Computational Geosciences (2006) 10:201–219
DOI: 10.1007/s10596-005-9019-x

Some considerations about the simulation of breach channel erosion on landslide dams

Corrado Cencetti, Andrea Fredduzzi, Ivan Marchesini,
Mara Naccini and Paolo Tacconi

Department of Civil and Environmental Engineering, University of Perugia, Perugia, Italy
E-mail: fredduzzi@unipg.it

Received 31 August 2004; accepted 4 August 2005

The analysis of the flood hazard related to the areas downstream of landslide dams is one of the most interesting aspects of studying the formation and the failure of natural dams. The BREACH code [14], simulating the collapse of earthen dams, both man-made and naturally formed by a landslide, was chosen in order to analyse the case of the Valderchia landslide (central Italy). The bed-load transport formula used in BREACH (Meyer-Peter and Muller, modified by Smart [27]) is based on flume experiments with well-sorted sediments. Such a methodology probably makes this equation not very suitable for describing the sediment transport peculiar to a landslide body presenting a very poor material sorting. The Schoklitsch [26] formula was implemented into the programme as an alternative to the Smart equation. However, because the landslide deposits may often have a strongly bimodal grain–size frequency curve, the percentile D_{50} (the typical granulometric parameter requested by bed-load sediment transport formulas) can sometimes correspond to one of the grain-size classes which are really present to a lesser degree. To consider this phenomenon, the BREACH programme (version 7/88-1) was implemented with a new procedure that calculates two granulometric curves, one for each mode of the original distribution, and evaluates transport of the landslide material separately. Results of the analysis show that the model is very sensitive to the bed-load equation and that the procedure implemented to consider the eventual bimodal distribution of the dam material simulates the armouring phenomenon (which can stop the erosion of the dam during the overtopping phase).

Keywords: landslide dams, dam breach, breach shape, sediment sorting, bed-load transport, sensitivity analysis

1. Introduction

The interference of landslides with river channels can generate many scenarios [7], from the partial blockage of the river, to the entire occlusion of the floodplain and the consequent flooding of the upstream lands (figure 1).

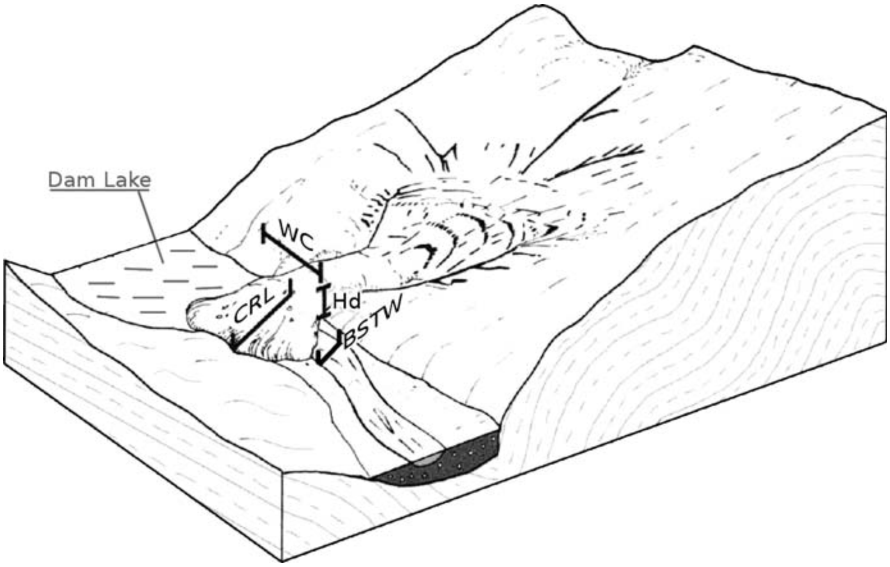

Figure 1. Geometric characteristics of a landslide dam: Hd = elevation of the top of the dam, CRL = length of crest dam, WC = width of crest dam, BSTW = top width of tailwater cross section. Abbreviations are based on Fread [14]; figure by Cencetti et al. [7], modified.

Analysis of the flood hazard related to the downstream areas of the blockage and generated by a possible failure of the landslide body is one of the most interesting aspects in the study of landslide dams. Several authors have studied the landslide dam phenomena, mainly by analysing case studies, classifying natural weirs [7,10,29] and simulating the dam-break (usually by overtopping).

The methods used for simulation include [1]:

- *Physically based methods* [14], which compute a breach size and shape using principles of hydraulics, sediment transport, soil mechanics, and material properties of the dam;
- *Parametric models* [13], which use observations of previous dam failure to estimate the size, shape, and time of breach formation; the final breach dimension is assumed and its size is developed by time-dependent linear geometric increments, and the discharge is computed at each increment using hydraulic principles;
- *Predictor models* [21], using the equation:

$$Q_{b\max} = CX^m \tag{1}$$

where $Q_{b\max}$ is the peak breach discharge, C and m are constants determined from historical data, the parameter X is usually dam height, reservoir volume, or the product of the two.

- *Comparison methods* [28] are used to estimate the breach characteristics and peak outflow of dam when the latter is very similar in size, construction and materials to a failed dam with known data.

The landslide dam failure is still frequently studied as an earthen dam failure, because the mechanism of breach formation is considered very similar, despite of different geometry, dimensions and material properties. To study the effects of the heterogeneity of the landslide material on the erosion of the breach, the BREACH code, one of the most widely used computer models, was applied to a real landslide dam: the landslide of Valderchia in central Italy [6]. The landslide dam is located just upstream of the town of Gubbio and the ensuing overtopping flood could have been dangerous. It must be noted that the landslide blockage (which occurred in 1997) did not lead to overtopping and flooding due to rapid technical mitigation (the pumping of the dam lake and the construction of a by-pass) carried out by local authorities. Moreover, we want to stress that we chose the Valderchia landslide because it was a landslide dam about which we had enough data and because it enabled us to apply the BREACH code to simulate a real case and not an artificial one. In particular, we decided to test some bed-load formulas, which can be used in the model. The objective was to determine which one best describes the sediment transport of poorly sorted materials (as landslide materials can be; for instance, when movement has started from lithologically heterogeneous slopes). Finally, a methodology was implemented in the BREACH code to consider the bimodal grain-size distribution of materials in the analysis of the erosion of a landslide dam by overtopping.

2. The BREACH code

The BREACH code is a mathematical model, used to simulate the collapse of earthen dams, either man-made or naturally formed by a landslide, developed by Fread [14] at the US National Weather Service. The model predicts some characteristics of the breach (such as size, shape, time of formation and outflow hydrograph emanating from the reservoir) by using the principles of hydraulics, sediment transport formulas, the theory of soil mechanics, as well as the geometry and the material properties of the dam and of the reservoir. The code assumes that the size of the breach developing along the crest of the landslide dam is governed by the capacity of the flowing water (which erodes and scours the bed of the breach channel) to transport the eroded materials.

