A Numerical Model of the Wave that Overtopped the Vajont Dam in 1963

Silvia Bosa · Marco Petti

Abstract The Vajont landslide took place in northern Italy on October 9th 1963 and caused a huge impulse wave to travel along the artificial reservoir and overtop the dam, flooding and devastating a considerable area along the Piave riverbed. In this event about 1900 people died, 1700 of them in the Piave Valley alone. The water depth of the wave in some points exceeded 50 m. Although the phenomenon is clearly tridimensional, the application of a pure 3D hydraulic numerical model to this wide and natural territory is very complicated. Recently, the authors have presented a numerical model of the impulse wave that wasted the Vajont basin as a consequence of the landslide Bosa and Petti (Environ Model Softw 26:406–418, 2011). In this paper, a 2DH numerical model has been applied to study the effects of the overtopping wave in the Piave Valley, in order to verify if the simplifications assumed by a 2DH model still make it possible to describe the evolution of the wave in the proper manner.

1 Introduction

On October 9th 1963 at 22:39 a huge landslide of about 270 million m^3 slid from Mount Toc into the Vajont artificial reservoir, in north-eastern Italy (Schnitter 1964; Slingerland and Voight 1979; Datei 2003; Genevois and Ghirotti 2005). The amount of water in the basin at that moment was about 115 million m^3. The resulting displacement of water caused the generation of an impulse wave that spread throughout the basin. Its impressive wave run-up on the north slope of the lake, in front of Mount Toc, reached and damaged buildings located in Casso about 235 m over the original height of the lake surface (Fig. 1a). The resulting wave rundown crashed into the front of the landslide and partially crossed over the slide bulk, reaching the depressions behind the slide (Fig. 1b). On the east side of the basin, a portion of the water which

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was pushed forward by the landslide formed a wave with smaller amplitude that travelled to the east, reaching the eastern most end of the reservoir in the mountains.

During the whole event several impulsive waves crested the dam or moved onto the surrounding slopes which became a way for the water to move out into the narrow canyon that connects the dam to the Piave Valley (Bosa and Petti 2011). The mass of water that poured into the canyon, compressing the air, generated a wave of pressure that acted as a wind. This "wind", propagating at a speed greater than the waterfront, preceded the waterfront and produced the first damage in Longarone, before the water reached the town (Reberschack 2003). The villages located along the Piave riverbed were completely devastated and turned into a flat plain of mud, with about 1700 casualties. The wave travelled upstream for about 5 km and in the downstream cross-sections of Ponte nelle Alpi and Belluno (located respectively at about 11 and 19 km from Longarone) the estimated maximum flow was 20 %–50 % higher than the one observed during the famous 1966 flood wave (Reberschak 2003; Bondesan et al. 2004).

Documentation available in literature consists mainly of historical pictures of the Piave Valley in the days just after the event. This allows one to estimate the maximum wave run-up in the villages located along the riverbed, based on the depicted damage. The evaluation of the time of propagation of the flow is much more debated. This is mainly based on witness statements, so that the time estimated to cover the path from the dam to Longarone ranges from 60 s to 4 min, for instance (Reberschack 2003).

Reconstruction of the hydrograph that overtopped the dam is not easy to do. In literature only an approximate evaluation of the water volume which poured over the dam was carried out, on the base of estimations of the water volume in the Vajont basin before and after the event.

Numerical models can be used in engineering practice as an aid to study hydraulic critical situations in country planning in order to prevent environmental disasters. Nevertheless, before
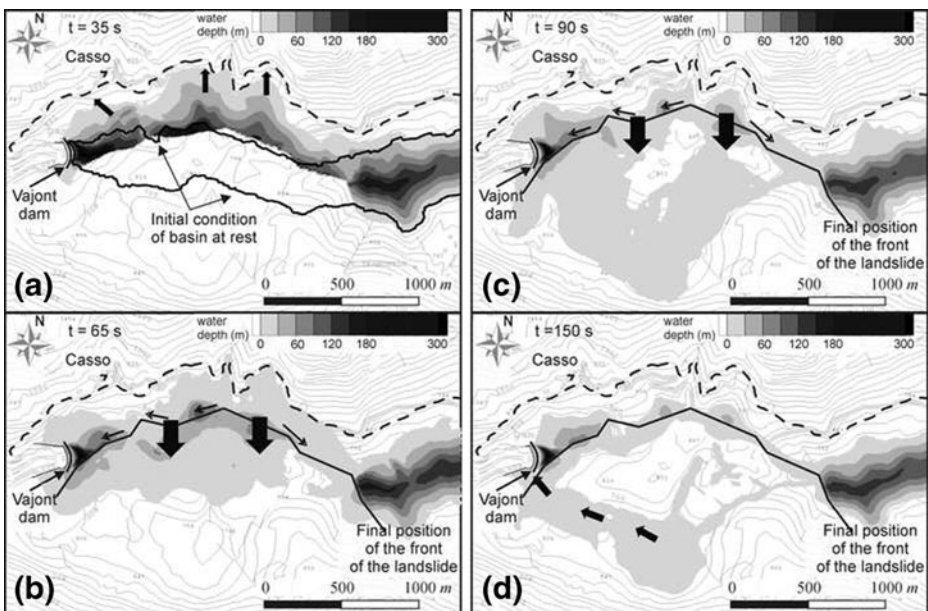

Fig. 1 Numerical results of the simulation in the artificial reservoir: water depth at sequential time steps; the dashed line represents the observed run-up limit, the continuous line is the initial basin (**a**) or the final position of the front of the landslide (**b**–**d**)

a numerical model can be considered as useful in applied research with the community benefiting from its applications, it must overcome at least two verification steps. First, it must be applied to benchmark tests with an analytical solution or to small scale laboratory tests. After that, the model can be verified on a large scale on site (e.g., Hervouet 2000; Valiani et al. 2002; Alcrudo and Mulet 2007; Begnudelli and Sanders 2007; Liao et al. 2007; Petaccia et al. 2008; Shi and Nyugen 2008; Gallegos et al. 2009; Pilotti et al. 2011). The first step alone does not ensure that the model works in a proper way in wide and complex natural domains. Moreover, one would often like to apply the models to real events which do not exactly match hypotheses made during the development of the model itself. Hence, the applicability of the model to unusual situations must be tested with particular care.

