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Discussions

# *Interactive comment on* "The use of FLO2D numerical code in lahar hazard evaluation at Popocatépetl volcano: a 2001-lahar scenario" *by* L. Caballero and L. Capra

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Pag 4584: according to the Statistic and Geography Nationals Institute (INEGI) of Mexico the population of Santiago de Xalitzintla is less than 3.000 inhabitants. The 10.000 inhabitants correspond to the total population of the municipality of San Nicolas de los Ranchos. Xalitzintla town is just part of this municipality.

The number of inhabitants of Santiago Xalitzintla was adjusted according to the 2010 census of Instituto Nacional de Geografía e Informática (INEGI) of Mexico to 2196.

Pag 4585, Line 1: The authors affirm that "nowadays a glacier is no longer present



on the Popocatepetl cone", which contradicts the findings of other authors like Muñoz-Salinas et al. (2010).

Julio-Miranda et al. (2008) performed detailed glaciological studies. They found that at Popocatépetl volcano, the climatic-induced recession of the glacier between 1958 and 1998 was drastically accelerated due to the increase on tephra fallout in the summit area, which led to the total glacier consumption in 2004. Iced masses present at the summit are not considered a glacier since they do not flow and the glacial regime is disrupted (Delgado-Granados et al., 2007). Besides, Muñoz-Salinas et al. (2010) did not present any glaciological data to support they hypothesis.

Pag 4586. Section 2: FLO2D is a Two-dimensional One Phase model. Lahars are a two phase flow. Its bulk properties cannot be accurately (at least) captured by one phase models, as they assume that the solid and fluid phases form a single phase material (Iverson, 1997). Two phase flows can have parts of them in the frictional regime, which are better described by models that use approaches like Mohr-Coulomb (Savage and Hutter, 1989; Patra et al, 2005). For parts with low solid concentrations, one phase models or even hydraulic approaches can be enough (Chow, 1969). Intermediate concentrations need to account for the different properties and interactions between phases, like the inter-particle drag (Dobran, 1991) that cannot be accounted for in one-phase models. Thus, I suggest that the authors should mention the limitations of the used model.

We agree that one phase models cannot accurately reproduce lahars since particle-particle interaction and particle-fluid interaction are important in flow behavior. Nevertheless, FLO2D takes into account both fluid and solid phases in constitutive equations. O'Brien and Julien (1985) developed a quadratic shear stress model that describes the continuum of flow regimes from viscous to turbulent/dispersive flow. The quadratic model involves five stress terms including the cohesive yield stress, Mohr-Coulomb shear, viscous shear stress, the turbulent shear stress, and the dispersive shear stress. The incorporation of such terms allows a good reproduction of lahars with high proportion of fine sediments where viscous forces dominates flow behavior. It also favors simulation of lahars where interaction of non-cohesive sediments develops dispersive stresses to the flow. Additionally, the 2001-lahar has a high proportion of fine sediments (silt+clay). It ranges between 6 and almost 17wt%. This fact make viscous forces very important in comparison to dispersive forces. Based on that, FLO2D allows reproduction of different flow behaviors accurately.

Pag 4586, Lines 20 to 25: The rheological parameters used in FLOD2D are empirical. They are limited for clay, silt and very fine sand (O'Brien and Julien, 1993). In the revised paper the authors pointed out that the solid material of the mixture are clasts within a matrix of sand, silt and clay (Line 25 in page 4585). If the authors are using the empirical data of O'Brien and Julien (1988), it would mean that they are neglecting the presence of clasts. A clear justification of this assumption is needed. Even the parameters used by the authors mentioned in line 2 page 4587 have the same particle size constrains.

Biggest clasts in debris and hyperconcentrated flows are transported by the flow by two different mechanisms: Buoyancy exerted by the fluid matrix or dispersive pressure. Additional dispersive pressure is generated by these larger clasts collisions, mainly at the front of the flow. As explained above, both stresses, viscous and dispersive, are taken into account by FLO2D during flow simulations. Considering these facts, our results do not neglect the presence of clasts in lahar behavior.

Page 4587, lines 7 to 11: A 30 m DEM flatters the topography in such a way that narrow gorges cannot be accurately represented. The result of the use of flattered topography representation is an artificially overspread flow prediction. It is advisable to choose the use of high resolution DEMs.

We agree that a 30m DEM resolution affects lahar distribution. We are preparing a new section of the paper where a sensitive analysis to DEM resolution is performed. The new simulations included are with 10m DEM resolution. This new simulations will also



allow the observation of the flow rheology sensitivity to the topography.

Page 4587, line 25: At high concentrations like the used by the authors (0.5), the interphase interactions cannot be neglected. Even more, is it possible that at such concentrations, the effect of particle-particle friction could become important. Particle-particle friction cannot be described by pure fluid models even with the use of empirically adjusted stress tensors, viscosities or "particle temperatures" (like in Dobran, 1991, or Bagnold, 1966, and others), Thus, as described in the paper, it is not clear the accuracy of the predictions, in special if the assumed concentration corresponds only to the head of the flow (Figure 4 in the revised paper) instead of its average.

