Simulations of Potential Runout and Deposition of the Ferguson Rockslide, Merced River Canyon, California

By Roger P. Denlinger

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SIMULATIONS OF POTENTIAL RUNOUT AND DEPOSITION OF THE

FERGUSON ROCKSLIDE

MERCED RIVER CANYON, CALIFORNIA

By

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INTRODUCTION

An active rockslide in Merced River Canyon was first noticed on April 29, 2006 when a few rocks rolled onto Highway 140 between mileposts 103 and 104, compromising traffic on this highway and signaling the onset of renewed activity of the Ferguson rockslide. State highway 140 is one of the main entrances toYosemite National Park and is the primary road for large commercial trucks access into the park from the west. Continued rockslide activity during 2006 built a large talus cone that covered the highway and encroached into the Merced River below it. Observations by the US Forest Service (USFS), the California Department of Transportation (CALTRANS), and the U.S. Geological Survey (USGS) confirm that the rockslide remained active through 2006 and represents a potential threat to traffic along the rerouted highway as well as to recreational users of the Merced River in the runout path below the rockslide. Delineation of the hazards posed by the Ferguson rockslide is a necessary prerequisite to mitigating them.

Field observations of the rockslide, shown in the photo of Figure 1, have constrained the geometry and structure of the slide mass (Beck, 2006; Gallegos and DeGraff, 2006). Based on initial estimates by geologists from USFS, CALTRANS and the USGS, the rockslide, active in 2006 and 2007, has an area of approximately 40,000 square meters and a volume of approximately 800,000 cubic meters. Structural mapping suggests that the motion of the slide is translational along a planar bed, and that differential motion of the slide from the toe to the headwall has resulted in formation of large tension cracks that transect the slide across the slope (Beck, 2006). These indications of persistent movement were confirmed during 2006 and 2007 by GPS measurements made by the USGS at three points on the rockslide (Rick LaHusen, USGS, written communication). The larger of these cracks divide the slide into regions that moved at different rates in 2006, with the toe of the rockslide moving five to ten times faster than the middle portion or headwall part of the slide. Downslope of the main rockslide mass, a talus slope consistin of angular blocks ranging in size from 0.1 to greater than 10 meters (Gallegos and DeGraff, 2006), buries Highway 140. Both the main rockslide and the talus consist of angular blocks ranging in size from 0.1 to more than 10 meters and are composed of highly fractured phyllite, slate, and chert from the Phyllite and Chert of Hite Cove (Bateman and Krauskopf, 1987).

The purpose of this report is to assess the hazard posed by the Ferguson rockslide by simulating the runout and deposition of a portion of the slide if rapid failure occurs. As discussed by Gallegos and DeGraf (2006), a runout analysis is needed to delineate slide hazards. The report is restricted to calculations of potential runout and does not address the likelihood of rapid failure. Based on discussions with Allan Gallegos (USFS), two end-member initial slide volumes were chosen: (1) the toe of the slide along boundaries defined by Tim Beck (CALTRANS) in (Beck, 2006), and (2) the entire sliding rock mass, again along boundaries defined by Tim Beck. The simulated runout of these volumes during rapid failure uses granular flow mechanics developed by Iverson (1997) and the model developed by Denliner and Iverson, (2004). This model has been thoroughly tested against experimental data and provides plausible, defensible results.

METHODS

The flow of blocky, rock debris down a slope is a form of dry granular flow and is expected to behave like granular flows despite large variations in block sizes such as those found in the Ferguson rockslide. Conservation of mass within flowing rock debris in cases where the square root of the planimetric area is larger than the average depth may be written

$$\int_A \left[\frac{\partial h}{\partial t} + \nabla \cdot h\mathbf{u} \right] dA = 0 \tag{1.1}$$

with conservation of momentum given by

$$\int_A \left[\frac{\partial (h\mathbf{u})}{\partial t} + \nabla \cdot h\mathbf{uu} \right] dA = -\frac{1}{\rho} \int_V \left(\nabla \cdot \boldsymbol{\tau} \right) dV + \int_A h\mathbf{g}\, dA \tag{1.2}$$

