INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS
Int. J. Numer. Meth. Fluids 2008; **56**:1505–1512
Published online 7 January 2008 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/fld.1699

A projection method-based model for dam- and dyke-break flows using an unstructured finite-volume technique: Applications to the Malpasset dam break (France) and to the flood diversion in the Red River Basin (Vietnam)

Yu-e Shi[1,2,*,†] and Kim Dan Nguyen[2]

[1]*Research Institute for Knowledge Systems, P.O. Box 463, 6200 AL Maastricht, The Netherlands*
[2]*UMR CNRS 6143 M2C, University of Caen, Caen, France*

SUMMARY

A numerical model is presented for simulating dam-break flows and flood diversions. The model is based on a projection method, which consists of combining the momentum and continuity equations to establish a Poisson-type equation for the water surface level. The computed domain is discretized by finite volumes on an unstructured grid. A second-order upwind scheme coupled with a least-square technique is used for handling advection terms. The accuracy, stability and reliability of the present model are verified by comparing numerical results with observed data for the Malpasset dam-break event. An application of flood diversion in Red River Basin is also reported. Copyright © 2008 John Wiley & Sons, Ltd.

Received 9 May 2007; Revised 11 July 2007; Accepted 24 October 2007

KEY WORDS: projection method; 2-D model; shallow water; unstructured grid; finite-volume method; dam failure; flood control

1. INTRODUCTION

Dam- and dyke-break events produce in general an abrupt wave front that moves rapidly over a dry and irregular bed in downstream valleys. Therefore, dam-break models should be able to capture abrupt wave fronts by resolving the shallow-water equations (SWE), which are strongly hyperbolic. Most of the dam-break models have been based on resolving the SWE in the integral and conservative form by finite-volume methods (FVM). Several approximate Riemann solvers, which

*Correspondence to: Yu-e Shi, Research Institute for Knowledge Systems, P.O. Box 463, 6200 AL Maastricht, The Netherlands.
†E-mail: yshi@riks.nl

Contract/grant sponsor: FLOCODS Project; contract/grant number: ICA4-CT2001-10035
Contract/grant sponsor: IMECH (Institute of Mechanic of Hanoi)

were developed by researchers in aerodynamics such as Roe [1], Van Leer [2] and Harten [3], have been adapted for computing discontinuous free-surface flows. We can quote the works of Bradford and Sanders [4] and Valiani *et al*. [5] using an approximate Riemann solver proposed by Roe [1] and a FVM in structured computing meshes. In addition, a total variation diminishing technique has been introduced to prevent undesired oscillations in capturing dam-break wave fronts [6, 7]. It is well known that approximate Riemann solvers are suitable to solve a pure hyperbolic equation, without diffusion and source terms. Therefore, the application of such solvers to a real dam-break problem often produces numerical instabilities in the cases wherein the bottom variation is rapid, irregular and thus creates important source terms. This is why Ying *et al*. [8] have proposed an upwind conservative scheme, in which water surface gradients are evaluated by weighted averages of both upwind and downwind gradients. In this model, volume control cells still remain structured. Generally, the morphology and topography of dam-break valleys are complex. In this context, the use of unstructured meshes is necessary and even indispensable. Brufau and Garcia-Navarro [9] and Sleigh *et al*. [10] have proposed unstructured FVM for computing dam-break flows over a flat bed, using Roe's approximate solver.

Recently, Nguyen *et al*. [11] have developed an unstructured finite-volume model for computing shallow-water flows. This model is based on a projection method (PM) proposed by Chorin [12]. The continuity and momentum equations, including diffusion, Coriolis and source terms, are combined to establish a Poisson-type equation for only water surface levels as unknowns. In this model, a second-order upwind scheme combined with least-square technique for determining water surface gradient is developed to handle advection terms. The model is validated and approved by several benchmark tests. The PM-based model is thus proven to be able to compute shallow-water flows in rivers, estuaries and coastal zones of complex geometry. The objective of this paper is to present the recent results obtained from the PM-based model improved for computing real dam- and dyke-break flows over a dry and irregular bed: Malpasset dam-break event (France) and flood diversions in the Red River Delta (RRD) (Vietnam).