The dam-break may occur by overtopping, by piping, or by sudden structural collapse due to hydrostatic pressure. The BREACH code uses:

- the equation of the broad-crested weir [12]:

$$Q_b = 0.385 * \sqrt{2g} B_0 (H - H_c)^{1.5} \tag{2}$$

where Q_b (m^3/s) is the flow into the breach channel, g (m/s^2) is the gravitational constant, B_0 (m) is the instantaneous width of the initially rectangular-shaped channel, H_c (m) is the elevation of the breach bottom and H (m) is the water level in the reservoir, to simulate the outflow in the breach channel;

- the Smart [27] equation to calculate the sediment transport capacity for flow;
- the Manning equation of the uniform flow, to define the water depth;
- the mass conservation equation between inflow and outflow (from the breach, the crest, the spillway).

The flow is considered uniform because it varies little along the breach channel – both in artificial dams with a reduced channel length and a high bed slope, and in landslide dams with a bigger channel length but a lesser slope. Moreover, a stability analysis of the channel banks is made at each time step, and when the stability is not verified the slump of the banks is simulated. Each slump increases the size and changes the shape of the breach (from an initial rectangular shape to a trapezoidal one; figure 2). The programme simulates the erosion of the breach bottom, until the depth of the breach reaches a critical height (H_k)

$$H_k = \frac{4c * \cos\phi * \sin\theta_{k-1}}{\gamma[1 - \cos(\theta_{k-1} - \phi)]} \tag{3}$$

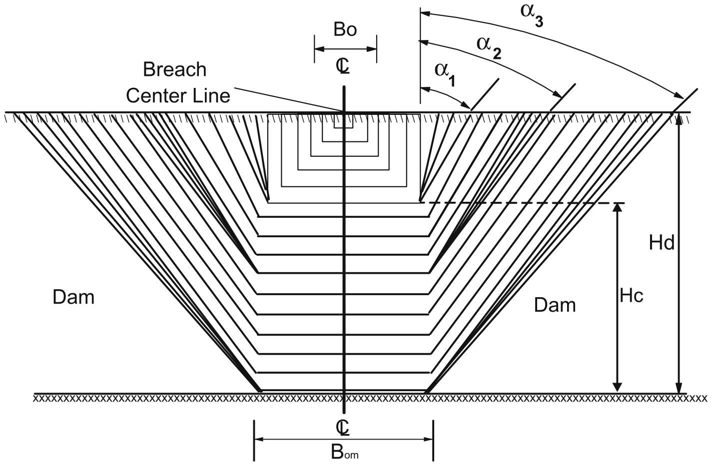

Figure 2. Cross_section view of a dam with breach formation sequence. $\alpha_k = \pi/2 - \theta$; θ = side slopes angle; B_0 = width of the breach; $B_{0\mathrm{m}}$ = final width of the breach bottom; H_d = elevation of the dam; H_c = elevation of the breach bottom; by Fread [14], modified.

(where c is cohesion, γ is the unit weight, ϕ is internal friction, θ is the side slopes angle) over which the banks of the channel slump, leading to a stable configuration of the slopes with angle (θ_k), defined by:

$$\theta_k = 0.5\pi - \alpha_k = \frac{\theta_{k-1} + \phi}{2} \tag{4}$$

(where $\alpha = \pi/2 - \phi$).

The width of the breach (B_0) is assumed to be initially defined by the next equation:

$$B_0 = 2y \tag{5}$$

where y represents the uniform depth of the flow inside the channel and is derived from the Manning open channel flow equation and B_0 is the width of the breach. The erosion takes place equally along the bottom and the sides of the breach channel, except when the sides collapse as described before. The erosion depth is evaluated iteratively, assuming an estimated erosion depth (ΔH) and solving for bed-load [27], flow (Manning) and breach dimension equations as above.

3. Bed-load equations

The breach dimensions during overtopping are related to the flow transport capacity and it is, therefore, important to carefully choose an appropriate bed-load equation to use in the simulation. Quantifying bed-load transport remains a considerable challenge, although there are several proposed theoretical and empirical equations to address this problem [3,11,15,22]. None of these is universally valid and each one would have to be used only under the conditions for which it was derived. In fact, a large part of the bed-load equations was developed for sand-bed rivers (where grain-size distribution is quite uniform). The definition of the values for the initiation of sediment motion is a difficult task for gravel-bed rivers (low sorting), and therefore also for the bed of a breach developing through the coarse material of a dam crest. The bed-load transport formula used in BREACH is the Smart [27] equation. This equation, however, presents a problem: it is based on flume experiments where the grain-size distribution ratio (D_{90}/D_{30}) was less than 10, which is really a low value. Such a methodology makes this equation not very suitable for describing the material transport over a breached and poorly sorted landslide deposit. Moreover, to evaluate the critical flow conditions (entrainment thresholds), the Smart [27] equation considers the Shields stress, which involves the calculation of the water depth along the breach. Often, however, it is difficult to measure or to evaluate the water depth under turbulent flow conditions. Under these conditions, the discharge per unit width can be used as a critical parameter. Therefore, we considered that the BREACH code can be enhanced by implementing the Schoklitsch [26] equation, which does indeed consider the discharge per unit width as a critical parameter:

$$m_s = 2,500 S^{3/2}(q - q_c) \tag{6}$$

$$q_c = 0.26\left(\frac{\rho_s}{\rho} - 1\right)^{5/3} d_{40}^{3/2} S^{-7/6} \tag{7}$$

where m_s is the transport rate per unit width (kg/s), S is the channel slope, q is the volumetric water discharge per unit width (m^3/s), q_c is the critical volumetric water discharge per unit width (m^3/s), ρ_s is specific mass of sediments (kg/m^3), ρ is the specific mass of water (kg/m^3), d_{40} is the diameter for which 40% of sediments are finer (m).

Moreover, this equation, as shown by Bathurst et al. [3], furnishes the best results under conditions of unlimited supply and for mountain rivers (coarse grain-size and steep slopes). We could assume that the breach channel developing on a landslide dam is very steep and is supplied with a large amount of material. Therefore we believe that bed-load transport rate can be adequately simulated using the Schoklitsch formula.