Here ρ is bulk density, $\mathbf{u}$ is horizontal velocity, V is incremental volume, $\boldsymbol{\tau}$ is the stress tensor, and **g** is an enhanced gravitational acceleration vector that contains variations in vertical momentum as well as gravity, *h* is the thickness of the flow measured vertically, and A is an incremental area in map view, such that $V = A \cdot h$. These equations are derived by integrating over the depth of the flow, with special care taken to approximate stresses and velocities in three dimensions. Stresses in dry granular flow, such as a rockslide, are derived from friction between the fragments or blocks making up the flow and from friction between the fragments and the bed as the flow slides along its bed. As shown in equation (1.2) the bulk density ρ normalizes the forces per unit volume resulting from gradients in stress $\nabla\boldsymbol{\tau}$: the heavier the slide material, the less a role stresses (such as those resulting from friction) play in determining flow behavior. The entire left hand side of equation (1.2) and the gravity term on the right are the same for any shallow flow and these equations can be used to model floods, avalanches, tsunamis, and debris flows. Mechanically, what distinguishes between these different types of flow is the stress term on the right hand side, which incorporates the physics embodied by the type of flow, whether it is rock debris, water, ice, or some mixture. At the onset of flow

($\mathbf{u}$ =0), the gravity term on the right hand side is the driving force, and is resisted by the bed friction embedded in $\boldsymbol{\tau}$. For the Ferguson rockslide, any imbalance of initial forces represented by the right hand side of equation (1.2) when the rockslide begins to move has a profound effect on the initial acceleration, the maximum velocity achieved, and therefore the final runout of the slide debris.

These equations are derived and numerically solved in Denlinger and Iverson, (2004), where their method is rigorously tested against experimental data. Solutions for granular flow over three-dimensional terrain were compared with sand flows over scale models of topography. Unpublished comparisons have also been done with flows of gravel down an 80 m long, 2m wide flume built into a steep hillside in Oregon (Iverson et al., 1992), establishing that these flows have mechanics similar to sand. The successful simulation of sand and gravel flows lends confidence to the applicability of this model for simulation of the Ferguson rockslide.

APPLICATION TO THE FERGUSON ROCKSLIDE

The purpose of this study is to delineate the hazards posed by the potential rapid release of all or part of the Ferguson rockslide. The flow and deposition of rock debris is modeled using the conservation equations above and the numerical method of Denlinger and Iverson (2004), applied to the three dimensional grid shown in Figure 2. The topography was defined using LIDAR data obtained by CALTRANS for the Ferguson rockslide. The data were gridded in an old stateplane coordinate system, in meters, in Zone 3326 (labeled ‘zone 3’ on the LIDAR data sheet), using the NAD83 datum to create a terrain model. Using the grid formed from these data I defined the boundaries of two potential slide volumes: one of the entire slide and one of a portion of the slide at the toe. Both volumes are based on the map of Beck (2006).

Two initial volumes were chosen based upon discussions with Allan Gallegos (USFS), and are shown in Figures 2, 3, and 4. Figures 2 and 3 show the full slide mass on the discretized terrain model, both in perspective view with no vertical exaggeration (Figure 2) and in a map view (Figure 3). Figure 4 shows the perspective view of the portion of the slide (the toe) used for the second initial volume. This initial toe volume is small enough to be shown together with map views of the final deposits obtained for this toe failure. Both volumes are presumed to slide on a plane close to the one estimated by Tim Beck (CALTRANS), shown in map view in Figure 5, which is sloping at an angle of 31 degrees towards the Merced River. If the basal sliding plane angle is greater than the bed friction angle, then their difference determines the initial acceleration of the rockslide and consequently, its runout. If the basal sliding plane angle is less than the bed friction angle, then the difference between the slope of the ground surface and the bed friction angle determine whether the rock debris will fail internally, forming a shear plane above the bed at some steeper angle than the basal sliding plane.

I estimated the sliding friction for two endmember scenarios: one based on the angle of repose of the talus slope below the rock mass, and the other estimate based on a minimum value of sliding friction to create two end-member scenarios. The existing talus slope, built by shedding rock debris, is at an angle of repose of 38 degrees. Thus one end member assumes that the friction angle between rock fragments within a potential flow, or the angle of internal friction, is 38 degrees, and that the friction angle between the rock fragments in the slide and the basal sliding plane, or bed friction angle, is also 38 degrees. The other set of conditions uses an internal friction angle of 38 degrees and a bed friction angle of 25 degrees. The lower effective friction angle represents either reduction of normal loads from pore pressure buildup in the slide from rainfall or snowmelt infiltration, or from work softening in the rock debris along the basal slide plane during creep of the rock mass. The latter condition requires the rockslide to be active. In all cases, the rockslide will fail only where the surface slope or the basal sliding plane exceeds the angle of bed friction, and the resisting force of friction is reduced by pore fluid pressure along this plane. The two end members chosen here represent very different initial conditions and thereby cause large differences in initial acceleration of a potential rock mass, with significant consequences for the final distribution of the rock debris.

