DOI: 10.4408/IJEGE.2013-06.B-39

LANDSLIDE-TRIGGERED TSUNAMI MODELLING IN ALPINE LAKES

Martin FRANZ(*), Yury PODLADCHIKOV(**),
Michel JABOYEDOFF(*) & Marc-Henri DERRON(*)

(*)University of Lausanne - CRET - Lausanne, Switzerland,
(**)University of Lausanne - ISTE - Lausanne, Switzerland

ABSTRACT

The Alps are the location of potentially catastrophic landslide-generated tsunami. Numerical modelling based on shallow water equations represents a valuable tool able to provide prediction in order to assess this threat. However, some inherent numerical problems (e.g. artefacts development when applied to real cases, difficulty for wet to dry bed transition) are well known, but not resolved yet. Our main objective is to find a method that is relevant for landslide-triggered tsunami modelling, as accurate as possible in order to use it as predictive tool.

Thus, we investigated numerical models, based on shallow water equations, which could run on high resolution bathymetry. Accordingly, four Godunov-type solvers are confronted to the exact solution. Interestingly, at high resolution, which is needed for bathymetry, the difference between monotonous first-order methods gradually disappears. The simplest Lax-Friedrichs scheme is suggested as the method of choice. The experiment of a 2D circular dam break, solved using Lax-Friedrichs scheme, is presented and the resolution at which results are converging is reported. Performance of high resolution 2D runs on CPU and GPU are reported, documenting 50 fold speedup on GPU. As result of this speedup, the high resolution run take less than an hour on GPU card that cost less than 1000 SFr.

Key words : *landslide triggered generated tsunami dam lake Alps modelling shallow water equations Godunov Lax Friedrichs GPU*

INTRODUCTION

Landslide triggered tsunamis are responsible of a lot of damages worldwide. [NOAA (*http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=70&d=7*); Slingerland & Voight, 1979; Semenza & Ghirotti, 2000]. Mountainous regions are particularly subject to this phenomenon due to steep topography and associated slope instabilities, as well as large amount of water body such as lakes, fjords or reservoirs. Moreover, the fact that the valleys are highly populated and that they concentrate the water flow, give to this type of region a particularly high potential of catastrophic events.

In Switzerland only, ten tsunamis generated by landslides are documented since 1923. The slides volumes range from 5'000 to 300'000 m^3 and the wave height from 1.5 to 15 m (Huber, 1982; Louis Ingenieurgeologie, 2010). In AD 563, a submarine landslide triggered a tsunami in the Geneva Lake leading to an 8 m run-up in Geneva, more than 70 km away from the source (Kremer *et alii*, 2012). In the recent history, the most catastrophic events that occurred in the Alps is the one of Vajont which involved a 260 x 106 m^3 slide that triggered a dam overflow causing over 2000 casualties (Slingerland & Voight, 1979; Ward & Day, 2011; Bossa & Petti, 2011). The fact that none of them are listed in the NOAA Tsunami Events catalogue shows how little it is known or studied Lynett & Liu, 2004; Zijlema & Stelling, 2008; Ward & Day, 2011).

We concentrate on the development of model based on shallow water equations, since some limitations were encountered. When applied to real cases, development of numerical artefacts were reported (WIECZOREK *et alii*, 2007; FRANZ *et alii*, 2012). SIMPSON & CASTELLTORT (2006) describe a model formulation based on the shallow water equations and numerical algorithm to solve it based on the approximate Riemann solvers allowing for dry bed transition. In KREMER *et alii* (2012) this approach was applied for real bathymetry but without the wet to dry bed transition (i.e. run-up). TORO (2001) is the most comprehensive presentation of the numerical techniques for the shallow water equations. More recently, TORO & GARCIA-NAVARRO (2007) review the remaining numerical problems, in particular the treatment of the wet/dry front propagation. ZIJLEMA & STELLING (2008) states that, in case of variable topography, the solutions of nonlinear shallow water equations are confronted to numerical difficulties, even with exact Riemann solver. To resolve these numerical difficulties, we reinitiated testing of the various methods described in TORO (2001) with emphasis on higher resolution amendable by modern computers. We introduced additional tests relevant for tsunami imitated by landslides and tests for treating of variable bathymetry.