The Vajont event was clearly a tridimensional phenomenon, but with present computer technologies, 3D models are still not applicable to natural and wide topographies like those of the Vajont Valley. So the two-dimensional models (2DH) remain the only applicable alternative. In this paper a 2DH numerical hydraulic model of the propagation in the Piave Valley of the wave that flowed over the Vajont dam is presented with the aim of evaluating if a 2DH numerical model is able to describe this event in its main aspects, in spite of all the simplifications implied in the model. In particular, in this paper it is not our intention to study the behavior of the wave near the dam. This area, characterized by jets in the air and aerated flows, cannot be studied with a 2DH simple model and requires at least three-dimensional modeling capable of capturing biphasic characteristics, determined by the presence of air in the fluid. Nevertheless, it is still unthinkable to use such a 3D model to study the behavior of the wave downstream of the dam, as the long computational times would prevent the application. Aware of these limitations, we decided to use the 2DH modeling presented in this paper to analyze the behavior of the wave in the Piave Valley.

Unlike other events which are usually adopted as classical verification for numerical models such as the Malpasset accident, the Vajont dam did not fall. Thus, the water reached the Piave Valley not as a consequence of a dam break, but as the result of a wave that overtopped the dam. The numerical model applied in the present work is able to describe both the evolution of the wave inside the Vajont basin and the wave that, after overtopping the dam, spread through the Piave Valley.

Moreover, numerical reconstruction of the waves that followed the Vajont landslide in 1963 could make up for some deficiencies in the description of the event as is currently available in the literature.

The paper is organized in the following manner. The numerical model is briefly recalled in the following section. In Section 3 the numerical simulations of the wave generated by the Vajont landslide inside the reservoir (Bosa and Petti 2011) are briefly described and the hydrographs of the waves that flowed towards the Piave river are analyzed. In Section 4, the numerical simulation of the wave that overtopped the dam and flooded the Piave Valley is described and the results are discussed and compared with direct evidence.

2 Numerical Model

In the present modeling, bidimensional shallow water equations are used:

$$
\begin{cases}
\frac{\partial h}{\partial t} + \frac{\partial Uh}{\partial x} + \frac{\partial Vh}{\partial y} = 0 \\
\frac{\partial Uh}{\partial t} + \frac{\partial}{\partial x}\left(U^2 h + \frac{gh^2}{2}\right) + \frac{\partial UVh}{\partial y} = -gh\left(\frac{\partial z_b}{\partial x} + S_{fx}\right) \\
\frac{\partial Vh}{\partial t} + \frac{\partial UVh}{\partial x} + \frac{\partial}{\partial y}\left(V^2 h + \frac{gh^2}{2}\right) = -gh\left(\frac{\partial z_b}{\partial y} + S_{fy}\right)
\end{cases}
\tag{1}
$$

being (t, x, y) temporal and horizontal spatial coordinates, h water depth compared to the

bottom, U and V mean velocity over the depth in x- and y- directions, g gravity acceleration and z_b bottom height. As this is a fixed bed model, bottom height z_b is constant in time. S_{fx} and S_{fy} are friction slope in x- and y- directions and are evaluated through the Manning equation:

$$S_{fx} = n^2 \frac{U\sqrt{U^2 + V^2}}{h^{4/3}}, \ S_{fy} = n^2 \frac{V\sqrt{U^2 + V^2}}{h^{4/3}} \tag{2}$$

n being Manning roughness coefficient.

The numerical scheme used to solve system (1) has already been described in Bosa and Petti (2011) and consists of a second order accurate fractional step method. The advective step is solved by means of a second order accurate finite volume scheme based on the application of an HLL approximate Riemann solver coupled with minmod limiters for the solution of the local Riemann problem. The particular case of a wet-dry front is treated in the same way as the wet-wet case, with the only difference being that the wave speed in the HLL solver is evaluated as in the exact solution of a Riemann problem with a dry bed (Ritter problem). The source term problem is also second order accurate, estimating the bed slopes with a central finite difference scheme (Petti and Bosa 2007). The spatial discretization is made by quadrangular irregular elements.

The present model has been applied to several test cases proposed in literature. As an example, in Fig. 2 the results of two transcritical bump tests with and without hydraulic jump are depicted. The topography is deduced from literature (Valiani et al. 2002), the inflow per unit length was 0.18 m²/s for both tests, while the downstream boundary condition of the water depth was set at 0.33 m (test with jump) and at 0.07 m (test without jump). The results show that the test is well represented.

Boundary conditions used in the present numerical scheme are classic transmissive or outflow boundary conditions, reflective or wall boundary conditions and inflow boundary conditions.

3 Numerical Simulation of the Wave Generated by the Vajont Landslide in the Reservoir

The phenomenon that gave rise to the impressive wave that inundated the Piave Valley on October 9th 1963 was a huge landslide that fell into the Vajont artificial reservoir. A portion of the water present in the basin overtopped the dam and reached the Piave Valley through a
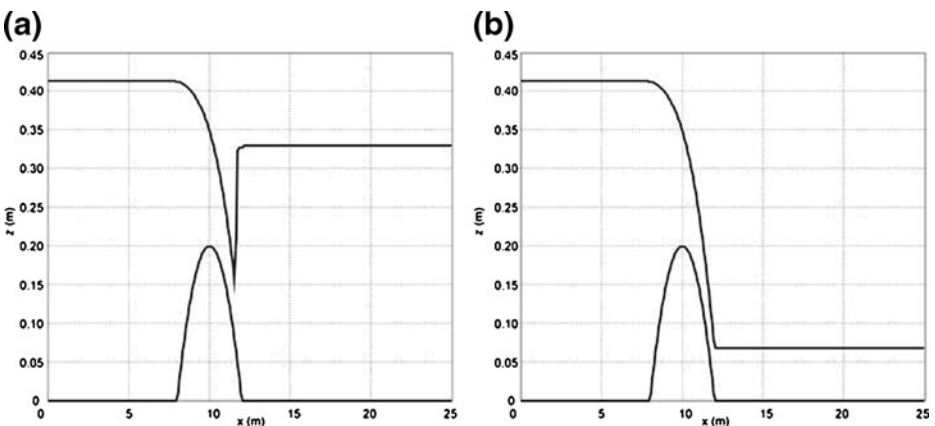

Fig. 2 Transcritical bump with (**a**) and without (**b**) hydraulic jump

narrow canyon. Thus, the landslide, the wave inside the artificial reservoir and the flooding downstream of the dam are definitively bounded, so they should be studied together. However, the area affected by the event is too wide to be analyzed in detail by a single model. Therefore, first the Vajont basin was studied (Bosa and Petti 2011) and then the Piave Valley. The models of Vajont basin and Piave Valley slightly overlap, the downstream face of the dam and the slopes surrounding the dam being the way out of the water in the Vajont basin model and the entrance of the water in the Piave Valley model. Since the motion of the current across the two domains is supercritical, it is reasonable to decouple the two models.

