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LEVEES CREATION IN DEBRIS FLOWS DURING RAPID DEWATERING: OBSERVATIONS FROM JOTUNHEIMEN, SOUTHERN NORWAY

ABSTRACT: DE BLASIO F.V., *Levees creation in debris flows during rapid dewatering: observations from Jotunheimen, Southern Norway*. (IT ISSN 1724-4757, 2006).

Field observations from southern Norway, theoretical analysis, and a simple experimental test indicate that levees in coarse-grained, water-rich debris flow may partly form as a result of strong dewatering during flow. Dewatering may also influence the runout distance of the debris flow.

KEY WORDS: Debris flows, Levees, Leirdalen, Norway.

SAMMENDRAG: DE BLASIO F.V., *Kantdannelse i en debris strøm under sterk uttørring: observasjoner fra Jotunheimen, SørNorge*. (IT ISSN 1724-4757, 2006).

Felt observasjoner fra Sør-Norge, teoretisk analyse og et enkelt eksperiment viser at kantene av en grovkornet og vannrik debris strøm delvis dannes som konsekvensen av sterk uttørring. Perkolasjon av vann må også påvirke utløpsdistansen.

NØKKELORD: Debris strøm, Levee, Leirdalen, Norge.

RIASSUNTO: DE BLASIO F.V., *Formazione degli argini naturali nei debris flow soggetti a rapida perdita d'acqua: osservazioni a Jotunheimen, Norvegia Meridionale*. (IT ISSN 1724-4757, 2006).

Osservazioni di campo (Norvegia meridionale), considerazioni teoriche e un semplice esperimento indicano che gli argini naturali in un debris flow a grana grossa e ricco di acqua potrebbero in parte formarsi come conseguenza di una forte perdita d'acqua durante il flusso. La perdita d'acqua puo' anche influenzare la distanza percorsa dal debris flow.

TERMINI CHIAVE: Debris flow, Argini, Leirdalen, Norvegia.

Debris flows deposits are often bordered by natural levees, usually interpreted either as a consequence of thinning of the debris flow at its margins, or due to debris overflowing the channel banks in a thin sheet (Johnson 1978). In both cases, the lateral deposits become very thin until they freeze when the shear stress falls below the yield strength of the material. In the present note I present indications that in particular conditions, coarse-grained debris flow might form lateral levees partly as a result of rapid dewatering during traveling. As a starting point I report a series of observations of debris flow deposits located in the Jotunheimen mountain region in southern Norway. At least three debris flows located a few hundred meters from the lake of Leirvatnet in the valley of Leirdalen at an average altitude of 1600 m were mobilized during periods of intense rainfall, two of them in 1994, and the third somewhat later. The resulting deposits, about 300 m long, involved recent colluvium composed of metamorphic clasts between about 3 cm to 1 m in diameter, embedded in a fine silt matrix. A general view is shown in figure 1A. Shakesby & Matthews (2002) have described in detail two of the debris flows (the ones at the center and on the right in figure 1A), so in the following description I can be brief and focus on the essential features of the levees. Because the debris flow characteristics are rather similar, they will not be discussed singularly.

The debris flows started when wet, soil-rich colluvium resting on steep metamorphic bedrock failed as a consequence of accumulated water pore pressure, leaving behind a smooth rock surface (see figure 1B). Few meters below the bedrock, the debris flow has deposited a chaotic accumulation of boulders. Levees composed of large clasts about half a meter in diameter initiate slightly below. In the upper part, levees are about ten meters distant, becoming closer downhill (about three meters). The average size of the clasts decreases downwards. They are boulder-sized at the escarpment, decrease to about 30 cm in diameter in the central part of the deposit, down to 2-5 centimeters at the front. The horizontal gradation probably

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indicates that the shear stress needed to transport larger clasts was fading during flow. Levees are neat and fresh-looking to almost resemble artifacts. In the eastern debris flow, levees are interrupted by a couple of sub-circular mass accumulations probably due to successive debris flow pulses. The levees terminate some meters before the end of the debris flow, where the deposited material has developed a bulge. The terrain on which the debris flows have traveled is particularly significant for the following discussion. Most of the terrain is composed of a granular bed with variable clast size deriving from previous mass wasting, such as talus deposits and possibly antecedent debris flows (even though the bulge of the eastern debris flow rests on a single very large boulder). Vegetated, wet soil lies distant from the last debris flow deposits and it is thus unlikely to have been involved in the flow. Figure 1C and 1D show two details of the levees in the eastern debris flow.