New technologies used for lahar monitoring (Thouret et al., 2007; Vázquez et al., 2014) have allowed to observe different behaviors of lahars. One of the constant observations, especially in debris flows, like 2001-lahar, is the identification of different pulses inside flows. These pulses are divided in a high concentrated head, a transitional body, and a diluted tail. Lahar distribution considering constant sediment concentration through all the flow would conduce to errors when an accurate lahar zonation is needed. Besides, sediment concentration variation with distance leads to changes in dynamic behavior. High sediment content increase the importance of dispersive forces and lower concentrations could favor turbulence. High fine sediment content will suppress turbulence and the importance of viscous forces inside the flows. Assuming an average concentration would neglect these facts. FLO2D has the advantage of incorporating this longitudinal sediment concentration profile. Finally, the equations used, balance these changes in sediment concentration and in dominant stresses.

Page 4588, Section 2.2: The Manning approach is valid for pure fluid flows and floods. Thus, the validity of an approach that extrapolates the use of Manning coefficients originally estimated for inundation flood plains to lahars is not clear. A justification and verification of their use in high particle concentration flows is needed.

For hiperconcentrated and debris flows an input parameter named flow resistance parameter (K) is used. K value is computed from the Manning n-value by FLO2D. Particle interaction in flows with high particle concentration increases flow resistance. Flow resistance of the turbulent and dispersive shear stress is combined into an equivalent Manning n-value for the flow. Unpublished data by O'Brien and Julien relates the Manning n-value by an exponential function of sediment concentration:

ntd = n(0.0538)eˆ(6.0896Cv)

where ntd is flow resistance of the turbulent and dispersive shear stress, n is Manning n-value, Cv is sediment concetnration.

Page 4589, Section 2.4: the assumption of a constant Froude number means that there are no changes in velocities, topographic slopes, cross sections or hydraulic jumps along a natural path. Lahars flowing in natural channels show very complex patterns. In reality, there are several gorges, variations in terrain slopes in the path of a flow towards Santiago de Xalitzintla that should not be disposed of in a model. It is better for this paper if the authors justify the assumption of neglecting the complexity of the lahar flow profile, despite the topographic complexities of the flow path.

FLO2D does not assume a constant Froude number during simulation. Input value just includes a maximum Froude value, in this case was set to 0.9. FLO2D calculates Froude number during simulations but a limiting value is used to restrict the flow regime. A limiting Froude number helps to maintain model numerical stability, avoiding surging, and keeps velocity under reasonable values (no peaks). We have no evidence based on field data that indicates a supercritical flow. Flows in the supercritic regime develop sedimentary structures like cross-stratification and dunes. Besides supercritical flows are suppressed by high rates on sediment transport or high fine sediment content like in 2001-lahar (up to 16wt% of silt and clay). So we have no evidence of a critical or supercritical behavior for 2001-lahar. Based on the previous statements a limiting Froude number of 0.9 reflects an accurate flow regime of the real lahar.

Page 4590, Line 18: The total volume of the flow almost coincides with the volume



estimated by Miranda (2005).

We added sediment volume calculation of 2.4*105 m3 and the reference in the article.

Page 4590, Lines 19 and 20: If the amount of water is 2.5*10ËĘ5 m3, the sediment load 1,6*10ËĘ5 m3, and the total volume is 4.1*10ËĘ5 m3, the concentration of the flow corresponds to 0.39, instead of the 0.5 initially assumed in the model. This is a contradiction that needs to be reviewed by the authors.

This volume is calculated considering a longitudinal sediment concentration as is indicated in the initial hydrograph. So 0.39 corresponds with the average of the sediment concentration. An initial sediment concentration is estimated at 0.5 but the recessional parts of the flow are more diluted considering the data from the CENAPRED geophone signals.

Finally, according with Flo-2D Reference Manual-2009, the program was developed for hydraulic and hydrological modelling of flood routing, which is in agreement with this revision. Therefore, I suggest that in order for it to be published, the authors should constrain the flow concentration to low concentrations (less than 0.1 as common practice in hydraulic engineering) in order to avoid modelling out of the range of the limits of development of the Flo2D, and keeping the flow within the range of validity of the mathematical approach of Flo2D.

One of the tools of the FLO-2D code includes mud and sediments transport. In the above paragraphs we explained that FLO2D equations for hiperconcentrated flows and debris flows include several terms that describe their behavior (i.e. viscous and dispersive stresses). Results showed here and data from Nevado del Huila (Worni et al., 2012) proved FLO2D a successful tool for lahar modelling if they are properly calibrated. Based on that, FLO2D can be applied to delineate lahar inundation zones.

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