2. NUMERICAL BACKGROUND

The Saint–Venant equations are written as follows (see detail in [13]):

Continuity equation:

$$\frac{\partial Z_s}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \tag{1}$$

Momentum equations:

$$\frac{\partial (hu)}{\partial t}+\frac{\partial (hu^2)}{\partial x}+\frac{\partial (huv)}{\partial y}=f(hv)-gh\frac{\partial Z_s}{\partial x}+\frac{\partial}{\partial x}\left[A_H\frac{\partial (hu)}{\partial x}\right]+\frac{\partial}{\partial y}\left[A_H\frac{\partial (hu)}{\partial y}\right]+\frac{\tau_{wx}}{\rho_o}-\frac{\tau_{bx}}{\rho_o} \tag{2}$$

$$\frac{\partial (hv)}{\partial t}+\frac{\partial (huv)}{\partial x}+\frac{\partial (hv^2)}{\partial y}=-f(hu)-gh\frac{\partial Z_s}{\partial y}+\frac{\partial}{\partial x}\left[A_H\frac{\partial (hv)}{\partial x}\right]+\frac{\partial}{\partial y}\left[A_H\frac{\partial (hv)}{\partial y}\right]+\frac{\tau_{wy}}{\rho_o}-\frac{\tau_{by}}{\rho_o} \tag{3}$$

DOI: 10.1002/fld

Chorin's PM has been applied here to split up the Saint–Venant equations [14, 15] in the successive steps: convection–diffusion, wave propagation and velocity correction. The relevant equations for these steps have been integrated by a technique based on Green's theorem and then discretized by an unstructured FVM (UFVM). The advection terms are handled by a ULSS (upwind least-square Scheme, [16]). This MUSCL-type scheme is based on the pointwise reconstruction by a piecewise polynomial, which is similar to the essential non-oscillatory scheme [16]. It is required to be consistent with averaging and of high order of accuracy. Nguyen *et al*. [17] test the second-order ULSS using a test case proposed by Hubbard [18], in which Hubbard has used several MUSCL-type unstructured finite-volume schemes such as the limited central difference (LCD) scheme, the maximum limited gradient (MLG) scheme of Batten *et al*. [19]. This test case involves the circular advection of the cone around a domain of $[-1.0, 1.0]\times[-1.0, 1.0]$, with a velocity vector of $\mathbf{u}=(-2\pi y, 2\pi x)^{\mathrm{T}}$. The initial conditions are $\varphi=\cos^2(2\pi r)$ for $r\leqslant 0.25$, otherwise $\varphi=0$ for $r^2=(x+0.5)^2+y^2$. The initial profile should be advected in a circle without change of shape until it returns to its original position with a pick value of 1, after one revolution, i.e. at $t=1.0\,\mathrm{s}$. The pick value obtained by Hubbard [18] using the projected LCD and the MLG schemes are 0.85 and 0.93, respectively, which is identical to Nguyen *et al*.'s [17] MLG results (0.925), while the second ULSS almost conserves the pick value (0.992) and thus is slightly superior to the MLG and the LCD schemes for this test case. The linear equation system issued from the wave propagation step is implicitly solved by a successive over relaxation [20] technique. Readers are referred to [11] for details of these techniques.

3. MALPASSET DAM-BREAK SIMULATION

3.1. Description

The Malpasset dam break, a real event that occured in 1959 in south France, has been proposed in European concerted action on dam-break modelling project as a benchmark test. Dam-break wave propagation, which is characterized by arrival time and maximum water levels at several well-distributed sites (P1–P17), was observed during this event, and then modelled with the help of a non-distorted basin in the EDF/LNH's Chatou laboratory (S6–S14) (see [13]). The overall dimensions of the study domain are $17\,500\,\mathrm{m}\times 9000\,\mathrm{m}$. Elevation of the valley bottom ranges from $-20\,\mathrm{m}$ ABS to $+100\,\mathrm{m}$ ABS. The dam failure was total and instantaneous. The initial water level inside the reservoir is set equal to 100 m ABS. Except for inside the reservoir and the sea, the bottom is dry. The inflow was imposed null at the upstream boundary. The boundaries of the plain part were proposed as transparent for any inflows or outflows. The computational domain is discretized by 13 541 points and 26 000 triangles, corresponding to the mesh (triangles) used by Hervouet [21]. The cell size varies from 5 to 300 m. The simulation duration is 4000 s with a time step of 0.1 s. Thus, the Courant–Friedrichs–Lewy (CFL) maximum number can reach up to 1.4 at the beginning of the simulation.