The Vajont Valley was represented through a mesh made up of about 133000 quadrangular irregular elements. The bottom height was first assigned according to current numerical cartography and then corrected using maps of the valley as it was before October 9th 1963 (Rossi and Semenza 1965). Areas characterized by homogeneous Manning roughness coefficients were estimated by means of numerical cartography and historical pictures, where available. Initial conditions were those of a basin at rest, as it was before the landslide occurred. The Vajont landslide was an extraordinary large, partially submerged rockslide with a thickness of about 200 m, that pushed forward the water as if it were a piston. Thus, in the model, the landslide was depicted as a moving impermeable vertical wall located at the landslide front; therefore, the headway of the slide is represented as a wall that pushed the water towards the slope in front of it, just below the village of Casso. The bottom height of the cells intercepted by the landslide was updated after the passage of the front with the post landslide elevation deduced by the post event maps (Rossi and Semenza 1965). Moreover, after the landslide stopped, the moving landslide boundary condition was removed to allow the rundown wave to cover the areas previously filled by the landslide (Bosa and Petti 2011).

In Fig. 1 the results of the simulation are depicted as a contour of water depth together with observed run-up limit by Rossi and Semenza (1965) and final position of the front of the landslide. The direction of the main waves involved in the event is also indicated.

In particular, Fig. 1a shows the situation during the movement of the front; here the water displaced by the landslide boundary condition forms a single direct wave that moves to the slope opposite Mount Toc (direction north), where it almost reaches the observed run-up limit. During this phase, part of the water was pushed over the dam and left the basin.

In Fig. 1b the behavior of the main rundown wave that impacts against the landslide front is presented. Part of the water moves along the landslide front, directed either towards the east part of the basin or towards the dam (thin arrows). The flow that moves towards the dam generates two more overtopping waves, the peak of the former being at about 60 s and the peak of the latter at about 90 s as shown in Fig. 5. Part of the rundown flow crossed over the slide bulk (thick arrows) and it either inundated the depression behind the slide itself, or it reached the left hand wall of the canyon and it definitively left the basin (Fig. 1c–d).

As is well-known, any well built mathematical or numerical model in the absence of well-posed boundary conditions is destined to fail. Thus, to properly investigate the subsequent evolution of the wave in the Piave Valley, particular care was taken in the analysis of the water that left the Vajont Valley to then reach the Piave Valley through the narrow canyon. An excellent solution was found by evaluating the flow over several sections (Fig. 3): 3 dam sections (DN, DC and DS) that take into account the water overtopping the dam, 7 sections located on the right hand slope of the canyon (R1 to R7) and 5 sections located on its left hand slope (L1 to L5). The sections were designed to be as perpendicular as possible to the maximum slope direction and their contribution to the water reaching the Piave Valley is then summed up to give the flow crossing the entire slope (R and L, being the sum R1 to R7 and L1 to L5 respectively) or the dam (D being the sum DN + DC + DS). The contribution of water volume greatly decreases as soon as it moves away from the dam, so that on the right
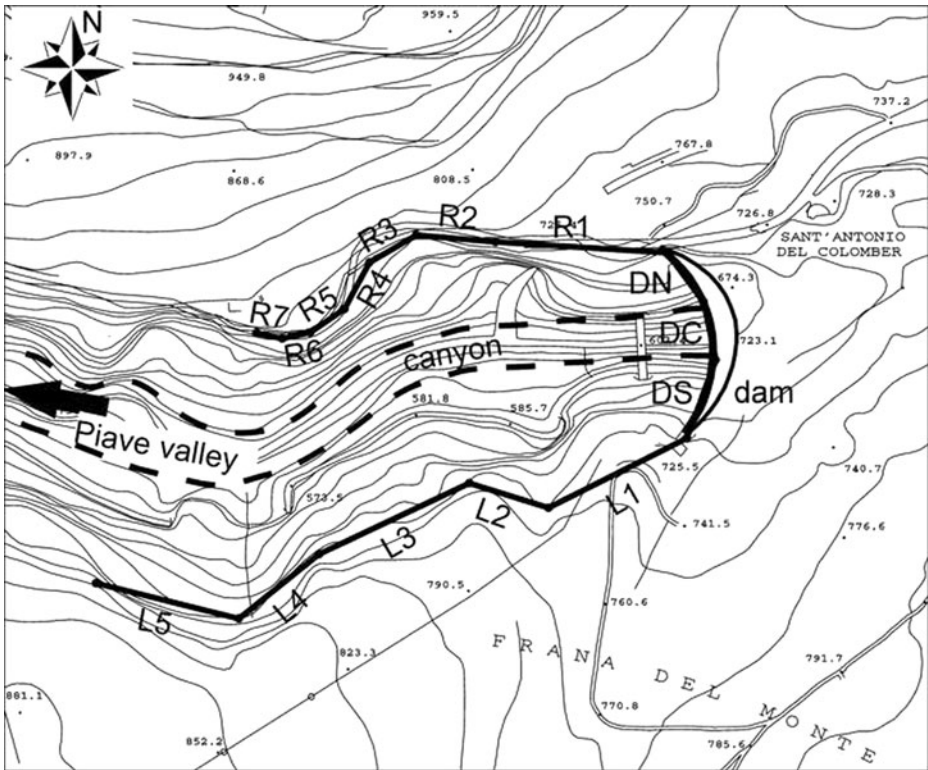
Fig. 3 Sections used to evaluate the flow leaving the Vajont Valley and directed to the Piave River

hand side the water volume through R4, R5, R6 and R7 was 11738 m³, i.e. only 0.33 % of the amount of water going through whole right hand side slope. On the other side, sections L4 and L5 were completely dry.

The flow hydrographs over the right slope (R), the dam (D) and the left slope (L) are depicted in Figs. 4 and 5, together with the main contributions of the single sections. Figure 4a shows that the right hand slope has a hydrograph characterized by two narrow peaks, where the former is much higher than the latter (188×10^3 vs 47×10^3 m³/s). Moreover, the two peaks are separate, the former being due to the first direct run-up wave and the latter due to the rundown wave. The contribution of section R1 is predominant and the input of R2 and R3 only concerns the first peak. At 100 s the flow over both sections is almost zero, underlining the impulsive nature of this hydrograph.

On the left hand slope (Fig. 4b) the major contribution is due to section L1, while sections L2 and L3 give only a small input to each of the three peaks. In this sense, the situation is similar to that of the right hand slope, i.e. the further a section is from the dam the smaller its contribution is to the resulting hydrograph. Nevertheless, here the peak reached by the flow is very low, compared to those of the right hand slope or of the dam (53×10^3 vs 188×10^3 m³/ s), but it lasts longer, being at 180 s still 13×10^3 m³/s. This is the reason for which the total water volume that flowed over left hand slope is higher than over right hand slope (5.11×10^6 vs 3.61×10^6 m³).

