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# PROSPECTS FOR PREDICTION OF LANDSLIDE DAM GEOMETRY USING EMPIRICAL AND DYNAMIC MODELS

O. Hungr

Earth and Ocean Sciences Department, University of British Columbia, 6339 Stores Rd., Vancouver, BC, Canada, V6T 1Z4

## INTRODUCTION

Some 50% of landslide dams fail within 10 days of emplacement (Schuster & Costa, 1986), producing dangerous flooding downstream. The risks deriving from such sudden, catastrophic scenarios could be substantially reduced, if it were possible to predict the geometry of a dam resulting from a given potential slope instability. Often, the location and volume of the landslide can be anticipated with reasonable accuracy. The remaining crucial question is how the unstable mass will deposit.

## RUNOUT PREDICTION

*EMPIRICAL MODELS*

Empirical methods useful for estimating landslide runout have been reviewed by Hungr (2005). They include correlations of travel angle and volume (Corominas, 1996), deposit area and volume (Iverson *et alii*, 1998) and similar. While these methods can roughly predict the overall travel distance of the landslide mass, or its areal extent, they can give no indication of the distribution of debris in the deposition area, information that is needed for planning protective measures such as a spillway or bypass tunnel, or even the all-important prediction of the pool elevation behind the dam. The empirical methods also suffer from great scatter of data, making even the limited predictions very unreliable.

*DYNAMIC MODELS*

In recent years, a number of numerical dynamic models for simulation of landslide motion have been developed (for a review, see Hungr, 2005). Most of the models are based on depth-integrated St.Venant solutions of the equations of motion and compatibility. Some models are resolved in a one-dimensional framework, to produce two-dimensional (2D) representations of flow depth and displacement (e.g. Savage & Hutter, 1989; Iverson, 1997). One model uses a combination of a user-defined path width outline and the equation of continuity to provide an approximate three-dimensional representation of flow (Hungr, 1995). Several new models resolve the governing equations in two dimensions, to derive true three-dimensional (3D) flow solutions (e.g. Lee & Chen, 2001; Iverson & Denlinger, 2001; McDougall & Hungr, 2004 and 2005). The constitutive relationships used in these models include Bingham flow (Sousa & Voight, 1985), frictional flow (Savage & Hutter, 1989), frictional flow with pore-pressure, combined frictional and turbulent resistance (the Voellmy model, Hungr, 1995) and other relationships. Some models can include more than one rheological component within the moving mass (Iverson, 1997; Iverson & Denlinger, 2001).

## EXAMPLES

*2D VERSUS 3D*

Three-dimensional solutions are preferred for dam geometry predictions, as there is often a large degree of lateral spreading. A sample back-analysis was carried out of the 1987 Val Pola Slide in Valtellina, Northern Italy (Figure 1).

*Figure 1 - The Val Pola slide deposit (Photo: Banco Popolare Sondrio)*

The analysis was carried out using the DAN 3D model described by McDougall & Hungr (2004) is shown in Figure 2. The analysis uses the frictional model with pore pressure. The basal frictional resistance is characterized by a single parameter, the bulk friction angle, defined by Hungr (1995):

$$\phi_b = \arctan\left[(1 - r_u)\tan(\phi)\right] \qquad (1)$$

where $\phi$ is the friction angle of the material and $r_u$ is a constant pore pressure ratio. Thus, even though pore pressure is included, the resisting stress on the base of the landslide is controlled only by total normal stress, similarly to dry sliding. In the present case, $\phi_b$=14° was used. The internal friction angle, $\phi_i$, used in a manner suggested by Savage & Hutter (1989) was 35°.