3.2. Results and discussion

Table I presents the comparison on the arrival times at transformers between results from the present model and from other numerical models such as TELEMAC [21] and Valiani *et al*. [5]. Our results are in good agreement with the field data and with TELEMAC's ones for points B and C. The relative errors of the wave travel times at point A calculated from both the present model and

DOI: 10.1002/fld

Table I. Shutdown time of electric transformers.

Electric transformers	A (s)	B (s)	C (s)
Field data	100	1240	1420
Valiani *et al.* (%)	98 to −2	1305 to 5	1420 to −1
TELEMAC (%)	111 to 11	1287 to 4	1436 to 1
Present model (%)	95 to −5	1186 to −4	1363 to −4

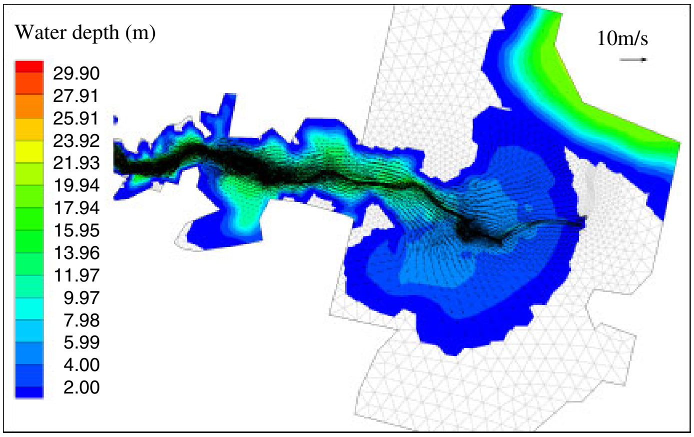


Figure 1. Wave front reaching sea at $t = 30$ min.

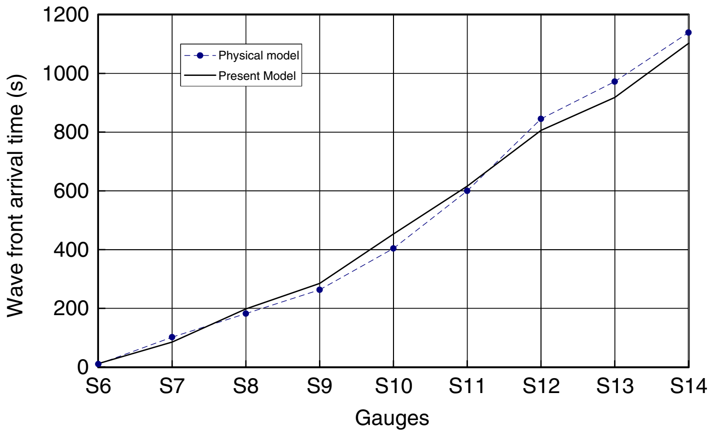
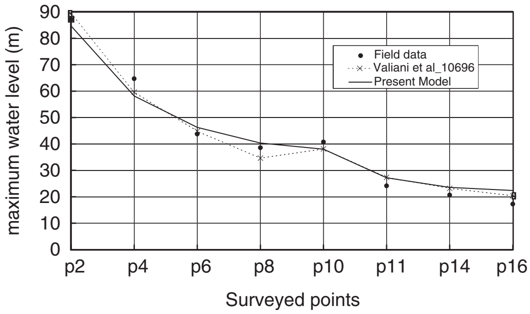


Figure 2. Arrival time of the wave front.

TELEMAC are −5% and 11%, respectively. Figure 1 represents the water depth map at $t = 30$ min when the wave front just reaches the sea. To precisely estimate wave speeds, a 1:400 scale physical model was investigated. The wave arrival time at several locations in the physical model was

DOI: 10.1002/fld



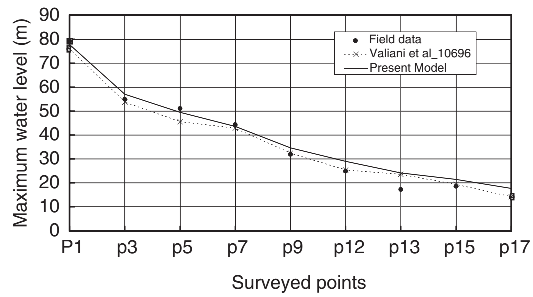


Figure 3. Maximum water levels at surveyed points located on the left(left) and right(right) banks.