The flow over the dam is shown in all its contributions in Fig. 5. The input of the three sections is very similar for both the peaks flows (82×10^3 vs 75×10^3 vs 79×10^3 m³/s) and the
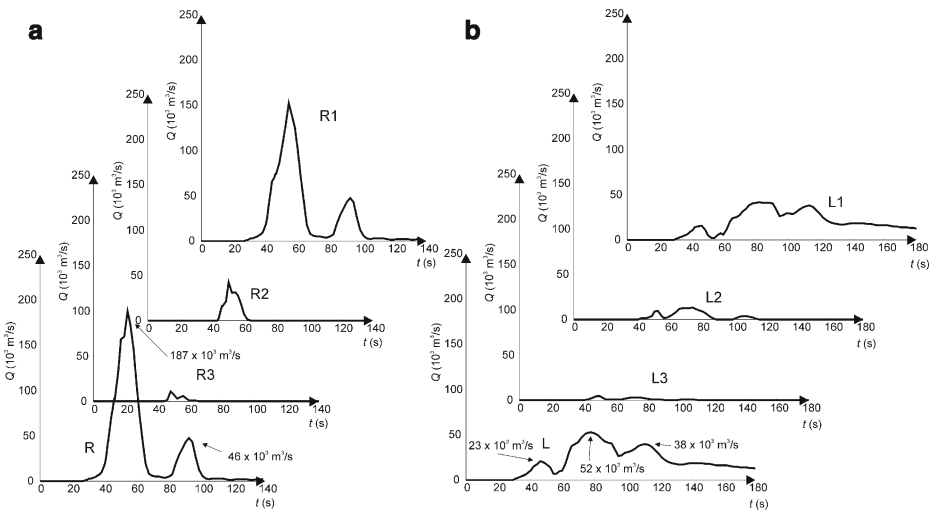
Fig. 4 a Flow hydrograph over right hand side slope (R) with its main contributions: R1, R2 and R3 together supply 99.68 % of its whole water volume. b Flow hydrograph over left hand side slope (L) with its contributions: L1, L2 and L3

hydrograph form; moreover, the total water volume which flowed through sections DN, DC and DS is also similar (3.47, 2.86 and 4.49 million m³).
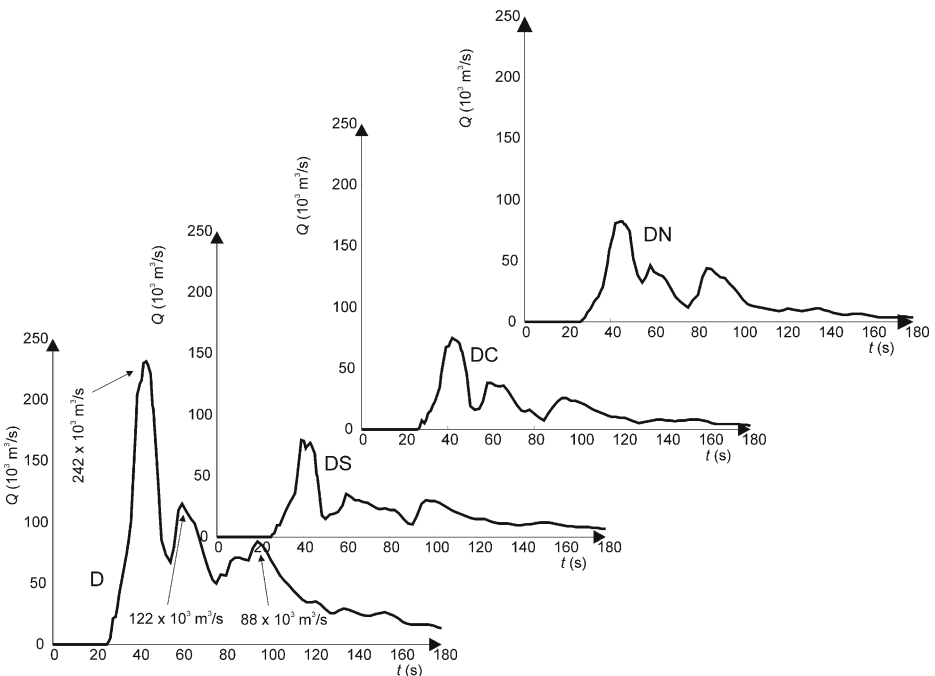

Fig. 5 Flow hydrograph over the dam (D) with its contributions: DN, DC and DS

Analyzing Figs. 4 and 5, it can be deduced that, both in terms of duration and intensity, the entire contribution of water coming from the right, the left, and the top of the dam, formed the wave that flooded the Piave Valley. For example, it can be roughly estimated that between 30 and 60 s, about 3.5 million cubic meters of water jumped over the dam, while about 3 million came from the right hand side and a much smaller amount from the left hand side. These results show that the intensity of the first pulse wave that arrived in the Piave Valley was half made up of the water that jumped over the dam and the other half of the water that passed the dam on the right side. Also, based on these results, only the water that passed the dam on the left side can be considered a phenomenon of inundation.

Integration of the hydrographs gives the total water volume that flowed out of the basin, estimated at 19.54 million m^3, which is the sum of the contribution of right-, dam- and left-sections (3.61, 10.82 and 5.11 million m^3).

All these hydrographs and the time series of the mean water depth over each section, as well as enriching our knowledge on Vajont, are applied as boundary conditions to the study of the Piave Valley as will be discussed later on.

4 Evolution of the Wave in the Piave Valley

The area which concerns this study begins at the crest of the Vajont dam, follows the canyon and reaches the Piave Valley near the town of Longarone; from this point it extends to the north up to Ospitale di Cadore and to the south it extends to just after Belluno on the western side and to the Santa Croce Lake on the eastern side, making up a surface of about 32 km^2 (Fig. 6). Longarone is located at about 460 m on the right hand side slope of the Piave river; behind the village there is a steep slope (about 60–70 %), which the run-up wave climbed. In this area the Piave riverbed is about 300 m wide, it has a height of about 430 m and it reaches a slope of about 0.5 %.

The mesh was developed by using the Italian numerical cartography at the scale 1:10000 and has almost 54000 quadrangular irregular elements, with cell surfaces ranging between 5 and 3100 m^2, where the larger ones are located along the Piave riverbed in areas that are not involved in the flow and the smaller ones are on the downstream face of the dam.

The bottom height was assigned by means of numerical cartography at the scale 1:5000; nevertheless, the canyon and the steep slopes where the water came into the domain were made more regular to assure the inflow boundary conditions work in a proper manner. The numerical model being a 2DH model, the inflow is introduced through a prismatic channel. Therefore the numerical model cannot describe local phenomena such as jets in the air and aerated flows. Nevertheless, as everybody knows results close to the boundary conditions cannot be considered as very significant.