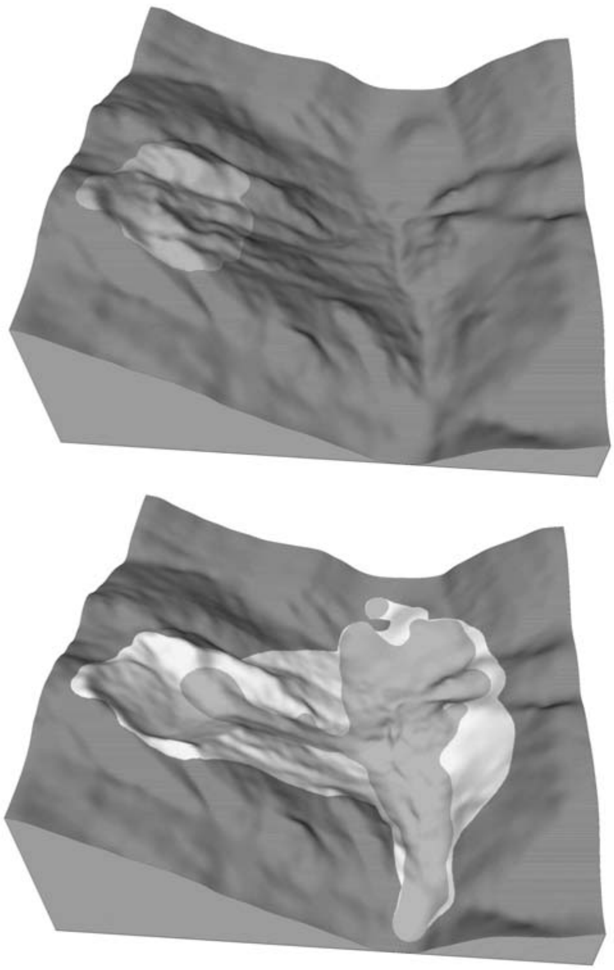


*Figure 2 - Val Pola Slide, Valtellina, Italy, analysed using DAN 3D McDougall & Hungr (2004). Frictional rheology, $\phi_b$=14°, $\phi_i$=35°. A) before slide; B) after slide. Light gray areas mark terrain overrun by the slide, but not covered by deposits. (Digital terrain models kindly provided by Professor G.B. Crosta, Università degli Studi di Milano-Bicocca)*

A comparative analysis carried out with the two-dimensional model DAN (Hungr, 1995) using the same input parameters and a path width estimated from a map is shown in Figure 3. This is a difficult test for the pseudo three-dimensional solution, due to great degree of spreading of the slide and the uneven topography of the valley slope opposite the source. However, the distribution of the debris across the valley corresponds very well to the 3D model and the 2D solution represents a reasonable preliminary analysis of the situation.

## *INFLUENCE OF RHEOLOGY*

Figure 4 shows the results of the 2D Val Pola analysis using DAN with three alternative rheological models. In all three cases, the model parameters were fitted so as to obtain the correct maximum runout distance and height on the bank opposite the failure, as well as a realistic velocity profile (cf. Hungr & Evans, 1996). Each of the three rheologies produces a different distribution of debris across the valley floor. The frictional run produced runup onto the bench on the opposite side of the valley, followed by a fall-back, leaving a small part of the deposit on the bench. The Voellmy deposit is similar, but more compact at the front, so that the bench crest was reached, but no deposit was left. The Bingham result left a large part of the mass on the proximal slope and did not predict any fall-back. Its deposit if of a fairly uniform ("critical") thickness.

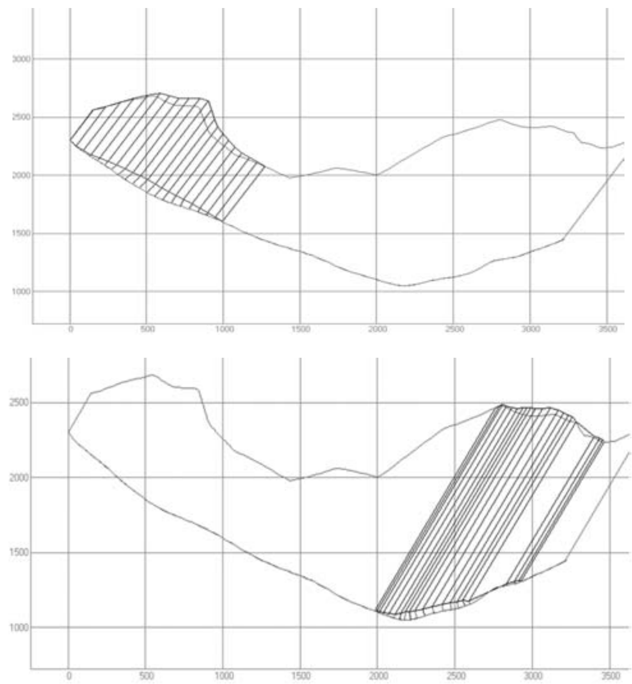



*Figure 3 - Val Pola slide analysed with the 2D program DAN (Hungr, 1995). The isometric view represents only the left half of the slide path. In the forefront is the scaled cross-section of the centerline of the slide path, showing the mean thickness of the debris 123 seconds after the beginning of motion. The upper green line is the left margin of the slide, measured from a map of the slide*