gauged. Figure 2 compares numerical results with the data measured from the physical model. The maximum error is only 5.5% at gauge S13. A good agreement of comparison is obtained. The profile of maximum water levels at the surveyed points represents an envelope of the flood-wave front during the accident. The comparisons between numerical results and the field data are plotted in Figure 3. These figures show that the numerical results of the present model for both right and left banks are closer to the field data than those obtained from Valiani's model, which is based on approximate Riemann solvers using fine meshes. The stability and accuracy of the present code are validated by the Malpasset dam-break case. Moreover, the numerical experience shows that friction has a strong influence on wave arrival times but does not affect the maximum water levels (for details, see in Shi [13]).

4. APPLICATION TO A FLOOD DIVERSION IN RED RIVER BASIN

The Red River system (RRS) is an internationally shared system, which goes through two countries: China and Vietnam, and flows into the South China Sea via the Tonkin Bay. About 80% of the annual rainfall takes place in summer (May–August). Therefore, river discharges vary enormously from low-flow season to flood season. Hence, flood risks are recurrent every summer in the Vietnamese RRB. One of the flood control measures in the case of emergency is to divert floodwater from the Red River into zones of flood detention. This measure permits to reduce flood threat to economically and politically important zones such as Hanoi. A typical example is the floodwater diversion into the Van-Coc zone, situated 30 km upstream from Hanoi. Historically, on 16th August 1996 when the water level in the Red River at Hanoi was already very high, and continued to rise, the National Centre for Meteo-Hydrological Forecasting predicted a typhoon coming soon in the RRD. Fortunately, the typhoon only landed in Thanh hoa province (south of RRD), and thus did not affect the Delta. It is interesting to know what could have happened if the typhoon really landed on the RRD. Now we propose two flowing scenarios for simulation: (i) Scenario 1—real situation, i.e. no typhoon landing on the RRD; (ii) Scenario 2—imaginary situation, the typhoon changes its direction, and it starts to land in the Delta at 9:00 p.m., 17th of August, with duration of 17 h, and will cause heavy rains in the Da River Basin only. We suppose that, for both situations, a dyke segment in the Van-Coc zone would be broken.

DOI: 10.1002/fld

4.1. Coupling the present model with a 1-D model and DYBREACH

The present model has been coupled with a 1-D model and the DYBREACH simultaneously to simulate the scenarios of a dyke segment broken in the Van-Coc zone in the 1996s flood with and without typhoon. The 1-D model has been developed to compute flood propagation in the RRS [22]. DYBREACH [23] model is an interface model developed by Laboratorio Nacional de Engenharia Civil to simulate the breaching process through the embankment as well as to perform the breach outflow hydrograph calculation. The reader can refer to [23] for details.

The 1-D and 2-D simulation time is extended up to 420 h. This long enough simulation is necessary to permit the comparison of the difference between the water levels in Hanoi with and without the typhoon landing on RRD on 16th August 1996. In the 2-D model, the Van-Coc zone with nearly a length of 12 km and a width of 4 km is discretized by 4628 triangles. The cell size varies from 1 to 20 m. The time step used is 1 h for the 1-D model. It is 3 s for the 2-D model, i.e. a CFL number can reach up to 0.8. The 2-D model is coupled with the 1-D of RRS by three nodes (Van-Coc gate, Upstream and Downstream Hatmon spillways) in the upstream boundary and one node at the Day Dam in the downstream boundary. As the grid size of the 1-D model is 1 km and of the 2-D model is between 1 m to 20 m, a segment of the 1-D model is in contact with nearly a hundred cells in the 2-D model. Because the time steps in the 1-D and 2-D models are very different, 1200 time steps of the 2-D model are computed for only one time step of the 1-D model. The coupling conditions between the 1-D and 2-D models are as follows: (i) water levels at three nodes (Van-Coc gate, Upstream and Downstream Hatmon spillways) and at the Day Dam node of the 1-D model are imposed as upstream and downstream boundary condition, respectively, for the 2-D cells in contact with these nodes. These water levels will be kept unchanged until a new 1-D time step; (ii) Discharges flowing out of/into the 1-D model should be equal to discharges flowing into/out of the 2-D model. As the Van-Coc zone is situated in a sub-tropical region, the Coriolis term is very weak and thus ignorable.