4. The landslide of Valderchia

The Valderchia landslide affected a portion of the mountain slope on the left bank of the St. Donato Creek (Tiber basin), close to the town of Gubbio (central Italy). It blocked the water course and formed a natural dam 9 m high, impounding a little lake upstream (42 m wide, 90 m long and 2 m deep). The type of the landslide is complex (rotational slide in the upper part and flow in the lower part, IGS [18]). The geological formations affected by the mass movement are:

- the “Marnoso–Arenacea” formation, composed of turbidites (alternation of grey marls over 1 m thick and grey-brown sandstones with decimetre-thick strata);
- the “Schlier” formation, composed of clayey marls and grey clays;
- colluvial sediments (main bodies of old landslides in figure 3), covering a wide part of the slopes

The landslide moved during the night between the 5th and 6th of January 1997 from an elevation of approximately 700 m a.s.l., and quickly arrived at the bottom of the valley (approximately 600 m a.s.l.); here, the landslide front damaged two houses and stopped against the bridge of the old abandoned national road (figure 3).

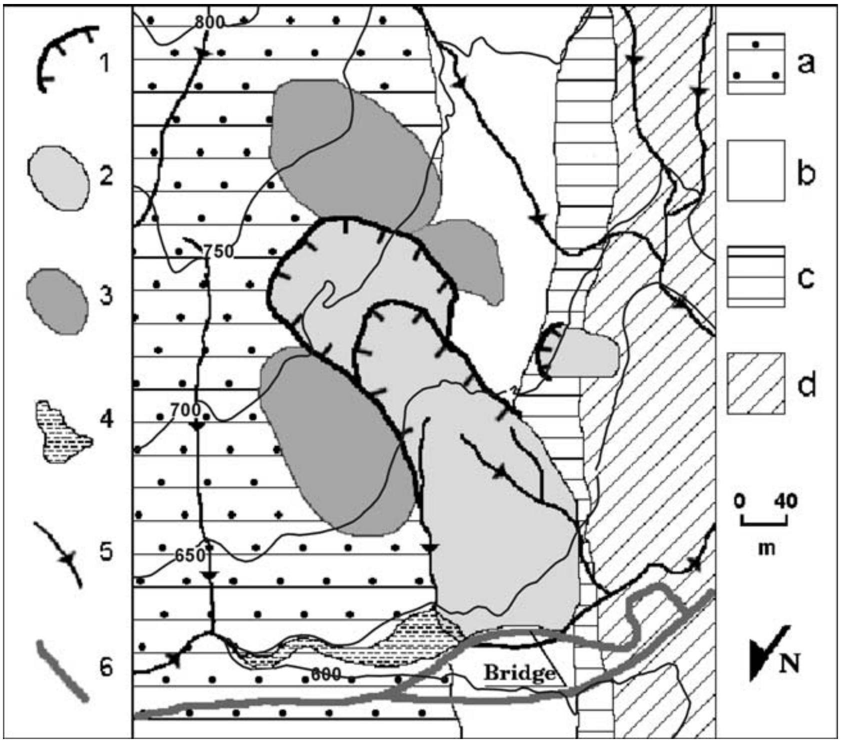

Figure 3. Geomorphological and lithological sketch of the landslide area. (1) Main scarp of present landslide, (2) main body of present landslide, (3) main body of old landslides, (4) dam lake, (5) stream, (6) main road; (a) "Marnoso–Arenacea" formation, (b) "Schlier" formation, (c) "Bisciaro" formation, (d) "Scaglia Cinerea" formation; after Cencetti et al. (1998), modified.

Table 1
Average values of the friction angle, cohesion, unit weight, porosity, plasticity index and the grain-size percentiles obtained from the analysis of the Valderchia landslide material samples.

Φ_r [°]	c [MPa]	γ [kN/m^3]	n	PI [%]	D_{90} [mm]	D_{50} [mm]	D_{30} [mm]
24.2	0.016	20.57	0.35	22.2	43.71	0.036	0.006

5. Characterisation of the landslide materials

The landslide body granulometry is poorly sorted, and may also contain cobbles and boulders (longest diameter >1 m). A sampling survey (boreholes) of the Valderchia landslide body was carried out by the local authorities immediately after the event [24]. The resulting samples were studied via laboratory analysis. Table 1 shows the values of the investigated parameters (required as input for the model). The data represent the mean values of nine samples, collected from the landslide body by means of seven boreholes. The sampling depth varied between 0.4 and 16.5 m. The sampling position was chosen by the local authorities to enable boreholes to be used to install seven inclinometers.

However, the mean diameter, D_{50}, and the ratio D_{90}/D_{30} obtained from the sample analysis (table 1) cannot be considered representative of the real grain-size distribution of the landslide materials. This is because it is often impossible to determinate the proper grain-size composition of the landslide materials using standard methods of investigation (sampling via geognostic drillers) when the present clasts are larger than the geognostic instruments. This is particularly true for the Valderchia landslide since the slope consists of fractured sandstones, with two families of joints (NW–SE and NNE–SSW oriented) spaced at a distance of 50 cm (see figure 4).

Therefore it is possible to assume the presence within the landslide body of clasts with an intermediate diameter of approximately 40 cm (boulders). Casagli et al. [5] proposed to assess the real grain-size distribution of landslide material by using the typical methods of gravel-bed rivers. There are fundamentally three kinds of methods [9,19]:

- volumetric sampling (sieve by weight);
- grid or transect line sampling [20,32];
- the photographic method [5,8].

To rapidly characterise large outcrops of landslide material, it is probably necessary to use all the aforementioned methods. Grid, transect and photographic methods (that

Figure 4. Example of fractured sandstones constituting the slopes of the Valderchia landslide.

enable the coarse fraction to be sampled) can be integrated via traditional volumetric sampling, which enables the fine sediments constituting the matrix to be analysed [2]. Unfortunately, due to the technical mitigation of the landslide, it was not possible to sample the landslide materials using the aforementioned methods because the outcrops of deposits were completely obliterated. Thus we assumed different weight percentages of boulders hypothetically present in the landslide body (10% up to 80%) and estimated all the related geotechnical parameters (table 2). First, the average granulometric curve was reconstructed for each percentage of boulders, and the value of D_{30}, D_{50}, D_{90} and the ratio D_{30}/D_{90} was calculated. The specific mass for each percentage of boulders was calculated by the weighted average of the specific mass obtained from the classical sampling survey (made by the authorities) and the specific mass typical of rocks (i.e., 26 kN/m^3). Porosity was evaluated by applying an empirical diagram, based on the ratio D_{60}/D_{10} [17]. Porosity for large values of D_{60}/D_{10} is asymptotic to a value of 0.2. We have assumed this constant value for all percentages of boulders. To estimate the friction angle and the cohesion, we distinguished two hypothetical situations: the boulders are dispersed into a matrix of fine materials or, instead, constitute a rockfill. We adopted a simple approach in order to determine the percentage of boulders that leads to the formation of a rockfill: assuming that the maximum “void ratio” (e) for a packing arrangement of spherical particles is 0.92 [4], we calculated the void ratio of landslide materials corresponding to each percentage of boulders, as though the deposits consisted only of boulders. For boulder frequency below 60% ($e > 0.92$), we assumed that the behaviour of the landslide deposit is controlled by the matrix and we used the matrix geotechnical parameters (Φ_r, c), as obtained from the samples. For boulder frequency equal to, or greater than 60% ($e < 0.92$), we considered the deposits as a rockfill and we estimated the parameters as follows: $\Phi_r = 35°$, as the friction angle between two blocks of quartz [23]; the cohesion $c = 0$.

