lowest order approximation of the shallow water hydraulic theory, namely Saint-Venant theory, which is based on a hydrostatic pressure distribution (Barré de Saint-Venant, 1871a, 1871b; Chanson, 2004). However, rigorous scaling of the equations of motion in terms of nonlinear and dispersion effects show that higher-order approximations are feasible, still corresponding to "shallow water" conditions (Barthélemy, 2004). These kind of higher-order approximations, called Boussinesq equations (Peregrine, 1966, 1967), are no longer based on hydrostatic pressure fields. Rather, they rely upon an approximate asymptotic treatment of the dynamic pressure into the depth-averaged governing equations (Barthélemy, 2004). There is a rich experience working with this type of models in maritime hydraulics (Brocchini, 2013; Peregrine, 1966, 1967), as well as in flow in hydraulic structures (Castro-Orgaz, 2010a, 2010b). The application of Boussinesq type phase resolving models to simulate dam break waves is however more recent (Cantero-Chinchilla et al., 2016; Kim & Lynett, 2011). There is no debate about the high relevance of a 3D flow computation, like that of the Authors, to get an accurate description of dam break flows. However, if one wishes to conduct a large-scale simulation, including propagation of surges, the depth-averaged framework using the Boussinesq equations is a reasonable practical tool, albeit one has to accept that the accuracy is lower than 3D computations. A fundamental wave resulting from the collapse of a dam is a surge propagating over initially wet terrain (see the Authors' Fig. 8). One of the most difficult issues to model in dam break waves using shallow water models relates to the transition from undular to broken surges (Betamio de Almeida & Bento Franco, 1994; Nakagawa et al., 1969). To illustrate the point, we simulate here undular and broken surges solving the so-called Serre–Green–Naghdi equations (SGN) equations (Barthélemy, 2004; Cantero-Chinchilla et al., 2016; Cienfuegos et al., 2006):

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{F}}{\partial x}=\boldsymbol{S}$$
$$\boldsymbol{U}=\begin{pmatrix} h \\ Uh \end{pmatrix},\quad \boldsymbol{F}=\begin{pmatrix} Uh \\ U^2h+\frac{1}{2}gh^2 \end{pmatrix},$$
$$\boldsymbol{S}=-\frac{\partial}{\partial x}\begin{pmatrix} 0 \\ \frac{1}{3}(U_x^2-UU_{xx}-U_{xt})h^3 \end{pmatrix} \tag{1}$$

where $\boldsymbol{U}$ is the vector of unknowns, $\boldsymbol{F}$ is the flux vector, $\boldsymbol{S}$ the source term, U is the depth-averaged velocity, h the flow depth, subindex indicates differentiation, x is the space coordinate and t time. Undular and broken waves are simulated using a hybrid SGN-SWE model solving Eq. (1) in the whole computational domain, and where breaking is detected the dispersive term is deactivated ($\boldsymbol{S}=0$) and the SWE are solved (Tonelli & Petti, 2009). We follow here the detailed work by Kazolea et al. (2014).

A criterion for defining the onset of breaking in the depth-averaged framework is required before describing the numerical

ISSN 0022-1686 print/ISSN 1814-2079 online
http://www.tandfonline.com

method of solution. Typically several conditions are implemented simultaneously (Kazolea et al., 2014). A first physical condition states that a wave breaks if the velocity of vertical displacement of the free surface exceeds a fraction γ of the long wave phase celerity (Kazolea et al., 2014):

$$\frac{\partial h}{\partial t} \geq \gamma (gh)^{1/2} \tag{2}$$

where γ is case-dependent and ranges from 0.35 to 0.65. A second condition is (Kazolea et al., 2014):

$$\left|\frac{\partial h}{\partial x}\right| \geq \tan(\phi_c) \tag{3}$$

which states that a wave begins to break once the local free surface slope exceeds a critical value, with ϕ_c as the critical front angle. The value of ϕ_c ranges from 14° to 33°. Dividing the computational domain in cells of width Δx, Eqs (2) and (3) are checked in each cell. If either of the two conditions is satisfied, the cell is marked as breaking (dispersive terms switched-off). Breaking cells are clustered to avoid instability induced by dispersion. For this purpose, breaking cells at a distance equal or less than $4\Delta x$ are grouped into larger rollers. For each wave the Froude number F may be defined as:

$$\mathsf{F} = \left[\frac{1}{8}\{(2H_2/H_1 + 1)^2 - 1\}\right]^{1/2} \tag{4}$$

by analogy with the moving hydraulic jump (Chanson, 2004; Lubin & Chanson, 2017), where H_2 and H_1 are the maximum and minimum flow depths of the roller, respectively. Equation (4) is used to decide when the breaking activation is finished, e.g. if $\mathsf{F} < \mathsf{F}_{\rm lim}$, the cells are considered again as non-breaking (dispersive terms switched-on back), with $\mathsf{F}_{\rm lim}$ a value of F which defines the onset of wave breaking. Based upon experimental observations, an undular surge breaks in the interval $1.5 \leq \mathsf{F} \leq 1.8$ (Leng & Chanson, 2017), but a typical value used in Boussinesq models is $\mathsf{F}_{\rm lim} = 1.2$. Therefore, a wave is broken only if the Froude number is above a limiting value $\mathsf{F}_{\rm lim}$. If $\mathsf{F} > \mathsf{F}_{\rm lim}$ the length of the numerical roller is incremented to satisfy a minimum value $L_{\min} = \Lambda(H_2 - H_1)$, with Λ typically ranging from 3 to 10. We used $\Lambda = 10$ to produce stable broken waves. In our simulations the values $\gamma = 0.5$, $\tan\phi_c = 0.35$ and $\mathsf{F}_{\rm lim} = 1.2$ were adopted.

The numerical method consists in a finite-volume finite-difference scheme (Cantero-Chinchilla et al., 2016), transforming Eq. (1) to:

$$\frac{\partial \boldsymbol{W}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} = \boldsymbol{S_d}$$
$$\boldsymbol{W} = \begin{pmatrix} h \\ \sigma \end{pmatrix}, \quad \boldsymbol{F} = \begin{pmatrix} Uh \\ U^2 h + \frac{1}{2}gh^2 \end{pmatrix},$$
$$\boldsymbol{S_d} = -\frac{\partial}{\partial x}\begin{pmatrix} 0 \\ \frac{1}{3}(U_x^2 - UU_{xx})h^3 \end{pmatrix} \tag{5}$$

where:

$$\sigma = Uh - \frac{1}{3}h^3 \frac{\partial^2 U}{\partial x^2} - h^2 \frac{\partial U}{\partial x}\frac{\partial h}{\partial x} \tag{6}$$

Equation (5) is solved using the finite volume method applying the MUSCL–Hancock scheme (Toro, 2001) neglecting the source term $\boldsymbol{S_d}$. MUSCL linear reconstruction is conducted within each cell using the minmod limiter to preserve monotonicity. The numerical flux is computed using the HLL approximate Riemann solver, and the Courant–Friedrichs–Lewy number CFL is limited below unity for stability of the explicit scheme. The auxiliary variable σ must be updated to include the effect of $\boldsymbol{S_d}$. A predictor-corrector finite-difference scheme to incorporate $\boldsymbol{S_d}$ in the solution is adopted with the spatial derivatives approximated using second-order central finite differences. Once σ is available at each cell taking into account $\boldsymbol{S_d}$, the non-hydrostatic velocity field is computed solving the Helmholtz Eq. (6) using again central finite differences. The resulting system of equations is tridiagonal and easily invertible. After solving the SGN equations at each time step, Eqs (2) and (3) are checked in each cell, thereby defining breaking portions of the computational domain, where the SWE are solved setting $\boldsymbol{S_d} = 0$ and $\sigma = hU$. Breaking ends when $\mathsf{F} \leq \mathsf{F}_{\rm lim}$.

Consider the surge experiments by Leng and Chanson (2017) in a 0.7 m wide, 19 m long rectangular and horizontal flume. A radial gate at the tailwater portion of the flume ($x = 18.1$ m) was used to create initial steady subcritical flow. The fast closing of a Tainter gate produced a surge that propagated in the upstream direction. A first run for discharge $Q = 0.1$ m^3 s^{-1}, $h_o = 0.1948$ m (initial conditions), partial gate closure (gate opening 0.071 m) and $\mathsf{F}_o = (U_o + V_w)/(gh_o)^{1/2} = 1.2$ is considered in Figure D1a (V_w = surge celerity), where it is observed that the surge is undular. This test was modelled with the SGN-SWE shallow water model simulating the gate boundary condition using a standard gate rating equation calibrated, and neglecting the small backwater effects. Numerical computations were accomplished using $\Delta x = 0.01$ m and $\mathsf{CFL} = 0.1$ to reduce truncation errors, and the results for the depth-hydrographs at $x = 8.5$ m are compared in Fig. D1a with observations. It is noted that there is a fair reproduction of the experimental results. A second run for discharge $Q = 0.101$ m^3 s^{-1}, $h_o = 0.172$ m, full gate closure and $\mathsf{F}_o = 1.6$ is plotted in Fig. D1b, synchronizing numerical and experimental signals to account for the gate closure time. Note that the SGN-SWE are able to reproduce the broken surge, albeit the small secondary waves in the tailwater portion of the surge are larger than those observed during the physical experiments. Overall, this comparison shows that the SGN-SWE, an approximate shallow water model implementing total pressure, is able to reproduce the transition from undular to broken surges, a major feature of the dam-break flows. Of course the SGN-SWE results are limited in terms of accuracy as compared to 3D computations, but the computational cost of the approach

