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THE 2005 LA CONCHITA LANDSLIDE, CALIFORNIA: PART 2 - MODELING

PARMESHWAR L. SHRESTHA(*), PHILIP J. SHALLER(**), MACAN DOROUDIAN(***),
David W. SYKORA(****) & DOUGLAS L. HAMILTON(*****)

(*) Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Vienna, Austria
(**) Grup d'Allaus (RISKNAT), Dept. Geodinàmica i Geofisica, Fac. de Geologia, Universitat de Barcelona, Spain
(***) Institute of Mountain Hazards and Environmnent, Chinese Academy of Sciences and Ministery of Water Ressources, Chengdu, China
(****) Mechanics College, Southwest Jiao Tong University, Chengdu, China
(*****) Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

ABSTRACT

This is Part II of a two-part causation analysis of the January 10, 2005 La Conchita landslide. This paper describes the development and application of a two-dimensional finite difference model (FLO-2D) model to simulate the debris flow over a fixed substrate. The model domain consisted of 25,614 square grid cells, each measuring 1.52 m on a side, and was developed using digitized pre- and post-event topographic maps. An inflow hydrograph, representing the volume of displaced material, was specified as a line input at the base of the headscarp area. The sediment concentration in the input hydrograph was varied (from zero to 0.7) over the 14-second duration of the hydrograph. Samples of debris collected from test pits in the debris flow provided a saturated density of 1,762 kg m-3. An initial estimate of the yield stress (stress) of the debris of 5,257 Pa was calculated using parameters derived from pre- and post-event topographic maps of the area. Because no independent means of calculation was available, the dynamic viscosity of the debris was adopted from values contained in the FLO-2D Users Manual. The Manning's bottom roughness coefficient for each grid cell was based on estimates of the surface and vegetation characteristics of the area. A series of simulations were performed to evaluate travel path variations for three differing wall and slope configurations present in the area between 1995 and 2005. Sensitivity analyses performed for each of the simulations by varying the yield stress (strength) and dynamic viscosity by ± 20% had a minor effect on the extent of debris flow runout. Sensitivity analyses were also performed by varying the debris volume by one-half and 1.5 times the original volume. Model results show a significant difference in debris runout as a result of these inputs. Two lobes of debris formed during the transport phase. The spatial distribution of the main lobe of the debris flow was similar to actual conditions in all of the simulations performed. The spatial distribution of the minor lobe, however, generally differed from that predicted by the analysis.

KEY WORDS: *Debris flow, Landslide, FLO-2D, Numerical modeling, La Conchita*

INTRODUCTION

Debris flows are very viscous hyperconcentrated sediment-laden flows that are non-homogenous, transient, and exhibit non-Newtonian behaviour. Properties such as density, viscosity and yield stress are functions of the sediment concentration in the sediment-water mixture. The high viscosity of debris flow results in slow velocities as compared to water flow on the same slope. The yield stress, which is a measure of the internal fluid resistance to flow, will affect both flow initiation and cessation. FLO-2D has the capability to simulate many of the complex behaviours of debris flow, and has been used to model debris flows at various sites (FLO-2D USERS MANUAL, 2007).

A two-dimensional finite difference model (FLO-

2D Version 2006.01) was utilized to simulate the La Conchita landslide as a debris flow. The FLO-2D model is a commercial software package that was developed originally in 1988 to conduct a Federal Emergency Management Agency (FEMA) flood insurance study (FIS) of an urbanized alluvial fan in Colorado (FLO-2D Users Manual, 2007). The model implements the Diffusive Hydrodynamic Model (DHM) of Hromadka & Yen (1987) to predict the spatial and temporal values of the attributes such as the flow depth and velocity at each grid element. The software package includes a grid developer system (GDS) that interpolates elevations from digital elevation model (DEM) data onto a square grid system; and a post-processor program (MAPPER) that depicts the model results as two- and three-dimensional graphical output and animation of results.