METHODS

The four numerical schemes tested here are: the Lax-Friedrichs, the 2 step Lax-Wendroff (or Richtmyer), the Godunov centred, and the Godunov upwind (TORO, 2001). Those are all based on the two-dimensional shallow water equations

$$U_t + F(U)_x + G(U)_y = 0\,,$$

where U the solution vector, F and G the flux vectors defined as

$$U = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix},$$

$$F = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \\ huv \end{bmatrix}, \qquad G = \begin{bmatrix} hv \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix}.$$

where h is the water depth, u and v are the components of the depth-averaged velocity vector, g is the gravity acceleration. Dimensional splitting is used to reduce it to the augmented one-dimensional problem

$$U_t + F(U)_x = 0$$

The conservative discrete form is

$$U_i^{n+1} = U_i^n - \frac{\Delta t}{\Delta x}\left[F_{i+\frac{1}{2}} - F_{i-\frac{1}{2}}\right],$$

where $F_{i+1/2}$ is the intercell numerical flux corresponding to the intercell boundary at $x = x_{i+1/2}$ between cells i and $i+1$.

The four numerical schemes are only different in definition of the intercell flux $F_{i+1/2}$.

The Lax-Friedrichs (LF) scheme uses (TORO, 2001, page 163):

$$F_{i+\frac{1}{2}}^{LF} = \frac{1}{2}\left(F_i^n + F_{i+1}^n\right) + \frac{1}{2}\frac{\Delta x}{\Delta t}\left(U_i^n - U_{i+1}^n\right),$$

The 2 step Lax-Wendroff (LW) scheme uses (TORO, 2001, page 164):

$$U_{i+\frac{1}{2}}^{LW} = \frac{1}{2}\left(U_i^n + U_{i+1}^n\right) + \frac{1}{2}\frac{\Delta t}{\Delta x}\left(F_i^n - F_{i+1}^n\right),$$

$$F_{i+\frac{1}{2}}^{LW} = F\left(U_{i+\frac{1}{2}}^{LW}\right).$$

The Godunov centred scheme (GC) uses (TORO, 2001, page 164):

$$U_{i+\frac{1}{2}}^{GC} = \frac{1}{2}\left(U_i^n + U_{i+1}^n\right) + \frac{\Delta t}{\Delta x}\left(F_i^n - F_{i+1}^n\right),$$

$$F_{i+\frac{1}{2}}^{GC} = F\left(U_{i+\frac{1}{2}}^{GC}\right).$$

GODUNOV UPWIND

The exact Riemann solution deals with tree type of waves (Fig. 1). The region between left and right waves is the star region. In this region h and u are characterized by h* u*, for which a nonlinear algebraic equation is solved by an iterative method. The flux of the Godunov upwind scheme (Gup) is computed for the exact local Riemann solution $U_{i+1/2}(0)$ at every contact between the cells (TORO, 2001):

$$F_{i+\frac{1}{2}}^{GU} = F\left(U_{i+\frac{1}{2}}(0)\right)$$

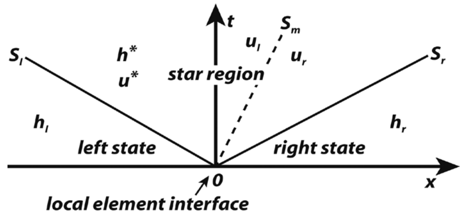

Fig. 1 - The left wave and the right wave (S_l and S_r as velocity) that can be rarefaction or shock waves. The middle is a contact wave (S_m as velocity)

Tab 1 - GPU time for the runs presented at Figure 7 (same physics and model tested but different resolution)

Iterations	GPU time [s]	Resolution
250	0.010	160x 160
500	0.039	320 x 320
3000	4.278	1920 x 1920
30000	4247.693	19200 x 19200

Test	h_L (m)	u_L (m/s)	h_R (m)	u_R (m/s)	x_0 (m)	T_{out}(s)
1	1.0	2.5	0.1	0.0	10.0	7.0
2	1.0	-5.0	1.0	5.0	25.0	2.5
3	1.0	0.0	0.0	0.0	20.0	4.0
4	0.0	0.0	1.0	0.0	30.0	4.0
5	0.1	-3.0	0.1	3.0	25.0	5.0
6	110.0	-1.0	100.0	1.0	25.0	0.5
7	0.2	0.0	0.1	6.0	12.5	5.0
8	19.0	0.0	10.0	50.0	25.0	0.3

