Modeling and measurement of muddy debris-flows

Dr Jean-Louis Boillat, Erik Bollaert

Laboratory of hydraulic constructions, Swiss Federal Institute of Technology Lausanne, CH-1015 Lausanne, tel ++41 21 6932385, fax ++41 21 6932264, email secretariat.lch@epfl.ch

Summary

The physical modelling of a discharge control structure during muddy debris-flows has to take into account the particular shear behaviour of a muddy fluid, governed by the Herschel-Bulkley law. Determination of the main flow characteristics was obtained by vertical velocity profile measurements by means of a U.V.P (Ultrasonic Velocity Profiler). The transducer was mounted on the bottom of the channel, in a zone where the muddy flow is fully developed. The results were used to calibrate a theoretical model based on the principle of maximisation of entropy. An equivalent kinematic viscosity of the laminar muddy debris-flows was determined in order to calculate head losses. The empirical law obtained experimentally shows that this viscosity varies exponentially with the critical shear stress.

1. Introduction

Heavy rainfall on the catchment area of the Nant of Pissot, situated in the western part of Switzerland, produced a debris-flow during the night of the 13th to the 14th of August 1995. This event displaced about 50'000 m^3 of materials that finally accumulated on the alluvial deposition cone. Some 19'000 m^2 of vineyards were destroyed, the industrial zone was severely damaged and the national roadway RN9 was crossed by the flow, burying in that way 11 vehicles (Fig. 1). Fortunately, this natural disaster didn't make any victims.

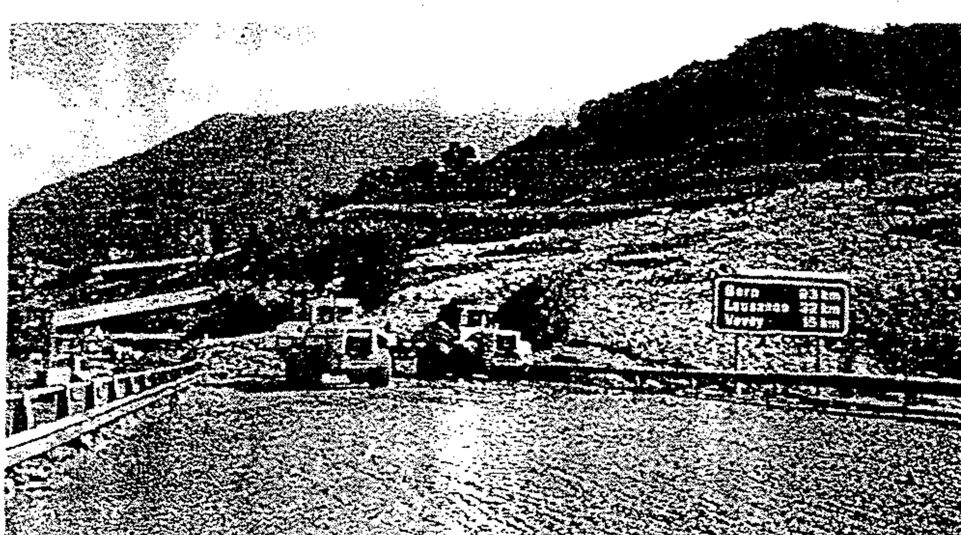

Fig. 1 View of the removal of debris on the RN9 after the avalanche of August 1995.

After the event of August 1995 several safety structures has been realized, namely two dumping basins, the first one with a volume of 20'000 m^3 at a height of 500 m a.s.l., and the second one with 5000 m^3 at a height of 380 m a.s.l., connected by a transition channel. Slightly downstream of the 500 dumping basin, at a height of 456 m a.s.l., the canal has been equipped by a discharge control structure. This device is one of the key elements of the concept established for the protection against debris-flows. Its function is to divert the debris-flow excesses lateral to the left bank in such way that water flows and moderate debris-flows still move straight ahead up to the dumping basin 380. The discharge control structure consists of a channel contraction, a 35 m long lateral spillway on the left bank and a deviating balk wall directing the overflow to the left bank. This innovative device has been submitted to hydraulic tests on a scaled model [1].