The Manning coefficient was assigned to homogeneous roughness classes deduced from cartography, aerial photographs and some historical pictures. The classes into which the territory was subdivided and the assigned Manning coefficients are shown in Fig. 7 and Table 1. In literature the presence of urban areas in flood plains is treated in different ways. The most rigorous approach represents all details of the street network, with vertical walls to simulate the presence of buildings. The drawback of this method is the requirement for a very detailed mesh. So, simplified approaches have been developed, such as equivalent porosity models, with the introduction of a porosity coefficient to account for the reduction of the area available for water storage due to the presence of impermeable buildings or models representing urban areas as an area with higher roughness (Costanzo and Macchione
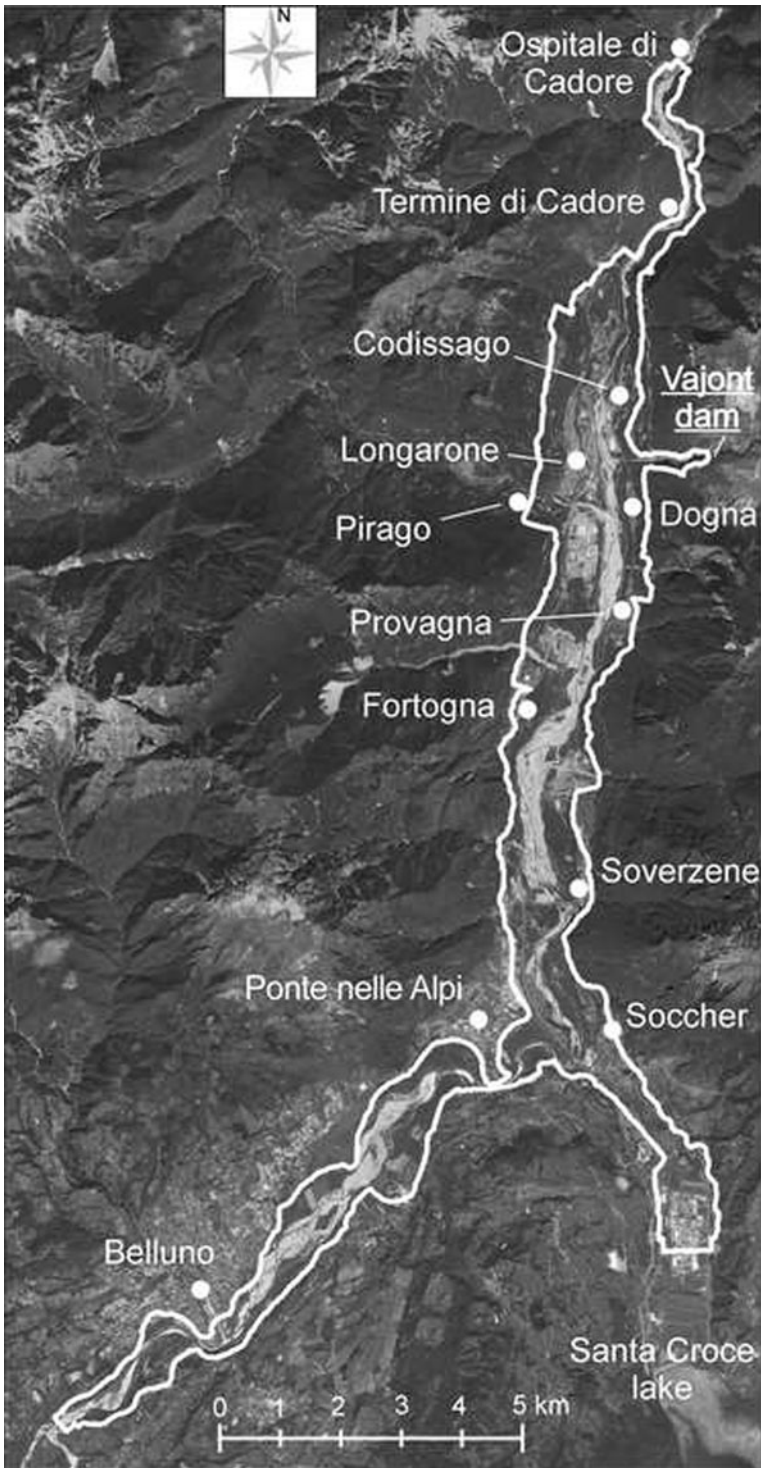
Fig. 6 Area covered by the study and mesh boundary

2006; Soares-Frazão et al. 2008; Petaccia et al. 2010). In the general case of flooding in an urban area, the presence of the road network could bring non-negligible local effects. Nevertheless, most of the buildings involved in the present simulation, i.e. the urban fabric of Longarone, were completely destroyed by the wave, that, as will be shown later on, reached values of the hydrodynamic force compatible with a sudden full devastation of the area. So, in this paper, the flow resistance due to buildings is considered as if they were an area with homogeneous high roughness and the effects of the flow movement through buildings have been neglected. Moreover, the Manning coefficient being constant through the whole simulation, as a first approximation a not-too-high value has been assigned (i.e. high density vegetation), considering that, the Longarone area turned into a pile of rubble in a relatively short time.

The boundary conditions applied to the model were: an inflow boundary condition at Ospitale di Cadore in the north; outflow boundary conditions at the two southern ends of the domain near Belluno and the Santa Croce Lake; wall boundary conditions along all other boundaries. The only exceptions are represented by the sections surrounding the eastern extremity of the canyon that forms the conjunction between the Piave Valley and the Vajont Valley domains (R1 to R7, DN, DC and DS and L1 to L5 as shown in Fig. 3). Here, hydrographs and water depth were imposed as they were deduced from the simulation performed in the Vajont basin. Moreover, the inflow at Ospitale di Cadore was negligible compared to the water entering the mesh through the canyon and for this reason the inflow at the northern end of the mesh was set to zero.

The initial conditions were those of a dry bed, i.e. any pre-existing tiny flow in the Piave river was neglected.

4.1 Numerical Results Compared with Literature Data

Hereafter the numerical results of the simulation in the Piave Valley are presented, starting from the canyon and Longarone and then proceeding first towards the north and then to the south. All mentioned villages are displayed in Fig. 6. The simulation begins when the landslide in the Vajont basin set in motion. So, until the wave reached the dam and the canyon slopes, the hydrographs were zero as shown in Figs. 4 and 5. The overtopping of the dam took place at about 24 s from the beginning of the simulation, i.e. the wave entered the canyon at this time.