This enabled a sensitivity analysis of the model to be carried out according to both the weight frequencies of boulders and to all the geotechnical parameters.

Table 2
Geotechnical parameters of the Valderchia landslide material estimated considering the hypothetical presence of different weight percentages of boulders (10–80%).

% Boulders	10	20	30	40	45	50	60	70	80
D_{30} [mm]	0.012	0.019	0.025	0.037	0.040	0.05	1.22	75	274
D_{50} [mm]	0.045	0.056	1.03	24.46	46.9	256	280	297	310
D_{90} [mm]	256	328	352	364	368	371.2	376	379.4	382
D_{90}/D_{30}	21,333	17,263	14,080	9,838	9,200	7,424	308	5	1.35
γ [kN/m^3]	21.00	21.44	21.91	22.41	22.66	22.92	23.47	24.05	24.66
Φ_r [$\circ$]	24.2	24.2	24.2	24.2	24.2	24.2	35	35	35
c [MPa]	0.016	0.016	0.016	0.016	0.016	0.016	0	0	0

6. Incoming discharge

Discharge entering the dam lake is another important input parameter for the BREACH model. No hydraulic parameter was measured during the event along the St. Donato Creek (because it is a small river and there is no gauging station). Since the aim of this study is to evaluate the sensitivity of the model (Schoklitsch equation [26] and the percentage of boulders in the landslide body), we decided to perform the simulation using a discharge value obtained from the statistic analysis of the pluviometric data of the meteorological station of Gubbio. The data were taken since 1929 up to 1991 and, using the "kinematic method" [12] we were able to obtain discharge values with different return periods. We decided to use the 100-year discharge (14 m^3/s) to start the simulations.

7. Application of BREACH to the Valderchia landslide dam using different bed-load equations

With the aim of stressing the importance of choosing the correct bed-load equation, we applied both the base BREACH code model and the same model modified by the implementation of the Schoklitsch equation [26] to the Valderchia landslide dam. Implementing the Schoklitsch formula into the BREACH source code (FORTRAN) was a straightforward process. Only a few rows have to be inserted to enable the critical discharge to be evaluated (equation (7)) and the value obtained to be compared with the discharge passing through the breach, as calculated by the model. The difference between them is used to calculate m_s as in equation (6). As previously explained, the Valderchia landslide blocked the St. Donato River and finally came to a halt against the bridge of the old abandoned, national road (see figure 3). We considered that, in case of overtopping, the bridge would have worked as an artificial spillway, because the water would be passed in part over the landslide and in part over the bridge. We have defined the dimensions of the "bridge-spillway", its roughness coefficient, and so we were able to perform a discharge rating curve (spillway flow vs. head) for the bridge. Using this data, the BREACH code is able to simulate the presence of a spillway on a dam [14]. A sensitivity analysis was performed on the two models with respect to the variation in the grain-size composition of the landslide body (percentage of boulders). We applied the base BREACH model to the Valderchia landslide dam using both original geotechnical parameters and the modified parameters according to the assumed different percentages of boulders in the landslide body (see table 2). We assumed that the boulders were uniformly distributed inside the landslide material. The performed simulations show that the model predicts the breach formation for overtopping for 0–45% of boulder content (figure 5). In contrast, the presence of approximately 50% in weight of the boulders within the landslide body does not allow breach formation. This occurs because the calculated transport capacity

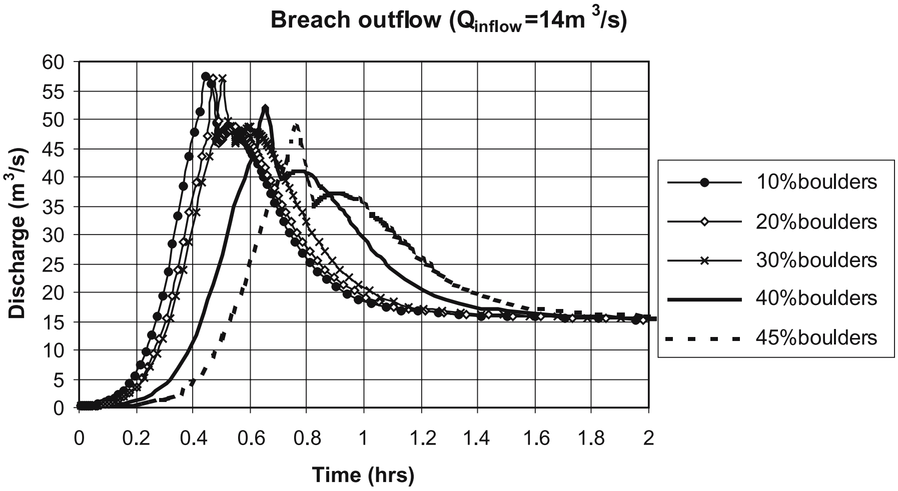

Figure 5. Valderchia landslide dam: predicted breach outflow using Smart formula.

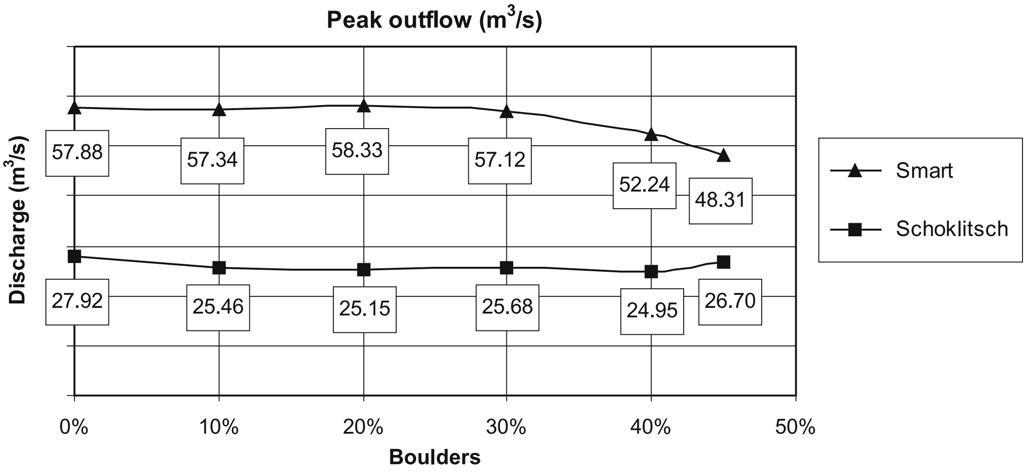

Figure 6. Valderchia landslide dam: comparison of the predicted peak outflow computed with the Smart and Schoklitsch formulas.

is not able to erode the landslide body, due to the fact that, with 50% of the boulders inside the dam, the value of the percentile D_{50} grows considerably. In effect, D_{50} is the only granulometric parameter used by the base model to calculate the breach erosion. Moreover, the model is not able to describe the preferential entrainment of the fine materials for a given boulder content. We verified that in order to obtain the breach formation with an assumed 50% of boulders content in the landslide, an unrealistic discharge, higher than 3,000 m^3/s, would be necessary.