MODEL DESCRIPTION

FLO-2D is a volume conservation model that simulates overland flow in eight directions. The flow is controlled by topography and resistance to flow. The governing equations include the equations for conservation of fluid volume and the dynamic wave momentum equations. For completeness, the equations are summarized below. The reader is referred to the FLO-2D User Manual (2007) and Julien & O'Brien (1997) for a more detailed description of the model features and computational procedure.

Continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial h V_x}{\partial x}=i \tag{1}$$

Momentum equation:

$$S_{fx}=S_{ox}-\frac{\partial h}{\partial x}-\frac{V_x}{g}\frac{\partial V_x}{\partial x}-\frac{1}{g}\frac{\partial V_x}{\partial t} \tag{2}$$

where h = flow depth; V_x = depth-averaged velocity component; i = excess rainfall intensity; S_{fx} = friction slope based on Manning's equation; S_{ox} = bed slope; the other terms represent the pressure gradient, the convective acceleration, and local acceleration terms. The above equations are solved with a central, finite difference scheme. The computational procedure involves computation of discharge across each of the boundaries in the eight potential flow directions and begins with a linear estimate of the flow depth at the grid boundary. The flow velocity across the boundary is computed from the solution of the momentum equation. The time step is limited by the Courant-Friedrich-Lewy (CFL) criterion for numerical stability.

For debris flows, the total friction slope in equation (2) is modified as follows:

$$S_f=S_y+S_v+S_{td} \tag{3}$$

where S_f = total friction slope (S_{fx}); S_y = yield slope; S_v = viscous slope; and S_{td} = turbulent-dispersive slope. Equation (3) can be written in the following form:

$$S_f=\frac{\tau_y}{\gamma_m h}+\frac{K\eta V}{8\gamma_w h^2}+\frac{n_{td}^2 V^2}{h^{4/3}} \tag{4}$$

where τ_y = yield stress; γ_m = specific weight of the debris flow mixture = $\gamma_w + C_v(\gamma_s - \gamma_w)$; C_v = sediment concentration by volume; γs = specific weight of sediment; γw = specific weight of water; K = resistance parameter for laminar flow; η = dynamic viscosity; V = depth-averaged velocity; and n_{td} = flow resistance (i.e., equivalent Manning's n-value) of the turbulent and dispersive shear stress components.

The dynamic viscosity (η) and yield stress (τ_y) are functions of the sediment concentration, and are expressed as follows:

$$\eta=\alpha_1 e^{\beta_1 C_v} \tag{5}$$

$$\tau_y=\alpha_2 e^{\beta_2 C_v} \tag{6}$$

where α_1, α_2, β_1, and β_2 are empirical coefficients determined from laboratory experiments (O'Brien & Julien, 1988). The FLO-2D Users Manual (2007) provides a library of dynamic viscosity and yield stress that can be used if these values cannot be independently established.

The assumptions and limitations of the FLO-2D model include (FLO-2D Users Manual, 2007): (1) steady flow for the duration of the time step; (2) hydrostatic pressure distribution; (3) hydraulic roughness is based on steady, uniform flow; (4) grid elements are represented by single values for elevation, flow depth, and Manning's roughness; (5) channel elements are represented by uniform channel geometry and roughness; and (6) rapidly-varying flows are not simulated.

Fig. 1 - Topographic map of the 2005 La Conchita landslide showing elevation differences reported in 2002 (pre-event) and 2006 (post-event) topographic maps. Areas of net accumulation and net depletion are shown in red and blue, respectively. The gray shaded area near the toe of the deposit was modified by grading activities in the immediate aftermath of the event