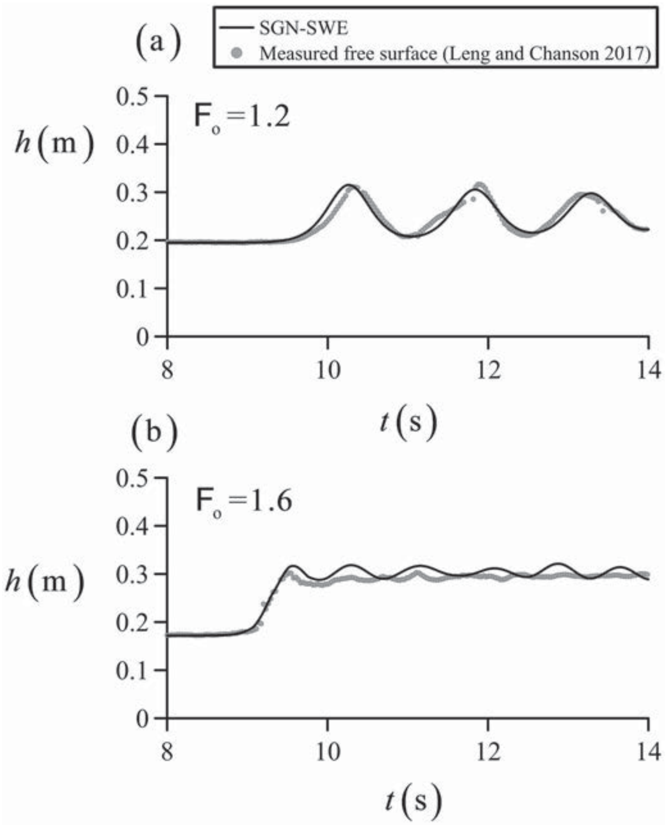

Figure D1 Comparison of surge predicted by SGN-SWE equations with experiments (Leng & Chanson, 2017) for F_0 = (a) 1.2, (b) 1.6

involves a small increase as compared to the Saint-Venant equations.

The Discussers hope the Authors will find in the dataset by Leng and Chanson (2017) additional material to compare with their 3D numerical solver for dam break flows. This dataset shows significant 3D features that could only be accounted for with a model like that proposed by the Authors.

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Closure to "Comparison between hydrostatic and total pressure simulations of dam-break flows" by LEONARDO R. MONTEIRO, LUÍSA V. LUCCHESE and EDITH B. C. SCHETTINI, *J. Hydraulic Res*. 58(5), 725–737. https://doi.org/10.1080/00221686.2019.167150

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First of all, we would like to thank the Discussers, Oscar Castro-Orgaz and Hubert Chanson, for their interest in our paper and for their discussion of shallow water equations (SWE).

The Discussers agreed with the main paper conclusions but did not think that a clear explanation was presented of what the Authors call SWE in the paper introduction.

When we introduced the SWE, we were discussing the SWE based on Saint-Venant theory, because we were discussing hydrostatic pressure distribution. We referenced the SWE that we were talking about, and our objective was not to have a wider discussion.

We want to make it clear by this closure that the main discussion of the paper was about hydrostatic and non-hydrostatic pressure and we did not use any SWE models in our simulation. Still, we cite SWE in the introduction because many programmes that are used to calculate dam-break flows consider the SWE based on Saint-Venant theory. We are not criticizing SWE in all aspects, but the use of hydrostatic pressure to represent complex flows.

We thank the Discussers for indicating the database in the article of Leng and Chanson (2017). We will certainly use it in our future work.

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