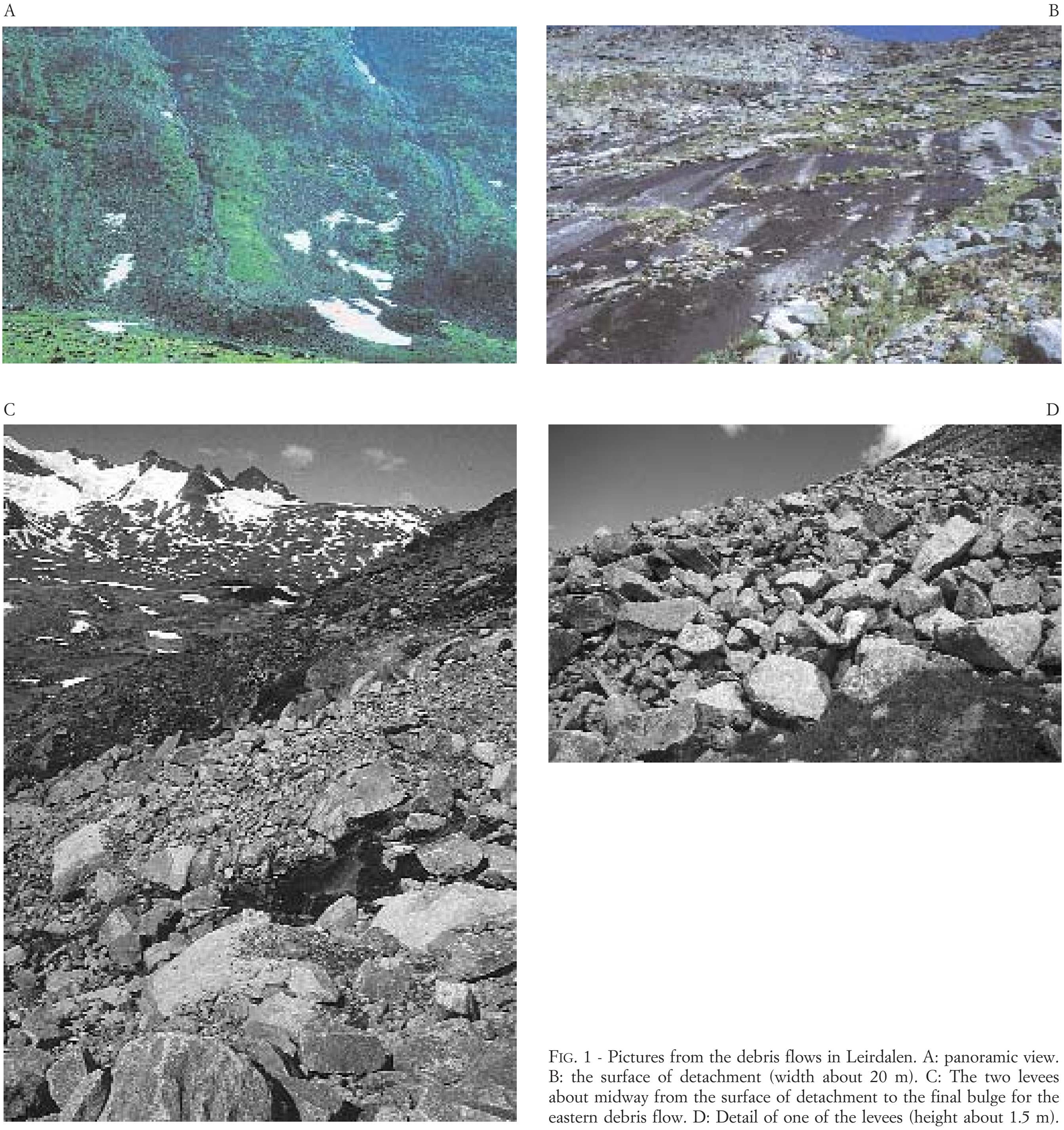

FIG. 1 - Pictures from the debris flows in Leirdalen. A: panoramic view. B: the surface of detachment (width about 20 m). C: The two levees about midway from the surface of detachment to the final bulge for the eastern debris flow. D: Detail of one of the levees (height about 1.5 m).

A peculiarity of the debris flows in Leirdalen is the apparent importance of dewatering in affecting the flow regime, as also recognized by Shakesby & Matthews (2002). Firstly, the debris flows came to a halt on a steep terrain (about 15°). Additionally, the fact that debris flows have traveled on a carpet of fractured large-sized clasts must have favored water seepage through the bed. Shakesby & Matthews (2002), identify large sieve holes in the final parts of the deposit as the preferential pathways of dewatering, even though a more uniform process of water loss also appears to be possible.