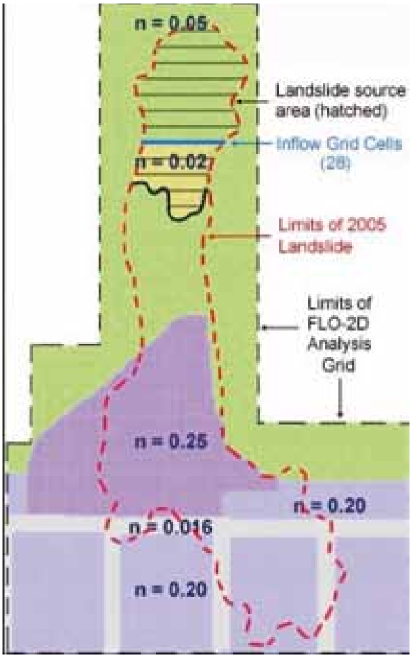

Fig. 2 - The limits of the FLO-2D model grid, with the location of the input grid cells, and the spatial distribution of the surface roughness (Manning's n) values

MODEL DEVELOPMENT

The key steps in the development of the FLO-2D model for the La Conchita event included: construction of a model grid using digital terrain data and supplementary elevation data for structures such as the temporary wall; development of an inflow hydrograph with corresponding volumetric sediment concentrations; delineation of surface roughness (Manning's n value) for grid elements; and estimation of the weight, dynamic viscosity and yield stress of the debris.

FLO-2D GRID

A model grid was created for the project site using the GDS program. Topographic elevations were based on the minimum topography resulting from the 2002 (pre-event) and 2006 (post-event) topographic maps (Fig. 1). This topography was selected to represent conditions experienced by the majority of the debris flow that occurred over the simulation period. The model domain consisted of 25,615 1.52 m square grid cells that cover the source and potential debris runout areas (Fig. 2). The high resolution unit grid cell size was selected to provide the level of detail required to resolve the key issues related to the study. Once the topographic elevations were rendered onto the grid elements, the height of the temporary wall was entered manually based on as-built drawings of the structure.

INFLOW HYDROGRAPH

The inflow hydrograph represents one of the key pieces of input data for model simulations. For flood events, the inflow hydrograph represents the discharge entering the model domain through the inflow grids. For simulation of debris flows, the volumetric sediment concentration is introduced as an additional input. The sediment concentration may be varied over the duration of the inflow hydrograph.

Four key elements were required to generate the inflow hydrograph for simulating the La Conchita event: 1) the volume of water and sediment; 2) the duration of the hydrograph; 3) the variation of sediment concentration as a function of the simulation period; and 4) the initial lateral distribution of debris emerging from the headscarp area.

The volume of debris input into the simulations

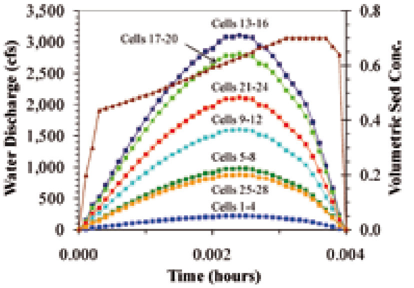

Fig. 3 - Inflow hydrograph and volumetric sediment concentration used for the FLO-2D simulations

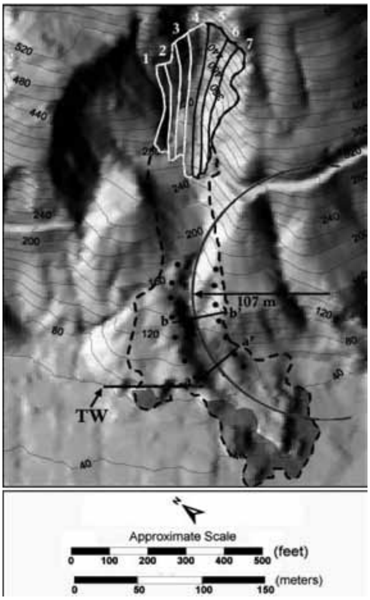

Fig. 4 - Shaded relief map of the 2005 La Conchita landslide. Black dots show approximate locations of main lobe lateral levees; 107 m radius circle indicates radius of curvature of levees. Transverse sections a-a' and b-b' show locations of profiles used for superposition calculations. Numbered area at top of page shows subdivision of headscarp area used for input hydrograph calculations. TW indicates location of temporary wall

was taken as the total volume of both the upper and lower depletion zones, since this represented the ultimate mass of debris moved in the event. This volume was added into the inflow hydrograph and input into the model along a series of 28 inflow grid cells distributed across the upper zone of depletion. The input grid cells were placed at a central location within the upper depletion zone to average out the effects created by the distributed nature of the debris in the source landslide.