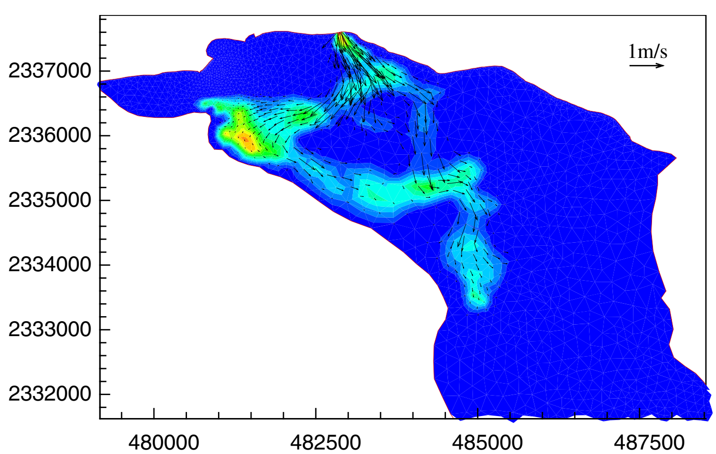


Figure 4. Velocity field and water depth at $t = 4$ h.

DOI: 10.1002/fld

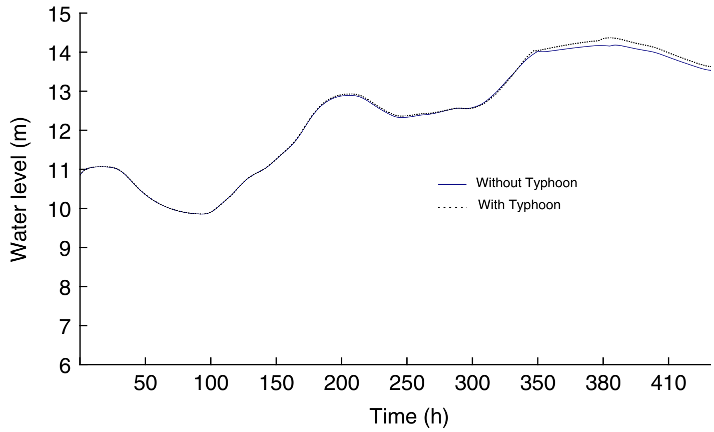


Figure 5. Comparison of water levels for two scenarios.

4.2. *Simulation and results*

The objective of this simulation is to understand: (i) What is the difference of impact between two scenarios; and (ii) what is the evolution of the velocity field and water depths in the case of a dyke break in the Van-Coc zone. This is important for preparing a rescue planning. The maximum dimension of the breach is 2.5 m in height and 50 m in width. The breach process lasted 10 h. It took 40 h to fill in the Van-Coc zone as a whole. Figure 4 presents the detailed velocity field and water depth in the Van-Coc zone at $t = 4$ h after dyke break for scenario 1 (without typhoon). Clearly, the velocity fields are very regular. This proves the efficiency of the numerical treatment for dry/wet areas problems, which is very delicate for all flood-diversion models. The maximum velocity observed in the Van-Coc zone for this case is about 3 m/s. The maximum water depth is nearly 3 m. A rescue planning should be prepared afterwards. The water levels at Hanoi in the case of broken dyke segments in Van Coc for both scenarios (1996s flood with and without typhoon) are presented in Figure 5. The water level evolution at Hanoi between two scenarios did not change significant. We can conclude that the typhoon would not affect the RRD.

5. CONCLUSION

As shown in [11], the present model has been validated by a lot of academic test cases. In this paper, the stability and the accuracy of the present model are once again proved by two real cases, in which the flows are strongly hyperbolic: (i) the famous Malpasset dam break and (ii) flood diversion by dyke break in the RRS. This model is able to simulate the propagation of flood waves over a dry, rough bottom in complex geometry.

ACKNOWLEDGEMENTS

The authors would like to thank the support of IMECH (Institute of Mechanic of Hanoi).