Examining the levees (figure 1), one is struck not only by the fresh surface appearance, but also by the neat contacts between the debris flow and the granular bed. It looks like water has copiously abandoned the material during flow, whereas the solid cohesive part was unable to penetrate through the interstices formed by the coarse bed owing to its finite yield stress.

In the following I suggest that rapid dewatering may have contributed to the formation of levees in the Leirdalen debris flows. A simple experimental test was performed by mixing water with natural beach sand. The mixture of about 2 liters was vigorously stirred to uphold sand suspended and then cast onto an inclined (35 degrees) plastic table about 1.5 m long. In the absence of water absorption (clean table surface) sand arranged into a myriad of small channels, which clearly do not resemble large-scale debris flow features (see figure 2A). However, when a layer of a few millimeters of dry sand was shed on the table prior to the experiment, the artificial debris flow exhibited features very similar to the natural debris flows. Sand tongues widened to about 2 cm across, and developed well-defined levees a few millimeters high and a final bulge (figure 2B). Comparing figures 2A and 2B, one concludes that the fast dewatering ensured by dry sand (which mimics the granular bed in Leirdalen) proves to be essential to the result.

It is possible to appreciate more quantitatively the experimental results by assuming that the sand-water mixture behaves like a Newtonian fluid with viscosity given by the Krieger-Dougherty law (See Coussot, 1997) $\mu = \mu_0 (1-C/C_*)^{-2.5\,C_*}$ where C is solid concentration, μ_0 is the viscosity of the percolating water and $C_* \approx 0.6$ is the concentration in correspondence to which sand particles interlock. One can define the water volume per unit base area of the debris flow $W = (1-C)\, D_0$ as where D_0 is the initial height of the debris flow (note that W has the dimension of a length). At a certain position and time, water seeps out from the debris flow and thus W changes as $dW / dt = -k$ where the rate is predicted by the Kozeny-Carman law (Rhodes 1998, Middleton & Wilcock 1994) $k \approx 0.0055\, \rho g d^2\, (1-C)^3 / C^2\, \mu_0 = \alpha\, (1-C)^3 / C^2$ where $\alpha = 0.0055\, \rho g d^2 / \mu_0$, d is particle diameter, and ρ is the density of the mixture. Neglecting exchange of matter and momentum along the lateral direction of the debris flow, the depth-averaged laminar velocity at some point can be obtained by integration of the time-independent Navier-Stokes equation along the flow direction $\langle u \rangle \approx \rho\, g \sin \beta\, D^2 / 3\mu$ where g, β, D are respectively gravity acceleration, slope angle and local thickness of the debris flow. From the above equations one finds the differential equation

$$\frac{dW}{dt} = -D_0 \frac{dC}{dt} = -\frac{\alpha(1-C)^3}{C^2} \qquad (1)$$

which can be integrated in time to find C. Imposing $C = C_*$ to the solution, I find the time when grains interlock and the debris stops locally as

$$t = \frac{D_0}{2\alpha}\left\{(1-C_*)^{-2} - (1-C_0)^{-2} + 2\ln\frac{1-C_*}{1-C_0} + 4\left[(1-C_*)^{-1} - (1-C_0)^{-1}\right]\right\} \qquad (2).$$