Evidence from the television videotape indicates that the debris flow was moving as fast as ~10 m s^{-1} near the toe of the upper depletion area. Based on the surface topography in this area, it was assumed that the initial landslide accelerated from rest to ~10 m s^{-1}

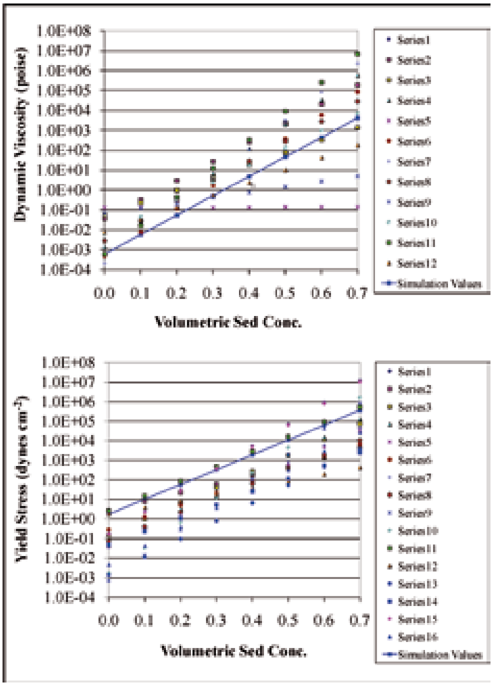

Fig. 5 - Dynamic viscosity (top) and yield stress (bottom) relationships adopted for the FLO-2D simulations plotted against literature values reported in the FLO-2D Users Manual (2007)

The dense, coherent appearance of the moving debris captured on video implies that the debris flow had a very high sediment concentration. Based on suggested parameters contained in the FLO-2D Users Manual (2007), the sediment concentration in the input hydrograph was therefore rapidly increased from a value of zero to 0.5, then ramped up more slowly to a peak value of 0.7 over the 14-second duration of the hydrograph as shown in Figure 3.

The upper zone of depletion exhibits a spoon-like shape, indicating that the debris did not exhibit a uniform lateral distribution at the initiation of the event. This geometric effect was modeled by subdividing the source area into seven parallel chutes (Fig. 4), with each of the 1-7 chutes supplying 2%, 8%, 14%, 26.5%, 24%, 18%, and 7.5% of the total debris volume, respectively. The input from each of the seven chutes was distributed between four grid cells. For example, as shown in Figure 3, Cells 1-4 represent the four grid cells for chute 1.

MATERIAL PROPERTIES

UNIT WEIGHT

Samples of debris collected from test pits in the western lobe of the debris flow were tested to assess the moisture content and dry density of this material. These results were used to estimate a saturated density of 1,762 kg m^{-3} for the debris at the time of the event. This value was used in all subsequent calculations.

DYNAMIC VISCOSITY

Because no independent means was available to estimate the dynamic viscosity of the debris, an intermediate value was adopted from values contained in the FLO-2D Users Manual (2007). The dynamic viscosity parameters α_1 and β_1 shown in equation (5) were assigned values of 0.000602 and 22.5, respectively. Figure 5 shows a comparison of the dynamic viscosity using the above α_1 and β_1 values with other published values from the FLO-2D Users Manual (2007).

YIELD STRESS

An initial estimate of the yield stress of the debris was calculated using parameters derived from the pre- and post-event topographic maps of the area by means of the following relationship (Johnson, 1970):

$$\tau = T_c \gamma_d \sin \delta \tag{7}$$

where τ = yield stress (Pa); T_c = critical thickness (m); γ_d = unit weight of debris (kg m^{-3}); and δ = slope angle (degrees).