Tab 2 - The initial parameters of the tests, where hL, and hR are the water level, u_L and u_R the velocity, respectively on the left and the right, x_0 the position of the wall and Tout the time of the simulation end

TESTS

The tests used here are those proposed in Toro (2001) (tests 1 to 5, Tab. 2). These tests are relevant to the dam break. As we are interested in landslide generated waves, we add three additional tests (6, 7 and 8 in Tab. 2) that better capture the generation of the wave by the penetration of a landslide in the water body.

GROUP 1: THE TORO (2001) TESTS

Left critical Rarefaction and Right Shock (test 1)

This test simulates a dam break over a wet bed in order to test the speed of propagation, the absence of oscillations, and the steepness of the front. Initial data (Tab. 2, test 1) produce shock wave to the right and rarefaction to the left.

Two rarefaction and nearly dry bed (test 2)

It simulates a sudden aperture in the water body. The initial data (Tab. 2, test 2) generate two rarefaction waves travelling in opposite directions. The water depth at the created aperture is close to zero. The test investigates the symmetry of propagation, the ability of the schemes to sustain the near zero water depth situation and smoothness of the velocities profiles.

Right dry bed Riemann problem (test 3)

Simulate a dam break with a dry bed on the right. The initial conditions (Tab. 2, test 3) produce a rarefaction wave. The test evaluates the capacity of a numerical scheme to handle the transition from dry to wet bed.

Left dry bed Riemann problem (test 4)

Simulate a dam break with a dry bed on the right. The initial conditions (Tab. 2, test 4) produce a rarefaction wave. The test evaluates the capacity of a numerical scheme to handle the transition from dry to wet bed and negative velocities.

Generation of a dry bed (test 5)

This test is similar to the second test, which simulate a sudden aperture in the water body. In this test the aperture reaches the bed and spontaneously generates a dry bed. It tests the capacity of the codes to generate a dry bed condition from a wet bed. It is considered as the most difficult of the five tests (Tab. 2, test 5).

All methods, including LF, work well with high resolution. The LF scheme, which is known to be too diffusive to be used in practice (Toro, 2001), becomes acceptable when the resolution is increased over thousand grid points. Moreover it is not oscillating and generally fits correctly the exact solution. The LF scheme, due to its simplicity, can be the best choice in order to model wave generation and propagation over complex bathymetry.

GROUP 2: ADDITIONAL TESTS FOR LANDSLIDE-GENERATED TSUNAMI

The first five tests do not explore interplay of initial water level jump (like in tests 1, 3 and 4) and divergent velocity jump potentially leading to the spontaneous formation of the dry state (like in tests 2 and 5). Similarly to the tests 2 and 5, we introduce tests 6 and 7 in such a way that test 6 does not lead to the spontaneous dry state while test 7 does. Tests 6 and 7 are different from tests 2 and 5 by allowing for a water level jump in initial conditions. These additional tests are relevant for the landslide-generated tsunami. Indeed, sliding into shallow water landslide can be accommodated by water level elevation on the top of the landslide and divergent horizontal velocity laterally displacing the water and creating the space for the landslide. The latter possibility may potentially lead to the spontaneous generation of the dry state. Newly suggested tests 6 and 7 are proposed as a validation for the ability of a numerical scheme to handle and to correctly predict the spontaneous dry state around landslide.