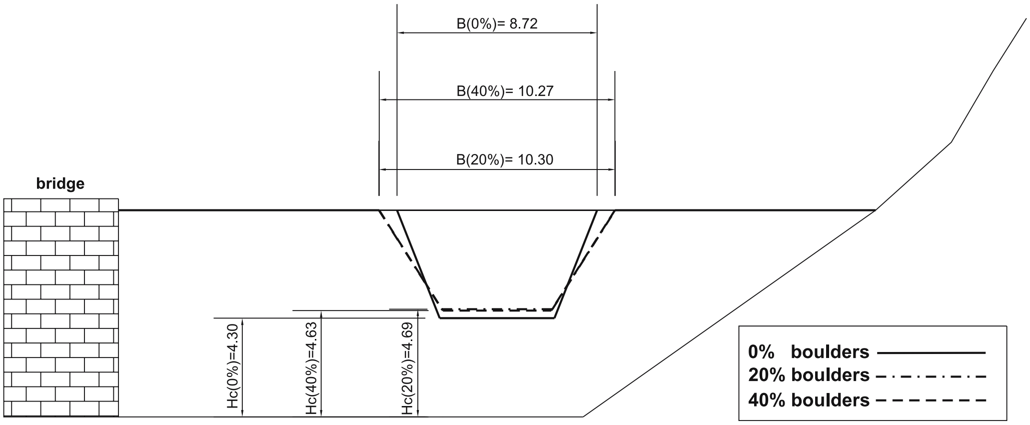

Figure 7. Schematic cross-section view of the breach in the Valderchia landslide dam, at the peak outflow computed with Smart formula (base model). $H_c(X\%)$ = elevation of the breach bottom with $X\%$ of boulders in the landslide body; $B(X\%)$ = width of the breach with $X\%$ of boulders in the landslide body.

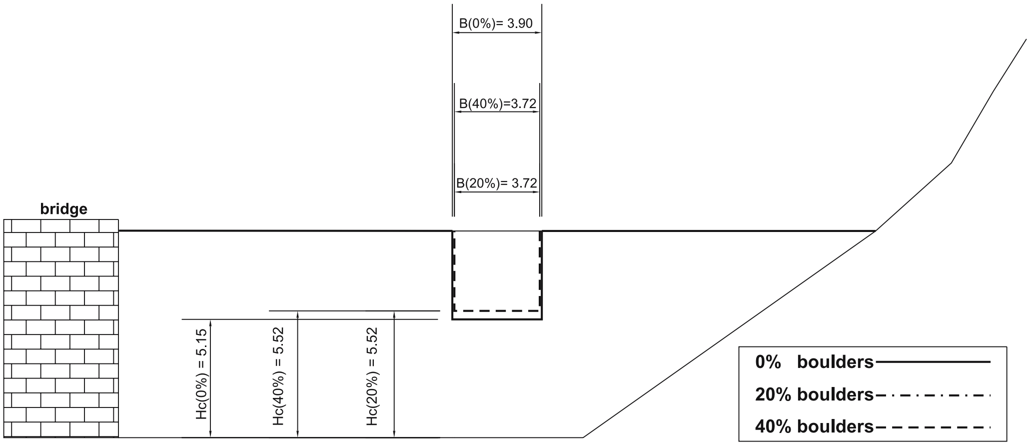

Figure 8. Schematic cross_section view of the breach in the Valderchia landslide dam, at the peak outflow computed with Schoklitsch formula. $H_c(X\%)$ = elevation of the breach bottom with $X\%$ of boulders in the landslide body; $B(X\%)$ = width of the breach with $X\%$ of boulders in the landslide body.

We observed (figure 5) a low sensitivity in the different percentages of boulders present inside the landslide body: values of peak discharge exiting from the breach (which varies from 50 to 60 m^3/s) and values of peak time (ranging within 20 min) have small variations. Moreover, results in the application of the base model show that the discharge passing through the breach is able to entrain the clasts when the median diameter is approximately 47 mm, but is unable to do so above 256 mm. This last observation was also verified for the implemented Schoklitsch model. The difference is that the peak discharges exiting from the breach are halved compared to the base model (figure 6).

Table 3
Lake inflow discharge, needed start the erosion, related to D_{50} of the landslide body (using Schoklitsch formula).

D_{50} [mm]	256	280	297	310
Reservoir inflow [m^3/s]	15.4	84.9	84.9	93.4

This is because the peak occurs before the banks of the breach catch up with the critical height (H_k in equation (3)) and slump. Therefore, at the peak moment, the cross-sectional area (figures 7 and 8) of the breach is much smaller than the one obtained using the base model (where the banks slump earlier).

Another important difference is that, with median diameters equal to or greater than 256 mm, the discharges (entering the dam lake) needed to prime the breach formation are considerably lower than those obtained with the base model (table 3). Indeed, considering $D_{50} = 256$ mm, for example, we observed that the dam lake inflow needed to start the erosion using the Schoklitsch formula, i.e., 15.4 m^3/s which, compared to 3,000 m^3/s, differs by 2 orders of magnitude.