The yield stress of the debris flow was calculated for each 1.52 m grid in the zone of accumulation using the calculated thickness of the debris (see Figure 1), the pre-event (2002) slope angle, and a unit weight of 1,762 kg m^{-3}. Because this approach produced unrealistically high stress values for debris captured in narrow channels, the median (rather than mean) value of the calculated yield stress of 5,257 Pa was adopted. This stress was taken to be equivalent to the yield stress of the debris at a volume concentration of solids of 0.59, considered representative of the average debris at the time of emplacement. The yield stress parameters α_2 and β_2 shown in equation (6) were assigned values of 1.75 and 17.475, respectively. Figure 5 shows a comparison of the yield stress using the above α2 and β2 values with published values from the FLO-2D Users Manual (2007).

SURFACE ROUGHNESS

Examination of the 2002 aerial photography for land cover indicated that a variety of surface roughness values (Manning's n) were appropriate for input to the FLO-2D simulations. As shown on Fig. 2, roughness values ranging from 0.016 to 0.25 were used in the analysis. Low surface roughness values were used for streets in the development (0.016) and to model the portion of the headscarp area located downslope from the inflow grid cells (0.02). High roughness values were added for the residential area (0.2) and for the area of dense chaparral located just upslope (0.25). Intermediate values (0.05) were used for the remainder of the undeveloped slope area, which supported a moderate vegetation cover.

MODELING OF TEMPORARY WALL

Three cases were considered to model the potential effects of the temporary wall on the debris flow. The first was to run the simulation with the wall as it existed prior to the failure (termed "With Wall"). Because there is no mechanism within FLO-2D to simulate the destruction of a structure, this simulation case assumes that the wall exhibits infinite stress. In the second case, the FLO-2D grid was manually modified to remove the topographic effect of the wall in areas where it was observed to have been overtopped and/or breached by the debris flow (termed "Breached Wall"). Elsewhere the wall continued to be treated as if it exhibited infinite stress. In the third case, the FLO-2D grid was modified to remove the temporary wall entirely and restore the topography present before the construction of the wall (termed "Without Wall"). A 1996 topographic map was utilized to establish the topography of the area to the earlier, pre-wall condition.

DISCUSSION OF MODEL RESULTS

GENERAL OBSERVATIONS

Figure 6 presents the results of the base-line FLO-2D simulations for the three cases. The three simulations consistently predict the formation of a large main (eastern) lobe, a smaller, more irregular minor (western) lobe, and a finger of material filling the pre-existing drainage channel in the mid-slope area.

MAIN (EASTERN) LOBE

The three base-line simulations predict very similar behavior for the main (eastern) lobe of the debris.

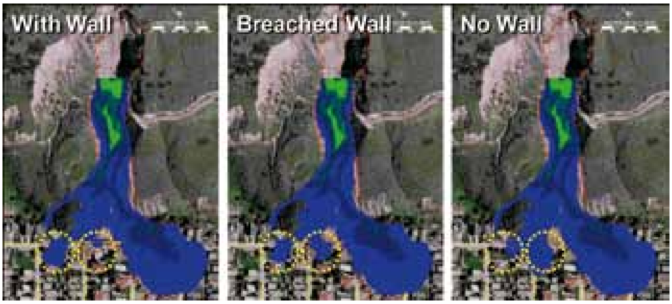

Fig. 6 - Results of FLO-2D simulationof debris flow depths (shaded colors) for the "With Wall," "Breached Wall," and "No Wall" conditions

The simulations consistently show that the modeled wall condition exercised a minimal effect upon the distribution of the main lobe of debris. The visible effects of the wall were limited to the extreme western margin of the main lobe near Vista del Rincon Avenue.

All three simulations consistently predict debris in the main lobe spreading one row of houses farther to the east than actually occurred. At least four factors likely contributed to the over prediction of debris inundation in this area: (i) incorporation of the full depletion volume in the inflow hydrograph, thereby raising the average potential energy of the debris in the simulation relative to the actual conditions; (ii) using the scoured topography in the FLO-2D input grid, resulting in a less-restrained travel path for the debris than under actual conditions, resulting in less material overflowing into the minor lobe; (iii) conceptual difficulties in modeling the interaction of the debris flow with houses and other large obstacles in the community; and (iv) simulation of the final stages of movement.