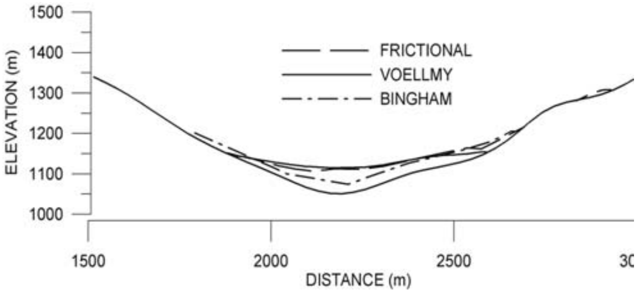



*Figure 4 - Three alternative mean deposit thickness cross-sections produced by the 2D program DAN (HUNGR, 1995)*

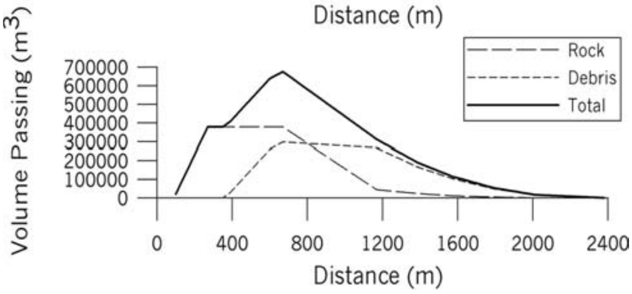



*Figure 5 - Volume balance diagram of the Nomash rockslide debris avalanche (after HUNGR & EVANS, 2004)*