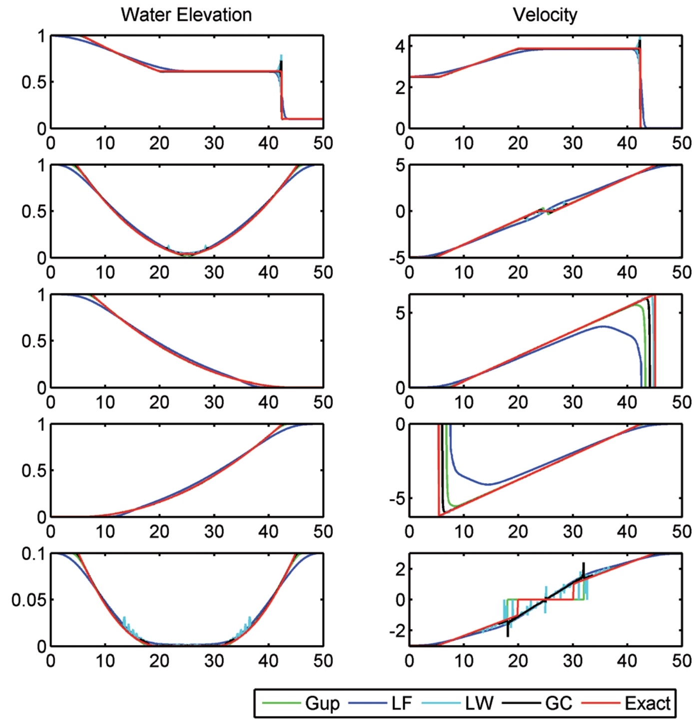

Fig. 2 - Four methods are compared with the exact Riemann solution, respectively from tests 1 to test 5 (from top to bottom) at a resolution of 2000 numerical grid points. At such a resolution, all the methods fit quite well to exact solution. The LF is the most numerically diffused solution (velocity & elevation). There are only two, LF and Gup, that show no numerical oscillations

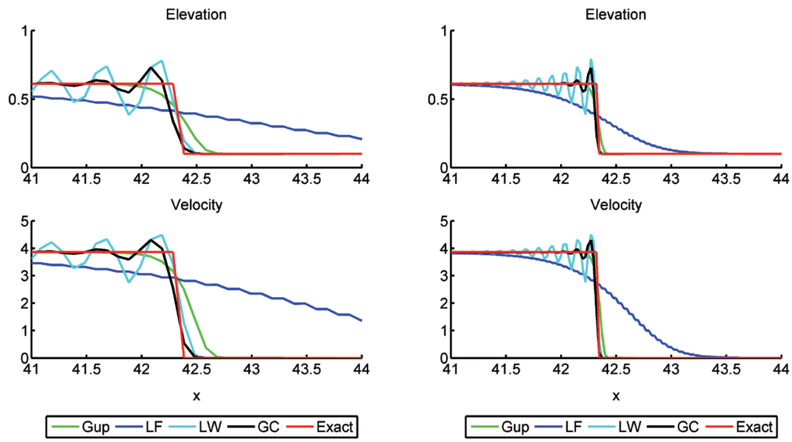

Fig. 3 - Close-ups on the shock waves (elevation and velocity) of the test 1.Left: grid resolution is 500; Right: grid resolution is 2000. Only Gup and LF schemes are not oscillatory. The LF is the most diffusive solution, but it captures the wave location well

<u>*Test 6: Moderate test of landslide penetration (100m depth, 1m/s velocity)*</u>

This test simulates the penetration of a landslide into a deep water body at a relatively slow velocity. The initial conditions (Table 2, test 6), as the low initial velocities, make this test similar to the test n° 1, where the elevation of water due to the landslide become affected by a rarefaction wave that propagates to the left and a shock wave that propagates to the right. The Figure 4 illustrates this test. The cross section is assumed perpendicular to the slide direction. For this test, as for the next two tests, there are only Gup and the LF schemes are shown.

The moderate test (Fig. 4) is successfully simulated by the both schemes (Gup & LF). The main relevant aspect is that an increased resolu-

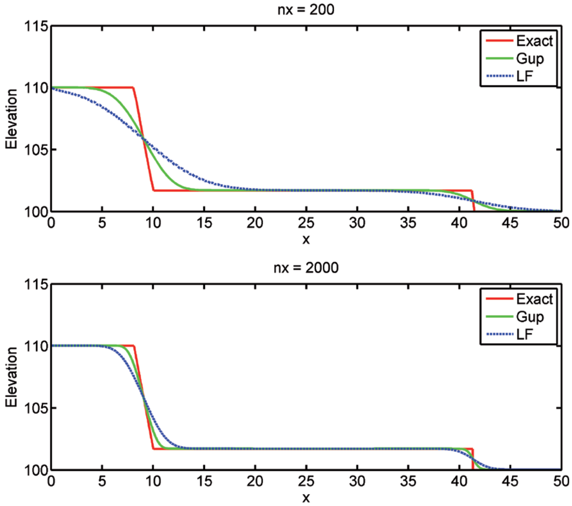

Fig. 4 - Results of the moderate test 6 for Gup and LF methods. Top: grid resolution is 200; Bottom: grid resolution is 2000