With respect to the final point, all the FLO-2D simulations predicted very slow movement of the debris upon reaching the vicinity of Santa Barbara Avenue. Such slow movement may be unrealistic because the elevated pore pressures required to keep the debris in a fluid state are maintained by the agitation of the moving debris, which is in turn a function of its velocity. As the velocity and agitation of the debris diminishes, the pore pressures will diminish in kind, ultimately falling below that needed to keep the debris in a fluid condition. A "critical velocity" necessary to maintain fluidity was not, however, determined in this analysis.

MINOR (WESTERN) LOBE

The most significant differences among the FLO-2D simulations and between the simulations and the actual behavior of the debris flow occur in the area of the minor (western) lobe. At the western end of the temporary wall (left-hand circled area on Fig. 6), the "With Wall" and "Breached Wall" simulations show a lobe of debris spilling out from behind the wall that did not occur in the actual event. The model results appear to be related to the remobilization of material that accumulates behind the wall. In the actual event, the debris that accumulated behind the wall arrived in pulses and came to rest. Evidently, this allowed the elevated pore pressures in the debris to dissipate, increasing its stress and viscosity such that it did not remobilize as predicted in the simulations.

The FLO-2D simulations also differ from each other and from the actual behavior of the debris flow near the center of the temporary wall (right-hand circled area on Fig. 6). The small lobe associated with the "With Wall" simulation is consistent with the anticipated behavior of the debris where the wall was present and indestructible; only a small amount of debris spills over the wall at a local low spot.

In the "Breached Wall" simulation, debris flows through the breach, but extends somewhat farther than it did in the actual event. Again, this can probably be ascribed to the pulse-like arrival of debris to the wall in the actual event and the interaction between the wall and the debris. Although the wall was breached by the impacting debris, the movement of the material would have slowed sufficiently to modify its rheology and diminish its mobility.

In the "Without Wall" simulation, the debris in the minor lobe is predicted to travel considerably farther than occurred in the other simulations and in the actual event. This simulated behavior appears to reasonably approximate the distribution of debris that would have occurred had the event occurred prior to 2000 (i.e., absent the temporary wall and the removal of debris from Vista del Rincon Avenue). This result suggests that the installation of the wall and the removal of debris from the roadway, though not intended to mitigate landslide hazards, protected one or two houses from the impact of debris that would likely have occurred in the ab-

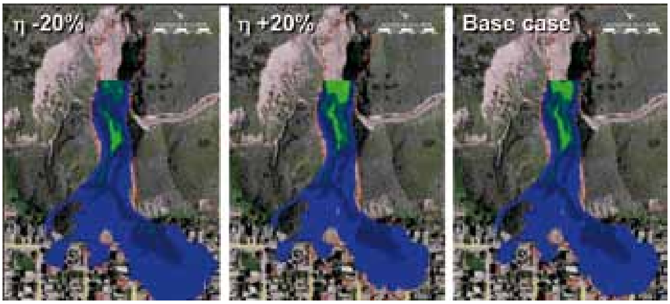

Fig. 7 - Results of sensitivity analyses of the dynamic viscosity values of ± 20% of the original for the "Breached Wall" condition. The base case is provided for comparison

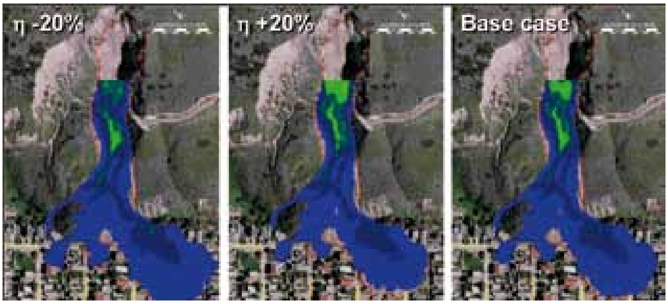

Fig. 8 - Results of sensitivity analyses of the yield stress values of ± 20% of the original for the "Breached Wall" condition. The base case is provided for comparison

sence of this work.