The model, realized on a 1/50 scale, also reproduces a part of the upstream and downstream channel. Parallel to the physical model tests a study was undertaken concerning the similarity of the model fluid. The model tests were dedicated in a first stage to the hydraulic behavior of the system as well as to the simulation of granular debris-flows. In a second stage, the simulation of muddy debris-flows was performed, respecting the following order:

- study of the rheological similarity of the fluid model ;
- optimization of the geometry of the structure ;
- verification of the functionality of the discharge control structure – critical diversion discharge, diverted ratio – for different properties of the fluid model ;
- study of the behavior of the discharge control structure for different degrees of clogging of the channel aperture.

2. Modeling of muddy flows

The muddy debris-flow was simulated by means of a dilution of kaolinite into water. For volumetric concentrations between 20 and 30 %, the shear behaviour of the fluid is totally different from that of Newtonian fluids and follows the Herschel-Bulkley law [2], given by the following expression:

$$\tau = \tau_c + K \cdot \dot{\gamma}^n \quad \text{if} \quad \dot{\gamma} \neq 0 \qquad \tau \leq \tau_c \quad \text{if} \quad \dot{\gamma} = 0 \tag{1}$$

τ_c : *critical shear stress*	*[N/m²]*
$\dot{\gamma}$: *velocity gradient*	*[s⁻¹]*
K et n : fluid parameters	*[-]*

The critical shear stress, as well as the fluid parameters, have been obtained by rheological tests, and a relationship between the critical shear stress and the volumetric concentration of the water-kaolinite mixture could be adjusted as represented on Fig. 2:

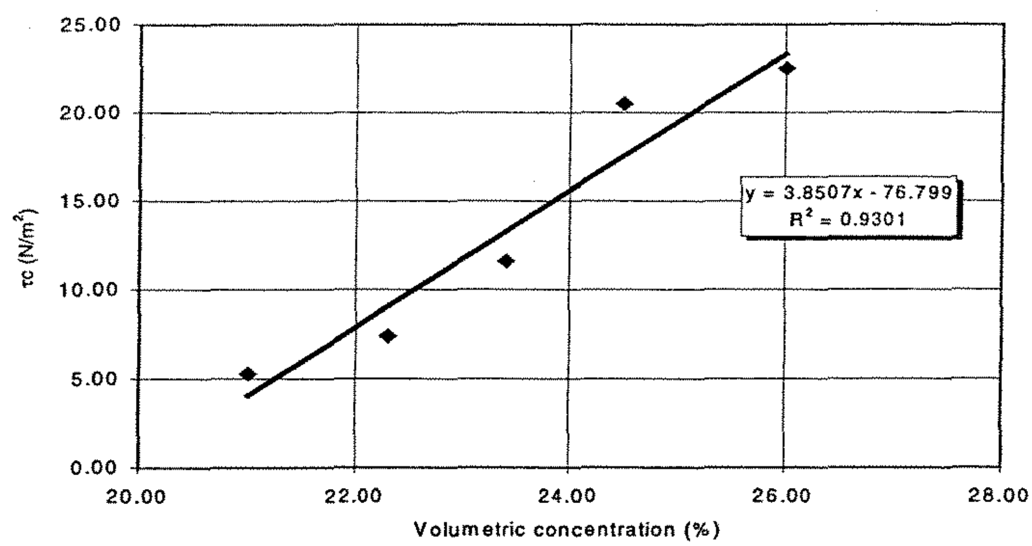

Fig. 2 Relationship between the critical shear stress and the volumetric concentration of the water-kaolinite mixture.

3. Comparison of experimental and theoretical velocity profiles.

The determination of the main flow characteristics has been obtained by vertical velocity profile measurements by means of a U.V.P (Ultrasonic Velocity Profiler). The transducer was mounted on the bottom, in the longitudinal axis of the upstream channel, in a zone where the muddy flow is fully developed. The UVP X-3-PS instrument functions by direct measurement in the fluid using ultrasonic waves with Doppler effect [3]. The analysis of the echo reflected by the particles that are moving in the measurement zone allows to identify velocity and direction of flow as well as the position of the control volume. The installation was completed by an ultrasonic level meter intended to measure flow height simultaneously. The results were used to calibrate a theoretical model based on the principle of maximisation of entropy [4]. The corresponding velocity profile has the following form:

$$u(\xi)=\frac{u_{max}}{M}\cdot\ln\left[1+\left(e^{M}-1\right)\cdot\frac{\xi-\xi_0}{\xi_{max}-\xi_0}\right] \quad (2)$$

u :	*longitudinal component of flow velocity vector*	*[m/s]*
ξ :	*curvilinear co-ordinate of the lines of equal velocity*	*[-]*
u_{max}:	*maximum flow velocity*	*[m/s]*
M :	*parameter of entropy*	*[-]*