8. Effects of material bimodality on the bed-load transport and description of its implementation on the BREACH code

The entrainment of particles under flow conditions depends on certain sediment characteristics, such as dimension, form and boundary roughness [16,25,30]. Since only the dimension is taken into consideration by the bed-load formulas, we will focus our attention on this parameter. The choice of the representative grain-size percentile to use in the bed-load sediment transport simulation is important, because D_{50} can sometimes correspond to one of the grain-size classes, which are less present in reality. This is the case with some multimodal distributions, such the materials consisting of the landslide body of Valderchia (see section 5). It is obvious that the sediment performance in reaction to the erosive force of the flow is different, according to whether the grain-size distribution curve is bimodal or unimodal. In the case of unimodal distribution, the critical shear stress for each size fraction is well represented by the shear stress required to entrain D_{50} particles. In accordance with the observations of Wilcock [31], in the case of strongly bimodal grain-size distributions, the finer fractions are set in motion by less shear stress as opposed to the coarse fractions. Moreover, values of critical shear stress for each fraction depend on how the material is distributed between the two modes. For instance, the same fine sediments (constituting a mode) can start motion at different values of shear stress, depending on the proportion of coarse sediments present in the second mode [31]. The preferential erosion of the fine sediments can have some important consequences in dam breach studies. Indeed, in the case of a breach formation along the top of a landslide dam, this behaviour can determine the armouring of the breach bed, with a resulting halt or delay in erosion. As described above, we assumed a bimodal distribution of Valderchia landslide material and also different percentages of boulders; the first mode represents the fine materials sampled during the geotechnical survey, while the second mode represents the hypothetical boulder fraction. To simulate the possible armouring of the breach bed, the BREACH programme was implemented with a new procedure that calculates for each time step two granulometric curves – one for each mode of the original distribution. The separation between the two curves is chosen to match the less frequent size class; percentiles and sorting parameters (D_{50}, D_{90}/D_{30}) are calculated for each curve. Thus it is possible not only to compute the sediment transport for each mode of the granulometric curve, but also to evaluate the eroded volume which will modify the grain-size distribution of the breach bed. Whilst distribution remains bimodal, the granulometric curves are again computed at each time step, using the weights of the remaining materials (not eroded); however, when one of the two modes is completely eroded so that the total granulometric distribution can be considered unimodal, the new D_{50} is estimated and simulation is resumed according to the original programme. It must be pointed out that the considered volume of material, over which the new granulometric curve is estimated in the implemented model, refers to the one located immediately below the breach bed.

9. Application of the BREACH model implemented with the bimodality code to the Valderchia landslide dam, and comparisons of results with the output of the original code

Some simulations were run with the modified BREACH code in order to evaluate the bimodality effects on the landslide erosion, determined by the varying percentage of boulders. The outflow hydrograph (figure 9) shows that the peak outflow varies from 21 to 23 m^3/s, for a percentage of boulders ranging from 10% to 20%. For a percentage of boulders varying from 30% to 50%, the peak outflow is subject to a marked decrease. For a percentage of boulders varying from 60% to 80% (rockfill domain), there is a small increase in the peak value and then another decrease. It is important to note that the peak time generally diminishes along with the percentage of boulders, because of the rapid armouring of the breach bed. For a percentage of boulders equal to or greater than 30%, the constant discharge flowing through the breach, after the peak, is lower than the dam lake inflow; the remaining flow is passing through the “spillway-bridge”. For percentages smaller than or equal to 20%, there is no “spillway-bridge flow” at the time of peak discharge.

The increase in percentage of boulders determines (at the time of peak discharge) a substantial decrease in the section area and a decrease in the breach depth. The incidence of boulder percentage is stressed if the section shape is analysed at the end of the simulated flood flow. In fact it was noted that:

- with a percentage of boulders of up to 20%, the breach assumes a large trapezoidal shape;

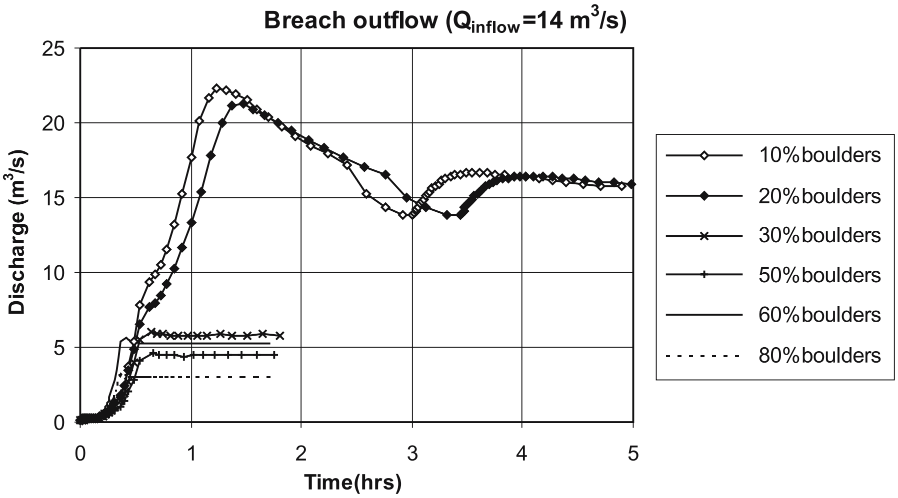

Figure 9. Valderchia landslide dam: predicted breach outflow using the bimodal model.

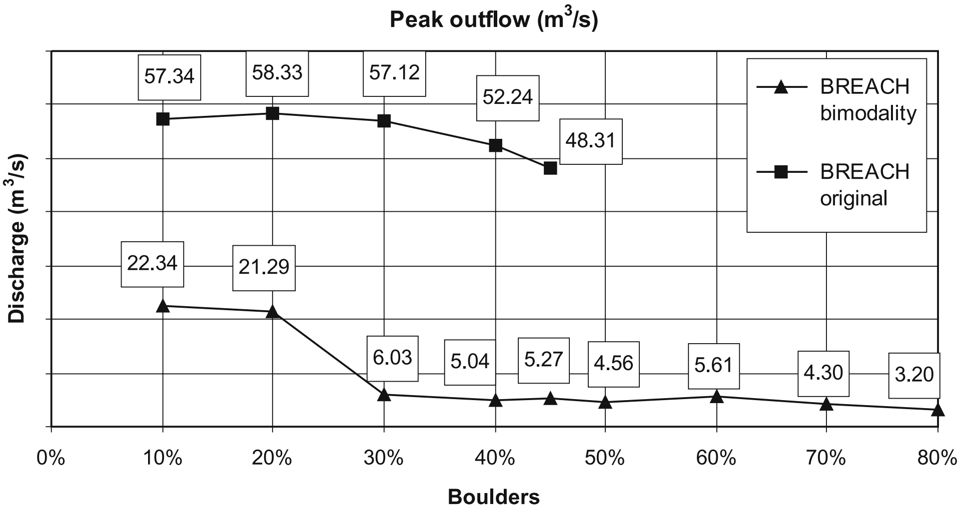

Figure 10. Valderchia landslide dam: comparison of the predicted peak outflow computed with the original and the modified code.

– with a percentage of boulders greater than or equal to 30%, the breach erosion stops after the time of peak discharge.

The original model predicts very high peak flows when compared with the modified model (figure 10).