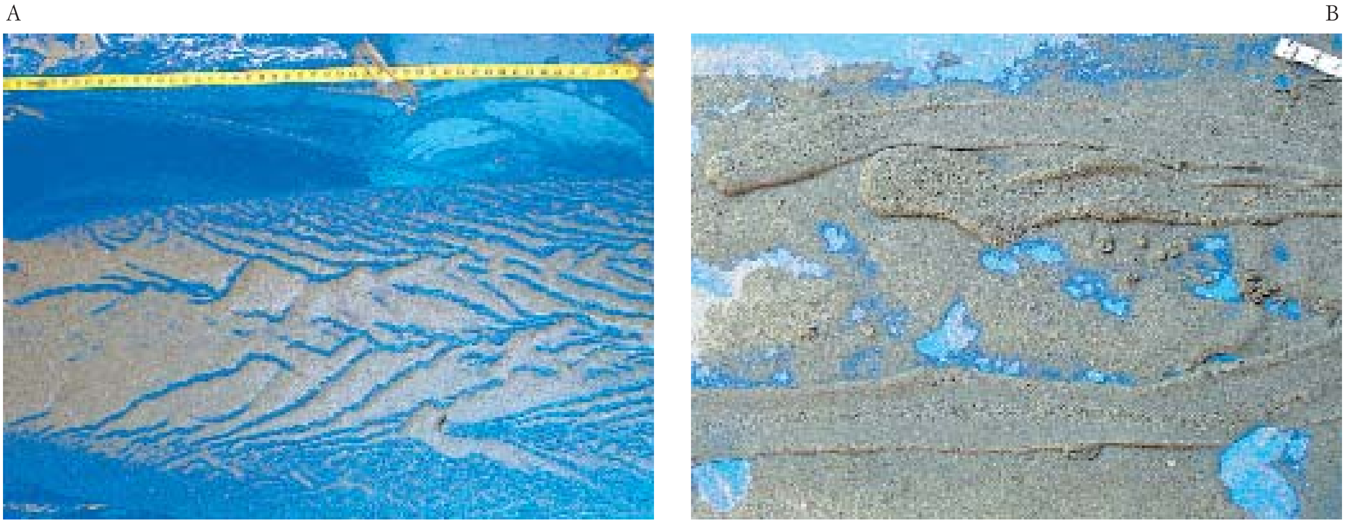

FIG. 2 - Experimental deposits. A: without antecedent dry sand deposit. B: With a layer of dry sand (length of 23 cm).

The result shows that the time of travel is proportional to the initial height of the debris flow, D_0. As a consequence, the central portion comes to a halt at a later time, whereas the sides stop earlier forming the levees. Little material is deposited in the central part, except for the final bulge. With values $C_0 \approx 0.4$; $C_* \approx 0.6$ equation 1 predicts that the central part in the experimental debris flow travels for about 3-6 seconds (the maximum $D_0 \approx 1cm$), which is consistent with the observation, whereas at the sides this value is reduced to less than one second. Thus, while the material along the sides of the debris flow comes to a stop, the one next to the central axis keeps flowing and expands sideways to form new levees. The process continues until water loss begins affecting also the center, which freezes forming the final bulge. A schematic view of the process is shown in figure 3.

The application to the field case is more intricate owing to uncertainties in the parameters, especially in the viscosity and in the effective particle diameter of the natural debris flow. The ratio of the characteristic time of stoppage between the large-scale to the small-scale debris flows is approximately

$$\frac{\tau_{large}}{\tau_{small}} \approx \frac{D_{0,large}}{D_{0,small}} \left(\frac{d_{small}}{d_{large}} \right)^2 \frac{\mu_{0,large}}{\mu_{0,small}} \qquad (3).$$

Because the grains in the Leirdalen debris flow are extremely variable in size, it not sensible to make use of the average grain dimension, as it is more the fine component which determines the pore size entering into the Kozeny-Carman relation. Tentatively, assuming that the viscosity of water in the flowing natural debris was only slightly higher than in the experimental test, and that the pore size was comparable, it is possible to speculate that the time ratio (3) is largely determined by the ratio in the height of the debris flow $D_{0,large} / D_{0,small} \approx 200$, which in equation (3) returns a time of the order of one minute.

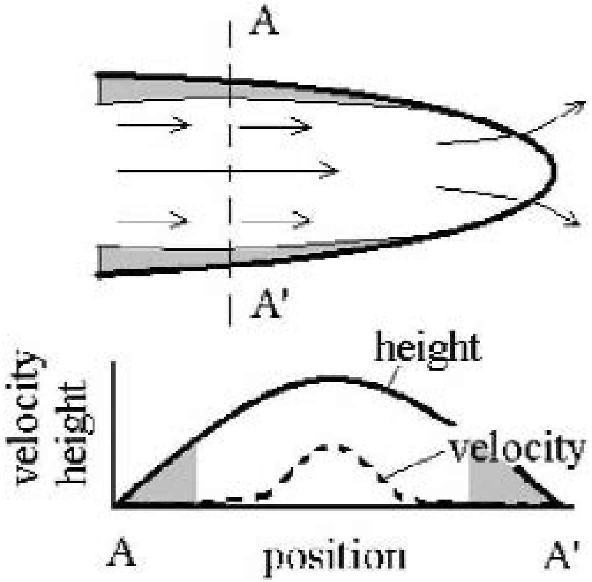

FIG. 3 - Schematic view showing the relationship between levees formation and water loss. Top: view from above. Bottom: horizontal velocity and height across the section AA'. Levees, indicated as shaded areas, are created when grains interlock and the velocity drops to zero. Because both shear stress and water content increase with thickness, the velocity is larger at the center where the debris flow is thicker.

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