With:

$$\xi=\frac{y}{D-h}\cdot\exp\left(1-\frac{y}{D-h}\right) \quad (3)$$

D:	*flow depth*	*[m]*
h:	*depth of maximum flow velocity*	*[m]*

In the above equations, D and h are measured values, while M is defined analytically. The parameter of entropy M has been determined as a flow constant on one hand, and as varying linearly with the flow depth on the other one. The results of the calibration of the theoretical velocity profiles are represented hereunder (Fig. 3) and show that a best fit is obtained by considering a linear variation of M with the flow depth. The data was collected for a frequency of 10Hz and a 0.748mm grid spacing along the axis of the transducer. This axis made an angle of 60° with the channel bottom, corresponding to one measurement every 0.648mm along the y-axis.

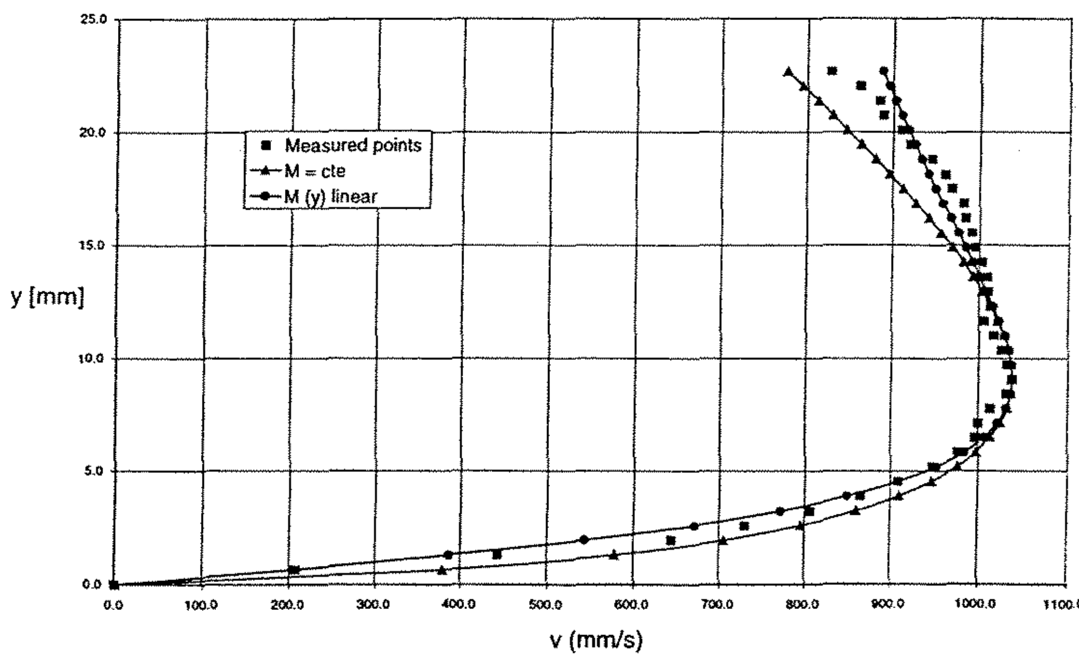

Fig. 3 Results of the calibration of the theoretical velocity profiles with M as constant and M varying linearly with the flow depth

This thermodynamic approach has been applied in order to determine an equivalent kinematic viscosity of the model flow and gives satisfactory results.

4. Hydraulic friction law for laminar muddy debris-flows

By the fact that all the observed muddy flows were laminar, an equivalent kinematic viscosity of muddy debris-flows was determined in order to calculate head losses. The empirical law obtained experimentally shows that this viscosity varies exponentially with the critical shear stress. The friction coefficient f, determining head losses, is then expressed by the following relationship (Fig. 4):

$$f = \frac{45.8}{R} \qquad \text{for } R < 2300 \tag{4}$$

f :	*friction coefficient of Darcy-Weisbach [5]*	[-]
R :	*Reynolds number* $= u_m . D_h / v$	[-]
u_m :	*mean velocity based on (2)*	[m/s]
D_h :	*hydraulic diameter*	[m]
v :	*equivalent cinematic viscosity of flow*	[m²/s]