The front of the wave reached the mouth of the canyon at about 55 s (Fig. 8a); thus the mean velocity of the wave in the canyon is estimated to be about 45 m/s, about 1400 m being the length of the canyon, from the dam to the mouth. In literature there is no firm evaluation of the time needed to cover this path, with values ranging from 60 s to 4 min (Reberschak 2003). The maximum water depth of the simulation (63–67 m) was registered at the mouth of the canyon first at 1′20″ and then again at 1′50″ with flow velocities ranging between 40 and 50 m/s. Moving to the west to the river bed of the Piave river, the water depth decreased to 20–30 m but there were higher velocities (up to 65 m/s at 1′). These values agree with direct evidence that talks of a water depth of about 70 m at the end of the canyon (Reberschak 2003).

At about 1′10″ the wave collided with the lowest hamlet of Longarone, located in front of the mouth of the canyon (Fig. 8b). Here, maximum water velocity in the town of Longarone was reached twice, first at about 1′25″ and then at 2′05″ with a velocity of about 40–45 m/s and water depth of 5–10 m. The centre of Longarone was flooded at about 1′10″; at about 1′25″ the maximum run-up was reached at the height of 550 m in the western most side of the town (Fig. 8c). Direct evidence talks of a run-up height of about 80–100 m compared to the Piave
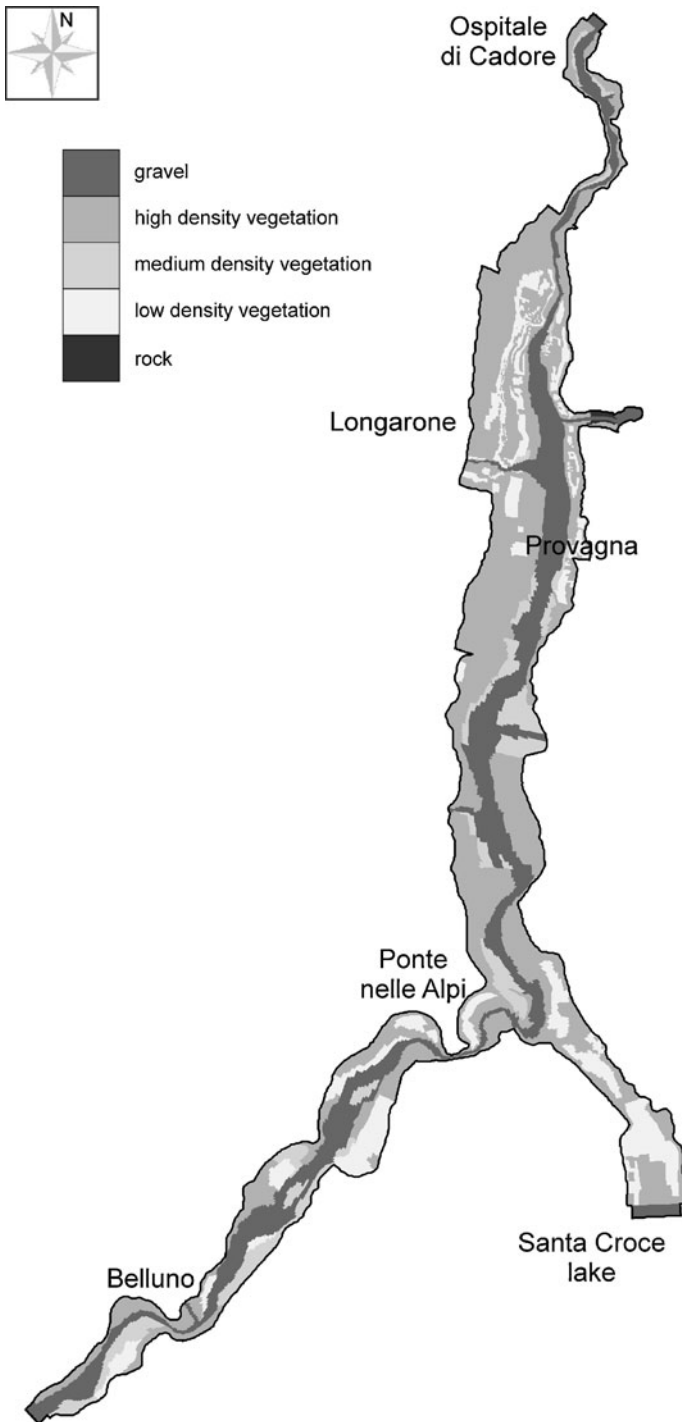
Fig. 7 Surface roughness homogeneous areas. As rock areas are limited in the canyon between the dam and Longarone, they are not very visible on the map

Table 1 Range of the Manning roughness coefficient representative of various bottom materials

Manning coefficient	Gravel	High density vegetation	Medium density vegetation	Low density vegetation	Rock
n (s/m$^{1/3}$)	0.024	0.045	0.030	0.025	0.020

riverbed, as can be deduced from Fig. 9, where Longarone is depicted before and after the event and where the lowest part of the Murazzi terraces is recognizable as the maximum run-up limit.

The consequent rundown wave between 1′25″ and 1′50″ brought a water depth of about 30–40 m into the town with velocities of 4–8 m/s. This water depth remained in the town for quite a long period as visible in Fig. 8d and e because the rundown wave collided with the direct wave coming
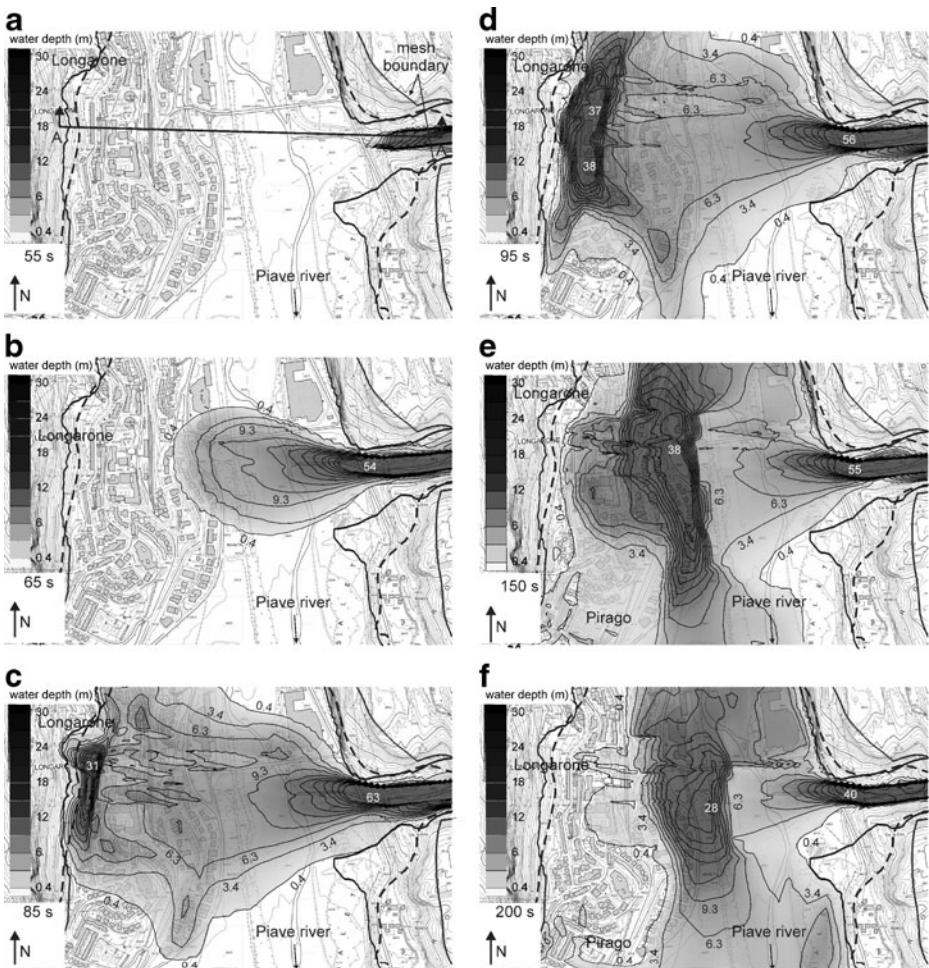