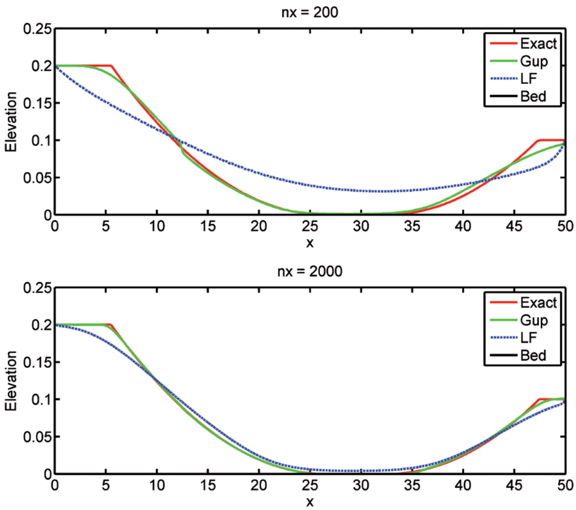

Fig. 5 - Results of the extreme test 7 for Gup and LF methods. Top: grid resolution is 200; Bottom: grid resolution is 2000

tion reduces numerical diffusion for both numerical schemes and reduces the difference between the two numerical solutions.

Test 7: Extreme test of landslide penetration (0.1 m depth, 6 m/s velocity)

This test, presented in Figure 5, simulates, as the test 6, the penetration of a landslide in a water body, except that the water is very shallow (0.1 m) and the initial velocity is faster (6 m/s). The initial data (Table 2, test 7) induce lateral displacement of the water leading to a spontaneous dry state like test 5.

This extreme test is simulated well by both methods (Fig. 5). Again we observe a better fit and less diffusion with a higher resolution (here 2000).

Test 8: a rough bed

This case tests the capacity of the methods to simulate the propagation of the waves over a rough bed (Fig. 6). This is a crucial point for a reliable numerical model for landslide-generated tsunami over real bathymetry. The Gup and the LF methods successfully passed this rough bed test (Fig. 6). Again the solutions at higher resolution are less diffusive. Moreover, both schemes have passed the consistency test: rough bathymetry does not cause wave motion if the water level is flat and initial velocity is zero. We conclude that both schemes are admissible while having similar computational cost. LF is preferred due to considerable simplicity of its implementation.

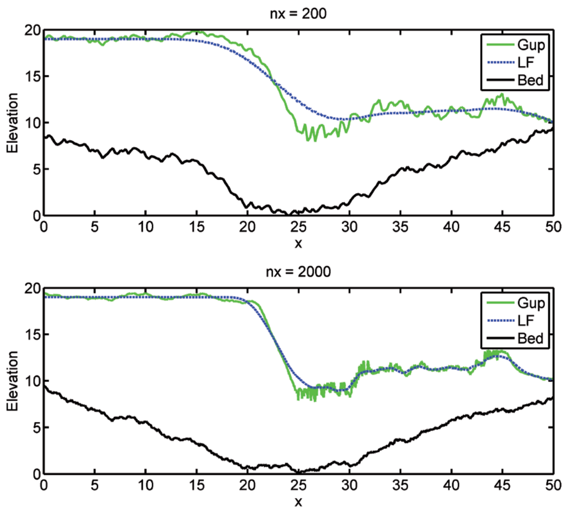

Fig. 6 - Results of the rough bed test 8 for Gup and LF methods. Top: grid resolution is 200; Bottom: grid resolution is 2000

GROUP 3: RESOLUTION TESTS IN 2D

Four runs of growing resolution are computed in 2D in order to confirm the positive effect of the resolution on the numerical diffusivity of the simplest LF scheme. They are performed on a regular workstation to check if needed high resolution is practically achievable. The Figure 7 presents the results of the exactly the same experimental setup (circular dam break) conducted at different grid resolutions.