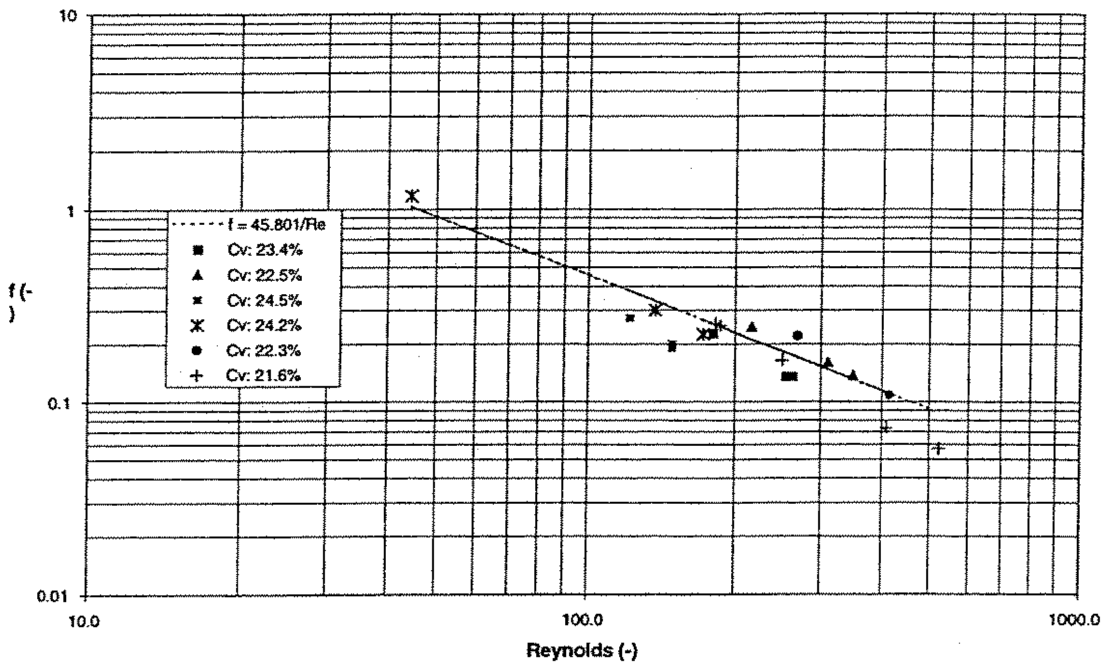

Fig. 4 Adjustment of the f(R) relationship over different volumetric concentrations

5. Conclusions

The physical modelling of a discharge control structure during muddy debris-flows took into account the shear behaviour of a muddy fluid following the Herschel-Bulkley law. The main flow characteristics were obtained through vertical velocity profile measurements by means of a U.V.P (Ultrasonic Velocity Profiler). The results were used to calibrate a theoretical model based on the principle of maximisation of entropy. An equivalent kinematic viscosity of laminar muddy debris-flows was then determined in order to calculate head losses. The empirical law shows that this viscosity varies exponentially with the critical shear stress. A friction coefficient f, determining the head losses following the Darcy-Weisbach equation, could be expressed in function of the Reynolds number of the muddy flow. This finally allowed the establishment of the "flow depth – discharge" relationship of the muddy flows at different volumetric concentrations. A reliable and detailed dimensioning of the discharge control structure could thus be achieved.

Bibliographical references

[1] Sinniger, R., Boillat, J.-L., "Modélisation de laves torrentielles granulaires et boueuses sur l'écrêteur 456 du Pissot", Rapport interne N°3, LCH-EPFL, mars 1998.

[2] Coussot, P., "Rhéologie des laves torrentielles boueuses" et "Lois d'écoulement des laves torrentielles boueuses", La Houille Blanche, mars 1994.

[3] MET-FLOW S.A.: Ultrasonic Velocity Profile Monitor – Operation Manual, Model UVP X-3-PS, May 1996.

[4] Chao-Lin Chiu, "Application of Entropy Concept in Open-Channel Flow.", Journal of Hydraulic Engineering, Vol.113, N°5, mai 1987.

[5] Sinniger, R., Hager, W., "Constructions Hydrauliques. Ecoulements stationnaires. Traité de Génie Civil, Vol.15", Ecole Polytechnique Fédérale de Lausanne, 1988.