Fig. 8 Wave evolution at the mouth of the canyon in front of Longarone (contour of water depth in meters, in white the maximum water depth). The dashed line represents the observed water mark (Carloni and Mazzanti 1964), the continuous line is the numerical water mark. In **a** the cross section represented in Fig. 12 is depicted as A-A
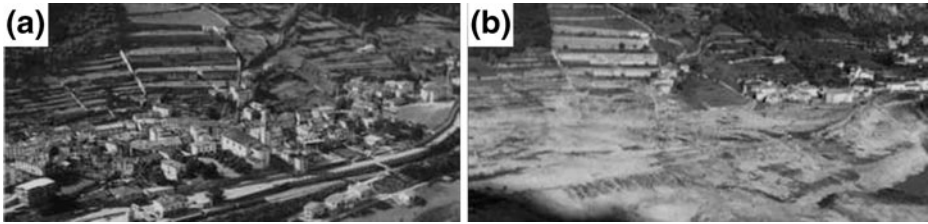
Fig. 9 Longarone before (**a**) and after (**b**) the wave. In the upper part of the pictures the Murazzi terraces are visible as the maximum run-up limit (Comune di Erto e Casso 2002)

from the canyon causing repeated run-up waves of lower intensity. The wave only definitively left the town of Longarone and flowed back in the Piave bed after about 3′20″ (Fig. 8f).

A share of the rundown wave moved towards the south, completely covering the village of Pirago (Figs. 8e–f and 10).

A portion of the wave coming from the dam went up the Piave river towards the north, causing major damage to the village of Codissago, located on the left riverbank, with the total destruction of some buildings and minor damage to the villages on the right riverbanks in a higher position over the river bed. The northern most point touched by the wave is not well defined in literature: some witnesses reported that the wave did not reached the village of Termine di Cadore (located about 5 km upstream from Longarone) and that it stopped at about 600 m from it (Longarone 2008); nevertheless, reports from the local Fire Department talk of finding corpses all along the Piave river from Longarone to Termine di Cadore. In the numerical simulation, the northern most section reached by the wave was located about 510 m north of Termine di Cadore along the river.

Moving from Longarone towards the south, the simulated wave spread all over river bed and holms, reaching the main "Alemagna" road on the right riverbank, but was contained by the steep slope on the opposite side of the river. All the villages on the left riverbank are located higher than river bed and so they were not quite touched by the wave (Dogna, Provagna, Soverzene, Soccher, etc.) and this is in agreement with literature (Longarone 2008).

Fig. 10 Pirago's bell tower: the only building left standing in the village after the transit of the wave (Zanfron 2006)
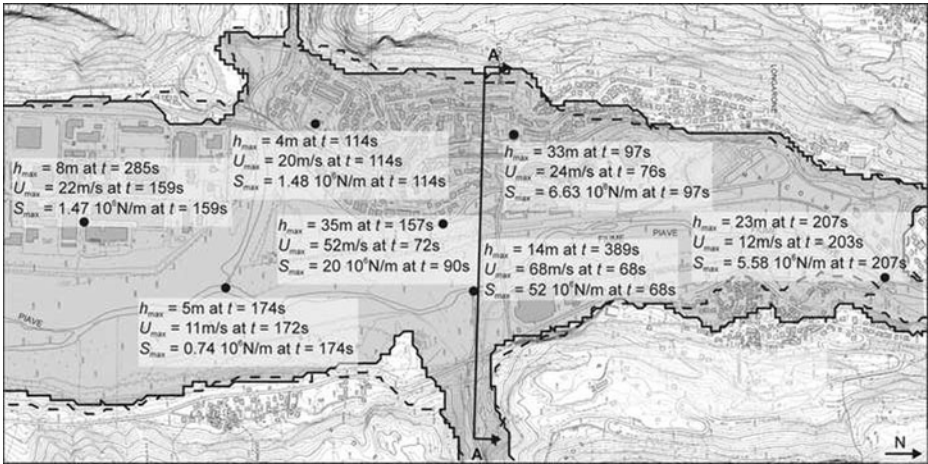
Fig. 11 Flooded area of the Piave Valley around Longarone. The dashed line represents the observed water mark (Carloni and Mazzanti 1964); the cross section represented in Fig. 12 is depicted as A-A. Maximum values of water depth, velocity and hydrodynamic force per unit length reached in the simulation are shown in some reference points

In Fig. 11 the flooded area of the Piave Valley around Longarone is depicted, together with the observed water marks (Carloni and Mazzanti 1964) and maximum values of water depth, velocity and hydrodynamic force per unit length reached in the simulation in some reference points. The numerical flooded area is almost in agreement with that the one observed, with only some local discrepancies, like the one on the left hand side of the mouth of the canyon. The hydrodynamic force reaches values of about 10^6 N/m in all the depicted area, with peaks of about 20–50 10^6 N/m at the mouth of the canyon. These values fully justify the almost complete destruction of buildings involved in the event. Moreover, in Fig. 12 the bottom height and water level on a cross section of the Piave Valley between Longarone and the mouth of the canyon (section A-A in Figs. 8 and 11) are depicted at different time steps, showing the impressive run-up reached in Longarone with respect to the Piave riverbed.