REFERENCES

1. Roe PL. Approximate Riemann solvers, parameter vectors and difference schemes. *Journal of Computational Physics* 1981; **43**(2):357–372.
2. Van Leer B. Towards the ultimate conservative difference scheme. IV. A new approach to numerical convection. *Journal of Computational Physics* 1977; **23**(3):276–299.
3. Harten A. High resolution schemes for hyperbolic conservation laws. *Journal of Computational Physics* 1983; **49**:357–393.
4. Bradford SF, Sanders BF. Finite-volume model for shallow-water flooding of arbitrary topography. *Journal of Hydraulic Engineering* (ASCE) 2002; **128**(3):289–298.
5. Valiani A, Caleffi V, Zanni A. Case study: Malpasset dam-break simulation using a two-dimensional finite volume method. *Journal of Hydraulic Engineering* (ASCE) 2002; **128**(5):460–472.
6. Louaked M, Hanich L. TVD scheme for the shallow water equations. *Journal of Hydraulic Research* 1998; **36**(3):363–378.
7. Wang JS, Ni HG, He YS. Finite-difference TVD scheme for computation of dam-break problems. *Journal of Hydraulic Engineering* (ASCE) 2000; **126**(4):253–262.
8. Ying XY, Khan AA, Wang SSY. Upwind conservative scheme for the Saint Venant equations. *Journal of Hydraulic Engineering* (ASCE) 2004; **130**(10):977–987.
9. Brufau P, Garcia-Navarro P. Two-dimensional dam break flow simulation. *International Journal for Numerical Methods in Fluids* 2000; **33**(1):35–58.
10. Sleigh PA, Gaskell PH, Berzins M, Wright NG. An unstructured finite-volume algorithm for predicting flow in rivers and estuaries. *Computers and Fluids* 1998; **27**(4):479–508.
11. Nguyen KD, Shi YE, Wang SSY, Nguyen TH. 2-D shallow-water model using unstructured finite-volumes methods. *Journal of Hydraulic Engineering* (ASCE) 2006; **132**(3):258–269.
12. Chorin AJ. Numerical solution of the Navier–Stokes equations. *Mathematics of Computation* 1968; **22**(745):762.
13. Shi YE. Résolution numérique des équations de Saint-Venant par la technique de projection en utilisant une méthode des volumes finis dans un maillage non structuré. *Ph.D. Thesis*, Université de Caen, Caen, France, 2006.
14. Guillou S, Nguyen KD. An improved technique for solving two-dimensional shallow water problems. *International Journal for Numerical Methods in Fluids* 1999; **29**(4):465–483.
15. Nguyen KD, Ouahsine A. 2D numerical study on tidal circulation in strait of Dover. *Journal of Waterway*, *Port*, *Coastal*, *and Ocean Engineering* (ASCE) 1997; **123**(1):8–15.
16. Kobayashi MH, Pereira JMC, Pereira JCF. A conservative finite-volume second-order accurate projection method on hybrid unstructured grids. *Journal of Computational Physics* 1999; **150**(1):40–75.
17. Nguyen KD, Hoang VL, Shi YE, Seille B, Ying XY. A 2-D shallow water models using unstructured finite-volumes methods. *Inter Report*, NCCHE, University of Mississippi, U.S.A., 2002.
18. Hubbard ME. Multidimensional slope limiters for MUSCL-type finite volume schemes on unstructured grids. *Journal of Computational Physics* 1999; **155**(1):54–74.
19. Batten P, Lambert C, Causon DM. Positively conservative high-resolution convection schemes for unstructured elements. *International Journal for Numerical Methods in Engineering* 1996; **39**:1821–1838.
20. Tannehill JC, Anderson DA, Pletcher RH. Governing equations of fluid mechanics and heat transfer. *Computational Fluid Mechanics and Heat Transfer* (2nd edn). Taylor & Francis: Washington, DC, 1997; 249–350.
21. Hervouet JM. A high resolution 2-D dam-break model using parallelization. *Hydrological Processes* 2000; **14**(13):2211–2230.
22. Nguyen VH, Ngo HC. On some numerical methods for solving the 1-D Saint-Venant equations of general flow regime. Part 2: verification and application. *Vietnam Journal of Mechanics*, *NCST of Vietnam* 2003; **25**(1):26–38.
23. Viseu T, Antao Da Silva P, Almeida AB, Franco AB. Dykes and failures. *Modelling Embankment Failures in the Red River Dyke System* (1st edn), vol. I. *Report 202/03-NRE/DHA*, LNEC. Springer: Berlin, 2003.

DOI: 10.1002/fld