This means that in a real case in which bimodal distributions of landslide materials are concerned, using a single D_{50} for the entire material mixture (not

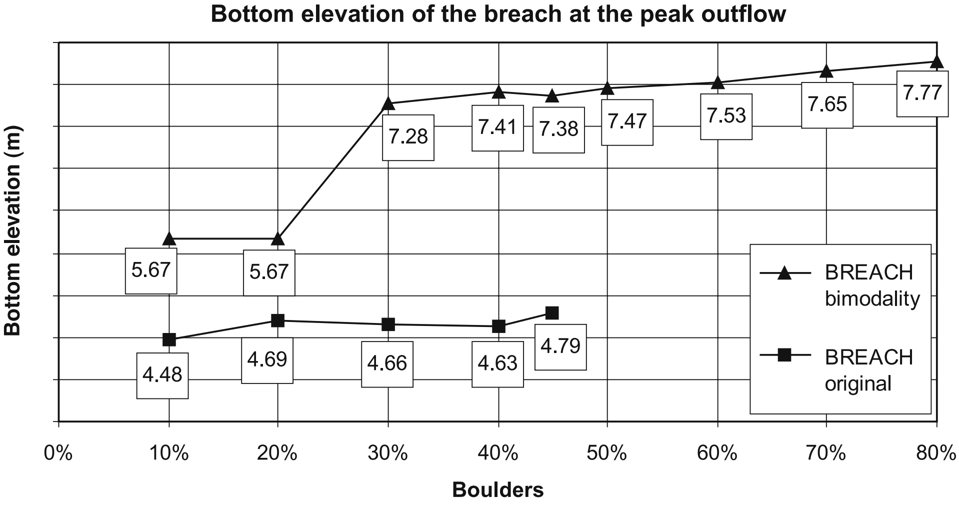

Figure 11. Valderchia landslide dam: comparison of the predicted bottom elevation of the breach at the peak outflow computed with both the original and modified code.

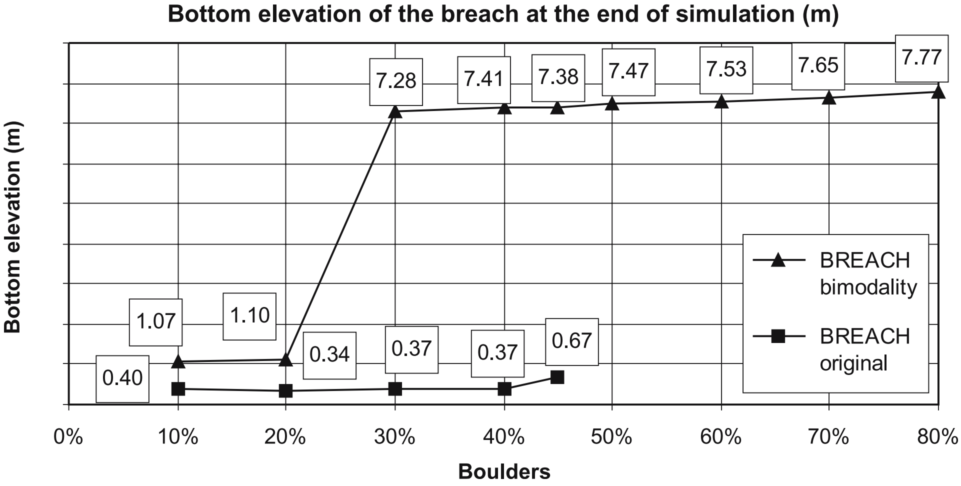

Figure 12. Valderchia landslide dam: comparison of the predicted bottom elevation of the breach at the end of the simulations computed with both the original and modified code.

representative of a real granulometric class) can result in an overestimation of erosion and of outflow hydrograph. The modified model, which takes into account the bimodal distribution, shows a higher elevation of the bottom of the breach channel both at the peak flow (figure 11) and at the end of the simulation (figure 12).

Furthermore, as a result of the formation of a threshold which cannot be eroded (armouring), erosion at the breach bottom ceases, due to the increase in relative frequency of the boulders in the breach bed.

10. Conclusion

Data on the Valderchia landslide dam (Gubbio, Italy) was used to test the BREACH model [14], a code for the simulation of the dam breach phenomena, and to implement some integrations. Due to the uncertainty in the weight percentage of boulders in the landslide grain-size distribution, we tested the model based on several different hypotheses (from 0% to 80% in weight of the boulders, in increments of 10%). Thus, the Valderchia landslide dam was considered a useful theoretical field test with which to perform a sensitivity analysis of the BREACH model. The aim was to analyse the relevance of the bed-load equation used by the model and to demonstrate the role played by the granulometric distribution of the landslide material. Results of the analysis show that the model is very sensitive to the bed-load equation. When the Schoklitsch equation is used, in place of the original Smart formula, the model supplies a different peak outflow. The peak discharge values are constant for D_{50} ranging from 0.045 to 15 mm using either the Schoklitsch or the Smart equation. However, the peak outflows calculated via the Schoklitsch approach are halved compared to those obtained using the Smart relation. The model showed that erosion was not possible above $D_{50} \geqslant 25.6$ cm. It must be noted that, although both formulas showed a scarce sensitivity to the increase in percentage of boulders inside the landslide body, differences in peak values obtained using the two formulas are considerable. Indeed, if we assume a trapezoidal (entrenched) channel cross-section, we can roughly evaluate the maximum flow that can pass through the channel without flooding, i.e., 25 m^3/s (hydraulic radius = 1.08 m; Chezy coefficient = 19.3 $m^{0.5}/s$; channel slope = 0.016; cross-section area = 9.7 m^2). It is obvious, when looking at figure 6, that the implemented Schoklitsch model would have forecasted a low risk flow (approximately 25 m^3/s, thereby eliminating the need for a by-pass construction for the landslide), whereas the Smart formula would have forecasted a flood (approximately 57 m^3/s). Although there are few elements from which to evaluate which is the most useful equation to describe overtopping, we think that the Schoklitsch equation can perform better. The theoretical reasons of our assertion are:

- the Schoklitsch equation was developed and tested using field data, whereas the Smart equation was derived by flume experiments on well-sorted sediments;
- the Smart equation is based on critical shear stress which cannot be a good criterion for entrainment in a self-formed channel because the critical conditions are often exceeded in only part of the channel; on the other hand, the Schoklitsch equation uses a critical unit water discharge which can be considered a good criterion in natural channels [3].

Figure 10 shows that the percentage of boulder has a big influence on the value of the peak discharge if the simulation is performed using the bimodality modified model (see section 9). This is due to the selective erosion of fine particles and to the creation of an armour on the breach bed, which does not enable the incision of the breach. This leads to the formation of a smaller breach section area and to a consequent smaller peak outflow. As explained at the end of section 8, the model performs the bimodal simulation assuming that the volume of material, over which the armouring process is developing, is located immediately below the breach bed until the bottom of the landslide dam. Therefore the procedure implemented to consider the eventual bimodal distribution of the dam material simulates both the armouring phenomenon (which can stop the erosion of the dam during the overtopping phase) and the reduction of erodibility of the landslide body related to the increase in the percentage of boulders. From this point of view, the correct characterisation of the granulometry of the landslide dam materials (also obtained using methods like those used for the gravel-bed rivers) increases its significance. This approach of selective transport can surely be improved and modified to permit simulation of breach erosion into multimodal grain-size distributions. We think that the obtained results can be considered promising, and that the modified model is more suitable for simulating the erosion of poorly sorted landslide dam materials.