The Figure 7 illustrates that the diffusive problem decreases with the increase of the resolution. The run time rises with the resolution (see Table 1). We observe that GPU computing is practical already that very high resolution is affordable, even with 2D models, when computed on GPU.

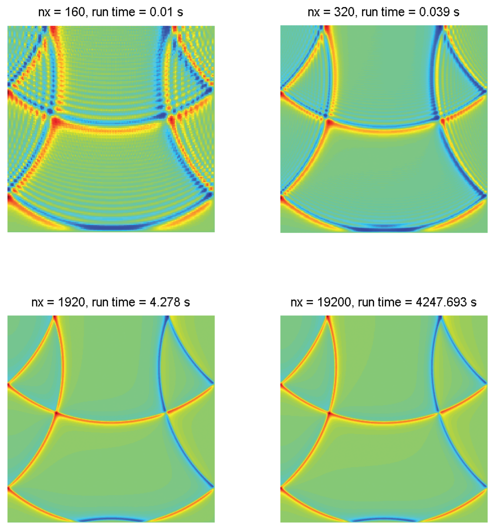

Fig. 7 - Results of four resolution tests in 2D

SUMMARY

We have conducted three different groups of tests. The group 1 consisting of five tests from Toro (2001) have been successfully passed by all four numerical schemes considered. Despite the fact that the LF method is commonly regarded as too diffusive and not practical (e.g. Toro, 2001), it appears that the LF method, together with the Gup method, are the best solutions, considering that they are not oscillatory. The groups 2 and 3 continued the testing with only these two methods. In our second testing suit (group 2) consisting of tests 6, 7 and 8, we have considered more difficult numerical scenarios related to landslides-triggered tsunami problems. Running these tests with different resolutions, it appears clearly that a higher resolution solves the diffusive problems. The test 8 demonstrates robustness of both LF and Gup over rough bed. Finally, the tests of the group 3 shows that very high resolution is affordable, even with 2D models, when computed on GPU.

With ever growing computer power, the choice of the method can be reconsidered. Indeed the LF method can be a good choice because: it is not oscillatory, its diffusive problems disappear with high resolution, it withstands rough beds, and its simplicity.

CONCLUSION

Landslide-triggered tsunami in alpine lakes or reservoirs can potentially lead to catastrophic events. Modelling this phenomenon is necessary in order to assess its consequences, but it is known to be problematic. This paper compares four numerical methods with the exact Riemann solution, proposes three new tests directly linked to the landslide-generated tsunami and investigates the effects and the feasibility of (very) high resolution 2D modelling tests. This study suggests modern reassessment of the Lax-Friedrichs method. Indeed, with modern high resolution computing, this method is no more too diffusive, captures correct propagation velocities, non-oscillatory and easy to implement.

REFERENCES

Assier-Rzadkiewicz S., Heinrich P., Sabatier P.C., Savoye B. & Bourillet J.F. (2000) - *Numerical modelling of a landslide-generated tsunami: the 1979 Nice Event.* Pure appl. Geophys., **157**: 1707-1727.

Bossa S. & Petti M. (2011) - *Shallow water numerical model of the wave generated by the Vajont landslide.* Environmental Modelling & Software, **26**: 406-418.

Franz M., Podladchikov Y., Derron M.-H., Jaboyedoff M., Michoud C., Baillifard F.J., Genton L. & Omlin S. (2012) - *Tsunami in Alps reservoirs: the case of Mauvoisin dam (Valais, Switzerland).* Geophysical Research Abstracts, **14**. EGU General Assembly 2012.

Geist E.L., Jakob M., Wieczorek G.F. & Dartnell P. (2003) - *Preliminary hydrodynamic analysis of landslide-generated waves in Tidal Inlet, Glacier Bay National Park, Alaska.* U.S. Geological survey Open-File Report 03-411.

Gonzalez-Vida J.M., Castro M.J., Sánchez-Linares C. & De La Asunción M. (2012) - *Simulation of landslide-generated tsunamis with the HySEA platform: application to the Lituya Bay 1958 tsunami.* Geophysical Research Abstracts, **14**. EGU General Assembly 2012.