Just downstream of Soverzene there is a hydroelectric power station and a traverse. The simulated wave reached this area about 17′ after the beginning of the slide motion, i.e. it
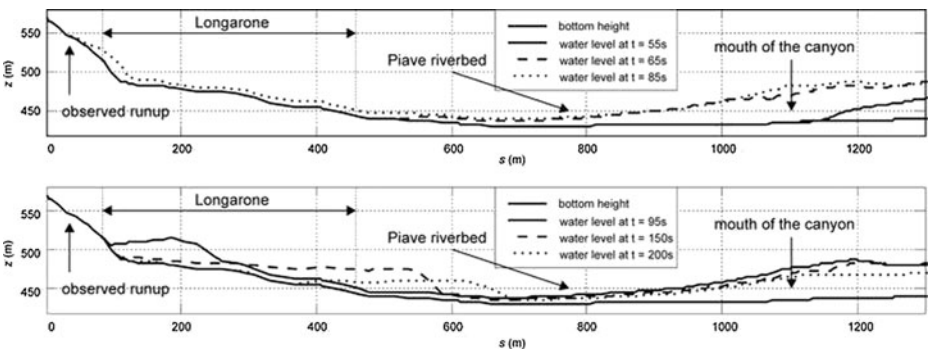

Fig. 12 Cross section of the Piave Valley between Longarone and the mouth of the canyon (section A-A in Figs.8 and 11). Bottom height and water level at different time steps are depicted
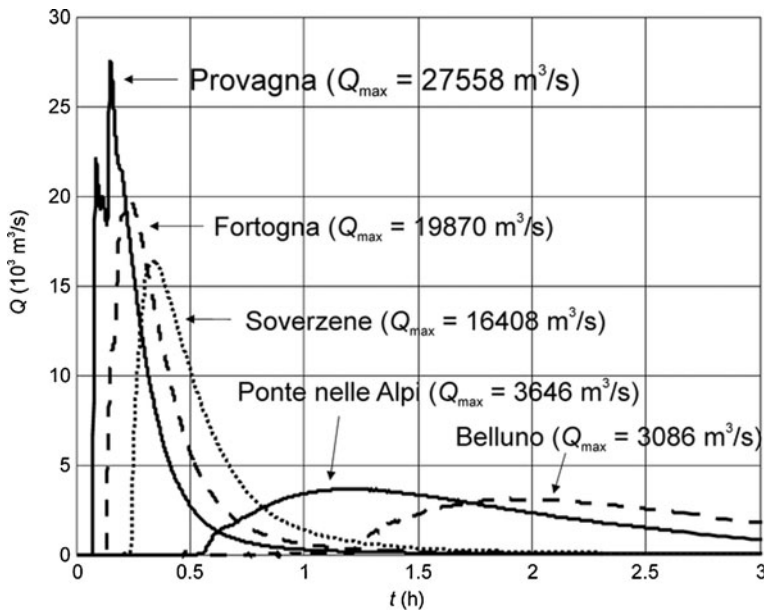
Fig. 13 Discharge hydrograph in some cross sections downstream Piave Valley

covered the path from the canyon mouth to Soverzene (about 7.5 km) with a mean velocity of 8 m/s. In literature, it is reported that this distance was covered in 21 mins, at the mean velocity of 6 m/s (Reberschak 2003).

Moving to the south, the Piave river approaches Belluno which was reached by the wave after 1 h15′ and where the maximum values for water depth and flow (10 m and 3180 m³/s respectively) were observed between about 1 h50′–2 h05′. Water depth and flow indicated in literature are 12 m and 4000–5000 m³/s in Belluno (Reberschak 2003).

The discharge hydrograph in some cross sections along the Piave Valley is depicted in Fig. 13. A consistent peak attenuation is immediately observed, having a maximum flow of about 27×10^3 m³/s in Provagna, 20×10^3 m³/s in Fortogna, 16×10^3 m³/s in Soverzene, located respectively at about 2.5, 4.5 and 7.5 km south of Longarone. Moving downstream the diffusion of the flood wave continues, with a peak of about 3.5×10^3 m³/s in Ponte nelle Alpi and 3×10^3 m³/s in Belluno, located respectively at about 11 and 18 km downstream of Longarone. Moreover, the form of the hydrograph becomes more regular moving downstream, i.e. the hydrograph in Provagna still shows some oscillations due to the combination of different waves, but already in Fortogna this phenomenon vanishes.

Mass balance was globally conserved during the propagation of the wave along the Piave Valley, with errors of about 1–2 %.

5 Conclusions

A 2DH finite volume numerical model was applied in order to study the wave that overtopped the Vajont dam and spread out in the Piave Valley as one effect of the huge landslide of about 270 million m³, that fell into the Vajont artificial reservoir on October 9th 1963.

In a previous paper (Bosa and Petti 2011), the authors described the consequences of the slide in the Vajont basin, recognizing the formation of different waves. The direct wave moved to the slope opposite to Mount Toc, where it showed an impressive run-up of about 270 m. The following rundown spread all over the slope: to the east part of the basin, against the slide and to the west, flowing out of the basin over the dam and surrounding slopes of the narrow canyon that connects the dam to the Piave Valley.

In this paper, the evolution of the wave generated by the landslide inside the artificial reservoir is briefly recalled. The hydrographs of the flows that left the Vajont basin are analyzed in detail in all their contributions, as they represent the inflow boundary condition for the study of the evolution of the wave that inundated and partially destroyed the Piave Valley. Moreover, a numerical finite volume model of the valley from Ospitale di Cadore to Belluno and the Santa Croce lake was developed to study the effect of the wave over a significant area. The results have been analyzed in depth and compared to data available in literature. These consist mainly of historical pictures before and after the event, where damages due to the wave are clearly visible and that allow an initial estimate of the run-up limit of the wave over the slopes and in the villages surrounding the riverbed. Moreover, a number of witness statements are available, mainly concerning the run-up limit and propagation times of the wave.

The present model being a fixed bed model, it cannot take into account the movement and deposition of debris carried by the flow, which could influence the results, at least locally. Nevertheless, the comparison of numerical results with direct evidence shows that the wave is described in a proper manner, where both the wave speed and run-up limit are almost in accordance with the observed effects of the real event.

Considering the complexity of the phenomenon, the results obtained show that a 2DH model can also describe the overtopping of a wave quite well and in this way this kind of application appears to be complementary to other case studies in literature.

Despite the limitations of classical two-dimensional modeling (Liggett 1994), the most important of which is the assumption of hydrostatic pressure distribution, this kind of model seems to be suitable for the study of the evolution of an impulsive wave like the one generated by a huge landslide, as in the Vajont case. This is an important result, because, even if the phenomenon to be studied is 3D, it encourages the use of 2DH models which can be more easily applied to large natural domains compared to 3D models.

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