References

[1] ASCE, *Downstream Hazard Classification Guidelines*, Technical report (American Society of Civil Engineering, Denver, CO, 1988).

[2] J. Bartoldy and P. Billi, Morphodynamics of a pseudomeandering gravel bar reach, Geomorphology 42(3) (2002) 293–310.

[3] J.C. Bathurst, W.H. Graf and H.H. Cao, Bed load discharge equations for steep mountain rivers, in: *Sediment Transport In Gravel Bed Rivers*, eds. C.R. Thorne and J.C. Bathrusts (Wiley, New York, 1996) pp. 453–477.

[4] A. Burghignoli, *Lezioni di meccanica delle terre*, 2nd edition (ESA, 1993).

[5] N. Casagli, L. Ermini and G. Rosati, Determining grain size distribution of the material composing landslide dams in the Northern Apennines: sampling and processing methods, Eng. Geol. 69(1–2) (2003) 83–97.

[6] C. Cencetti, P. Conversini, C. Ribaldi and P. Tacconi, The landslide in Valderchia near Gubbio, Umbria, Central Italy, in: *Proc. of 8th IAEG Congress*, Vancouver, British Columbia, Canada, Balkema (1998) 3, 1469–1476 ISBN: 90-5410-990-4.

[7] C. Cencetti, P. Conversini, C. Ribaldi and P. Tacconi, Studio dei sistemi alveo – pianura fluviale in relazione alle interazioni con fenomeni franosi di versante, Mem. Soc. Geol. Ital. 56 (2001) 249–263. ISSN: 0375-9857.

[8] C. Cencetti, A. Fredduzzi, I. Marchesini and P. Tacconi, Esperienze di rilevamento e determinazione dei caratteri granulometrici di alvei ghiaiosi, in: *I convegno AIGA, Atti,* Rendina Editori, Chieti (2003) 181–198 ISBN: 88-86698-40-2.

[9] M.A. Church, D.G. McLean and J.F. Wolcott, River bed gravels: sampling and analysis, in: *Sediment Transport in Gravel Bed Rivers*, eds. C.R. Thorne and J.C. Bathrusts (Wiley, New York, 1987) pp. 269–325.

[10] J.E. Costa and R.L. Schuster, The formation and failure of natural dams, Geol. Soc. Am. Bull. 100(6) (1988) 1054–1068.

[11] V. D'Agostino and M.A. Lenzi, Bedload transport in the instrumented catchment of the Rio Cordon. Part 2: Analysis of bedload rate, Catena 36(3) (1999) 191–204.

[12] V. Ferro, *La sistemazione dei bacini idrografici* (McGraw-Hill, 2002).

[13] D.L. Fread, *DAMBRK: The NWS Dam-Break Flood Forecasting Model*, Hydrologic Research Laboratory, National Weather Service, Silver Spring, MD, HLR-149 (1984) 56 pp.

[14] D.L. Fread, *BREACH: An Erosion Model for Earthen Dam Failures*, Hydrologic Research Laboratory, National Weather Service, Silver Spring, MD, HLR-256 (1987) 315 pp.

[15] B. Gomez and M. Church, An assessment of bed load transport formulae for gravel bed rivers, Water Resour. Res. 25(6) (1989) 1161–1186.

[16] J. Hattingh and W.K. Illenberger, Shape sorting of flood-transported synthetic clasts in a gravel bed-river, Sediment. Geol. 96 (1995) 181–190.

[17] I. Herle and G. Gudehus, Determination of parameters of a hypoplastic constitutive model from properties of grain assemblies, Mech. Cohes.-Frict. Mater. 4(5) (1999) 461–486.

[18] IGS, Multilingual Landslide Glossary, in: *International Geotechnical Society's UNESCO Working Party on World Landslide Inventory*, Biotech, Richmond, British Columbia (1993) p. 59.

[19] R. Kellerhals and D.I. Bray, Sampling procedures for coarse fluvial sediments, J. Hydraul. Div. 97(8) (1971) 1165–1179.

[20] L.B. Leopold, An improved method for size distribution of stream bed gravel, Water Resour. Res. 6(5) (1970) 1336–1357.

[21] T.C. MacDonald and J. Langridge-Monopolis, Breaching characteristics of dam failures, J. Hydraul. Eng. 110(5) (1984) 567–586.

[22] Y. Martin, Evaluation of bed load transport formulae using field evidence from the Vedder River, British Columbia, Geomorphology 53 (2003) 75–95.

[23] J.K. Mitchell, *Fundamental Soil Behavior*, 2nd edition (Wiley, 1993).

[24] Regione Umbria, *Progetto di sistemazione dell'area in frana di Valderchia* (Comune di Gubbio, Provincia di Perugia, 1999).

[25] K. Schmidt and P. Ergernzinger, Bedload entrainment, travel lengths, step lengths, rest periods, studied with passive (iron, magnetic) and active (radio) tracers techniques, Earth Surf. Processes Landf. 17 (1992) 147–165.

[26] A. Schoklitsch, *Handbuch des Wasserbaues* (Springer, Wien, 1962).

[27] G.M. Smart, Sediment transport formula for steep channels, J. Hydraul. Div., ASCE 110(HY3) (1984) 267–276.

[28] T. Strelkoff, D. Schamber and N. Katopodes, Comparative analysis of routing techniques for the floodwater from a ruptured dam, in: *Proceedings of Dam-Breach Flood-Routing-Model Workshop held in Bethesda* (1977) 227–291.

[29] F.J. Swanson, N. Oyagi and M. Tominaga, Landslide dams in Japan, in: *Landslide Dams: Processes, Risk and Mitigation*, ed. R.L. Schuster (Geotechnical Special Publication, Seattle, WA, 1986) pp. 131–145.

[30] J. Warburton and T. Demir, Influence of bed material shape on sediment transport in gravel bed rivers: A field experiment, in: *Tracers in Geomorphology* (Wiley, Chichester, UK, 2000) pp. 401–410.

[31] P.R. Wilcock, Experimental investigation of effect of mixture properties on transport dynamics, in: *Dynamics of Gravel-Bed River*, ed. Billi, P. et al. (Wiley, Chichester, 1992) 109–139.

[32] M.G. Wolman, A method of sampling coarse river-bed material, Am. Geophys. Union Trans. 35(6) (1954) 951–956.