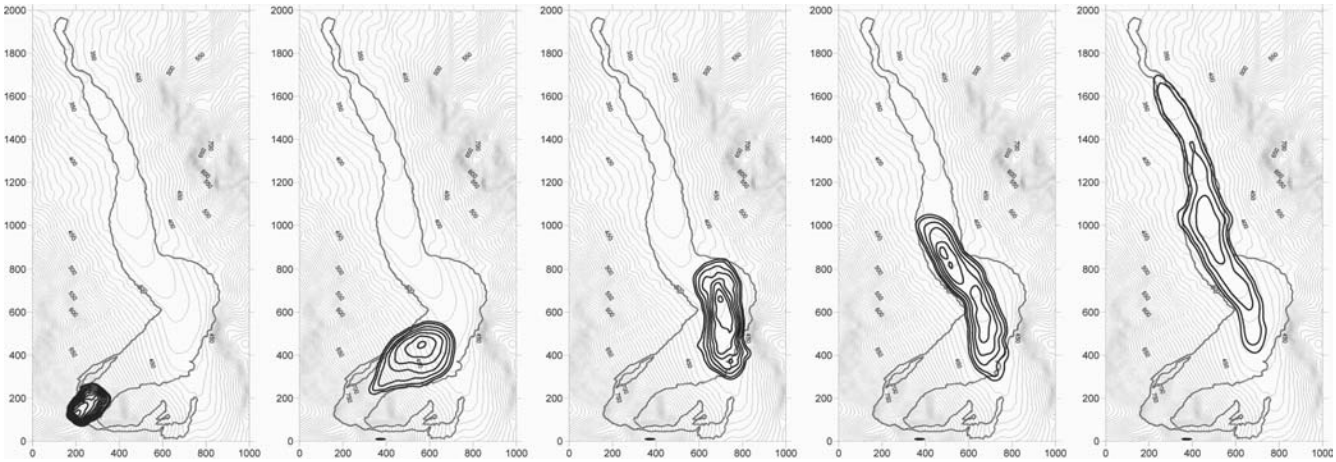
*MATERIAL ENTRAINMENT*

Many rapid landslides entrain saturated soil from their path during motion. In doing so, their base may be lubricated by liquefied mud (e.g. SASSA, 1985; HUNGR & EVANS, 2004). Thus, the rheology controlling the landslide motion may change dramatically, and with it the mode of emplacement of the debris and the dimensions of a potential dam. A striking example of such behaviour is the 1999 rock slide debris avalanche on Nomash River near Zeballos, Vancouver Island, Canada, described by HUNGR & EVANS (2004). The event started as a rockslide in marble and andesite, with a fragmented volume of approximately 400000 $m^3$. The slide debris collapsed onto an apron of relatively fine-grained colluvial and glacial soils accumulated at the foot of the source slope. A volume approximately equal to the source volume was entrained from this apron and incorporated into the moving mass. A volume balance ("mass") diagram of the landslide estimated from field observations is shown in Figure 5. Most of the fragmented rock debris deposited in the proximal part of the deposition area. The distal part was made up mainly of liquefied mud originating from the entrained debris. The slide ran a total distance of 2000 m from the toe of the initiating rock failure. An overall view of the rockslide debris avalanche is shown in Figure 6a. As a result of the long spreading of the debris, practically no damming of the Nomash River occurred. The upstream margin of the slide debris was only about 5 m thick and only a small pond accumulated above it. The river filtered through the coarse debris and cut a poorly defined channel in the fine part.

*Figure 6a - An aerial view of the slide*

Figure 6b shows a dynamic analysis of the landslide produced using the model Dan 3D (MCDOUGALL & HUNGR, 2005). The input parameters are equivalent to those used in a 2D DAN analysis by HUNGR & EVANS (2004), (see also HUNGR, 2005). The initial slide is frictional and dry, with a friction angle of 30°. The slide entrains the requisite amount of material from the path in accordance with Figure 5. At the same time, the rheological model is changed to Voellmy, with a friction coefficient of f=0.05 and $\xi$=400 m/s$^2$. These are the same parameters as used in the 2D analysis and the resulting distribution of debris is also very similar, corresponding approximately to the actual distribution observed in the field. Thus, both the 2D and 3D models give good agreement with field observations, using the same parameters.

A second analysis was carried out, in which the uniform frictional model was used, with an average bulk friction angle, $\phi_b$ of 20°. As shown on Figure 6c, this produces a very different distribution of debris and forms a landslide dam 16-m high. Thus, neglect of the rheological change due to liquefaction and entrainment of saturated substrate would lead to a very unrealistic result.



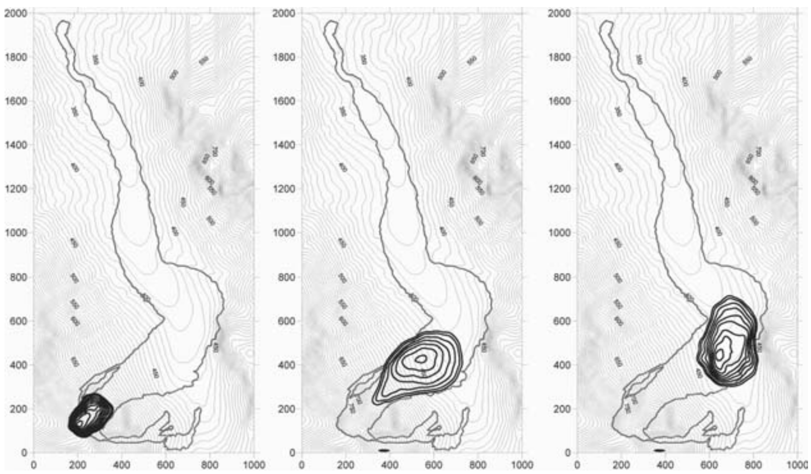




*Figure 6 - Analyses of the Nomash River rock slide debris avalanche using the program DAN3D (McDougall & Hungr, 2005)*
*B - analysis using the Voellmy fluid model as described by Hungr & Evans (2004);*
*C - analysis using the frictional model, with a bulk friction angle of 20°. Plots at 40 s intervals. The depth contour interval is 2 m. The gray line is the actual path outline*

## CONCLUSION

Powerful tools exist for analysis of landslide dynamics. These tools have the potential to produce reliable predictions of the geometry of landslide dams. However, much work remains in calibrating these models so as to facilitate reliable choice of the rheology and allow for the important influence of material entrainment.

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