Finally, the simulations all predict the occurrence of a small clear area between the main and minor lobes that was in fact mantled by the debris flow. This difference between actual and predicted behavior was probably related to the incorporation of the lower depletion zone into the FLO-2D simulation grid. In the actual event, early arriving material in the main lobe was at a higher elevation and, as a result, could more readily spill over into this area due to superelevation as the debris flow curved to the left.

CHANNEL FILL

All of the FLO-2D simulations predict a finger of debris extending down the incised channel in the mid-slope area. Review of the simulation output indicates that this is early, water-rich material mobilized in the early stages of the landslide. Later-arriving material exhibiting a higher sediment concentration subsequently clogs the steep-sided channel, resulting in avulsion of debris from the channel. This behavior is generally consistent with field observations of the channel downstream from the portion choked by the debris flow.

SENSITIVITY ANALYSES

A sensitivity analysis was conducted for each of the FLO-2D simulations, in which the yield stress and dynamic viscosity were independently varied by ± 20%. These variations had a minor effect on the behavior of the debris in the simulations, with changes to the yield stress having the larger effect. A 20% reduction in the yield stress resulted in a maximum of 12 m of additional runout of the main lobe compared to the baseline case, whereas a 20% increase in stress reduced the runout by up to about 9 m. By comparison, variation of the dynamic viscosity by ± 20% resulted in a change of about ± 3 m in the runout distance. Figure 7 shows the model results of debris flow depth for dynamic viscosity ± 20% for the “Breached Wall” condition. A plot of the base case is provided for comparison. Figure 8 shows the model results of debris flow depth for yield stress ± 20% for the “Breached Wall” condition. Again, a plot of the base case is provided for comparison.

Sensitivity analyses were also carried out for the “No Wall” condition for debris input volumes equal to one-half and 1.5 times the original input. Figure 9 shows a plot of the model results of this sensitivity analyses. When the input is one-half of the original volume, the debris runout does not approach the actual limits; whereas if the input is 1.5 times the original volume, the debris runout extends beyond the actual limits.

CONCLUSIONS

The La Conchita landslide was simulated as a debris flow using the FLO-2D model. Of interest was to assess the mechanics of the debris flow and the role, if any, played by a temporary wall in altering the path taken by the debris flow as it traversed the community.

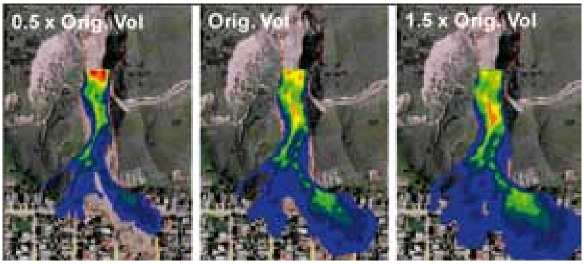

Fig. 9 - Results of sensitivity analyses of the debris input volume as one-half and 1.5 times the original debris volume for the "No Wall" condition. The base case (original volume) result is provided for comparison

To the best of our knowledge, this investigation is the most detailed application of the FLO-2D model for analysis of a debris flow with a high grid resolution of 1.52 m. The model simulations offered a good approximation of the actual behavior of the debris flow. Based on the modeling results, the destructiveness of the event can be attributed to the large volume of debris mobilized, the geometry of the flow path, and the yield stress and viscosity of the flowing debris. Differences between the model and actual behavior principally resulted from the fixed character of the terrain over which the flow was routed, the behavior of the debris at low velocities and the remobilization of stopped material. The different model runs provided useful insights into the behavior of the debris flow as it descended the hillside, as well as its interaction with the temporary retaining wall. Model response to variation of the dynamic viscosity and yield stress parameters by ± 20 % did not significantly change the model results. Varying the inflow debris volume by on-half and 1.5 times the original debris volume caused large differences in debris runout.

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