Heller V., Hager W.H. & Minor H.-E. (2009) - *Landslide generated impulse waves in reservoirs: basics and computation.* Mitteilungen 211, VAW, R. Boes, Hrsg., ETH Zürich.

Hubert A. (1982) - *Felsbewegungen und Uferabbrüche an Schweizer Seen, ihre Ursachen und Auswirkungen.* Eclogae Geologicae Helvetiae, **75** (3): 563-578.

Kremer K., Simpson G. & Girardclos S. (2012) - *Giant Lake Geneva tsunami in ad 563.* Nature Geoscience, **5**: 756-757.

L'heureux J.-S., Glimsdal S. Longva O., Hansen L. & Harbitz C.B. (2011) - *The 1888 shoreline landslide and tsunami in Trondheimsfjorden, central Norway.* Mar. Geophys. Res., **32**: 313-329.

Louis Ingenieurgeologie (2010) - *Bürgenstock Ehemaliger Steinbruch Obermatt, Gefahren- und Sicherheitsbeurteilung.* Louis Ingenieurgeologie, UNIL, IGAR, ETHZ, VAW.

Lynett P. & Liu L.-F. (2002) - *A numerical study of submarine-landslide-generated waves and run-up.* Proc. R. Soc. Lond., **458**: 2885-2910.

Lynett P. & Liu L.-F. (2004) - *A two-layer approach to wave modelling.* Proc R. Soc. Lond., **460**: 2637-2669.

Moler C. (2011) - *Experiments with MATLAB.* Electronic edition published by MathWorks, Inc.

Murillo J., Burguete J., Brufau P. & García-Navarro P. (2005) - *Coupling between shallow water and solute flow equations: analysis and management of source terms in 2D.* Int. J. Numer. Meth. Fluids, **49**: 267-299.

Pudasaini S.P. & Miller S.A. (2012) - *A real two-phase submarine debris flow and tsunami.* American Institute of Physics Proceeding, **1479**: 197-200.

Roe P.L. (1986) - *Characteristic-based schemes for the Euler equations.* Ann. Rev. Fluid Mech., **18**: 337-365.

Semenza E. & Ghirotti M. (2000) - *History of the 1963 Vaiont slide: the importance of geological factors.* Bull. Eng. Geol. Env., **59**: 87-97.

Simpson G. & Castelltort S. (2006) - *Coupled model of surface water flow, sediment transport and morphological evolution.* Computer & Geoscience, **32**: 1600-1614.

Slingerland R.L. & Voight B. (1979) - *Occurrences, properties, and predictive models of landslide-generated water waves.* In: Voight B. (ed.). *Rockslide and avalanches*. Vol. 2: 317-397, Elsevier, Amsterdam.

Tinti S., Pagnoni G. & Zaniboni F. (2006) - *The landslides and tsunamis of the 30th of December 2002 in Stromboli analysed through numerical simulations.* Bull. Volcanol., **68**: 462-479.

Toro E.F. (2001) - *Shock-capturing methods for free-surface shallow flows.* Wiley, New York.

Toro E.F. & Garcia-Navarro P. (2010) - *Godunov-type methods for free-surface shallow flows: A review.* Journal of Hydraulic Research, **45**: 736-751.

Ward S.N. & Day S. (2011) - *The 1963 Landslide and Flood at Vajont Reservoir Italy. A tsunami ball simulation.* Ital.J.Geosci., **130**: 16-26.

Wieczorek G.F., Jakob M., Motyka R.J., Zirnheld S.L. & Craw P. (2003) - *Preliminary assessment of landslide-induced wave hazards: Tidal Inlet, Glacier Bay National Park, Alaska.* U.S. Geol. Survey Open-File Report 03-100.

Wieczorek G.F., Geist E.L., Motyka R.J. & Jakob M. (2007) - *Hazard assessment of the Tidal Inlet landslide and potential subsequent tsunami, Glacier Bay National Park, Alaska.* Landslides.

Zijlema M. & Stelling G.S. (2008) - *Efficient computation of surf zone waves using nonlinear shallow water equations with non-hydrostatic pressure.* Costal Engineering, **55**: 780-790.