The bulk density and pore-fluid pressure from water at the base of the flow complete the assigned parameters for the flow of debris. Bulk density was estimated from the phyllite and slate composition of the debris to be about 2000 kg/m^3, and is listed in Table 1. Fluid pressure was assumed to be zero everywhere except in the Merced River channel, where it was assumed to be either zero or the pressure given by a layer of water 1 meter deep. Potential fluid pressure at the base of the rockslide mass is implicitly incorporated in the scenarios using a low bed friction of 25 degrees.

Table 1. Properties of Ferguson Rockslide used in model

Bulk composition	Pervasively fractured phyllite, slate
Internal friction angle	38^o
Bed friction angles	25^o, 38^o
Bulk density	2000 kg/m^3
Pore fluid pressure head	1 meter in Merced River

RESULTS

The results of the simulations indicate that the final distribution of rock debris is controlled primarily by the initial conditions at failure, particularly the initial volume, slope of the failure surface, and the value of bed friction along the basal slide plane. The results for these conditions are summarized in Table 2, including the times for all of the debris to come to rest and the depth of burial along the Merced River channel. Results using water depths up to 1 meter in the Merced River channel had little affect on the final distribution of slide debris and are not shown.

The simulations for the toe volume in Figures 6 and 7 illustrate the pronounced difference in depositional pattern produced by the two end-member values chosen for bed friction. In Figure 6, given a conservative estimate of bed friction equivalent to the observed angle of repose for the debris, the rockslide forms a steep talus fan that encroaches on the river channel but does not cross it. In contrast, Figure 7 shows that the small volume will nonetheless fill the Merced River channel with debris to a maximum depth of 22 meters if bed friction is low enough at failure for all of the toe debris to be shed rapidly from the slope.

The simulations for release of the full 780,000 m^3 volume encompassing the 2006 active slide, shown in Figures 8 and 9, repeat this pattern. If the bed friction at failure is approximated by the observed angle of repose (38^o), then the rockslide slowly fails and forms a steep talus cone extending back up to the position of the original slide debris. The final deposit extends about 2/3 of the way across the channel and part of the debris does not move from its initial position. In contrast, if bed friction at failure is low enough for rapid acceleration to occur, then all of the debris rapidly accelerates and fills the river valley to a minimum depth of 10 m and a maximum depth of 33 meters (Figure 9). These two contrasting results are shown in perspective views in Figures 10 and 11, and in Figure 12, which compares the deposit thicknesses in cross section for both a toe release and the release of the entire slide mass active in 2006.

Thus the final results depend critically on conditions along the sliding basal plane of the rockslide as it is released. The angle of repose of the talus makes it unlikely that friction will be higher than 38^o. At the lower end of the range of friction values investigated, mechanisms that reduce the influence of rock friction, such as a buildup of pore pressure along the base of the slide, are required to produce a resistance equivalent to a bed friction below 30^o. A conservative estimate for a number of processes, including pore pressure buildup, gives the five degree reduction I used. Larger reductions, particularly at or near the onset of failure, will have correspondingly larger initial accelerations and thus larger consequences on the final distribution of slide debris.

Table 2. Results of Ferguson Rockslide Simulations

Figure Number	Slide Volume (m^3)	Bed Friction Angle	Internal Friction Angle	Range of Dam Thicknesses (m)	Percent Channel Obstruction	Time to final deposition (s)
6	128,000	38	38	0 – 15	30	320
7	128,000	25	38	3 – 22	100	80
8	780,000	38	38	0 – 22	66	515
9	780,000	25	38	10 – 33	100	275
10	780,000	38	38	0 – 22	66	515
11	780,000	25	38	10 – 33	100	275

CONCLUSIONS

If the Ferguson rockslide, which blocks Highway 140 between mileposts 103 and 104 in Merced River Canyon in 2006, fails rapidly, then the resulting runout of debris will either completely or partially dam the Merced River. Two possible failure volumes derived from the boundaries of the active 2006 rockslide, one of the toe (128,000 m^3) and one of the full slide (780,000 m^3), represent two drastically different volumes that may be mobilized by rapid failure. With either volume, the extent of the final deposition depends primarily upon the conditions of slip along the base of the sliding rock debris (or bed) at the time of failure. If bed friction is about 25 degrees, then either volume will dam the river to heights of between 3 and 33 meters. If, on the other hand, bed friction is comparable to the angle of repose of the talus fans already formed, then both volumes build steep talus cones that only partially dam the river. In the latter scenario the river will flow around the final deposit.

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1. Photo, looking northwest, of the east-facing Ferguson Rockslide, Merced River, with the talus covering Highway 140 (Mark Reid, US Geological Survey).

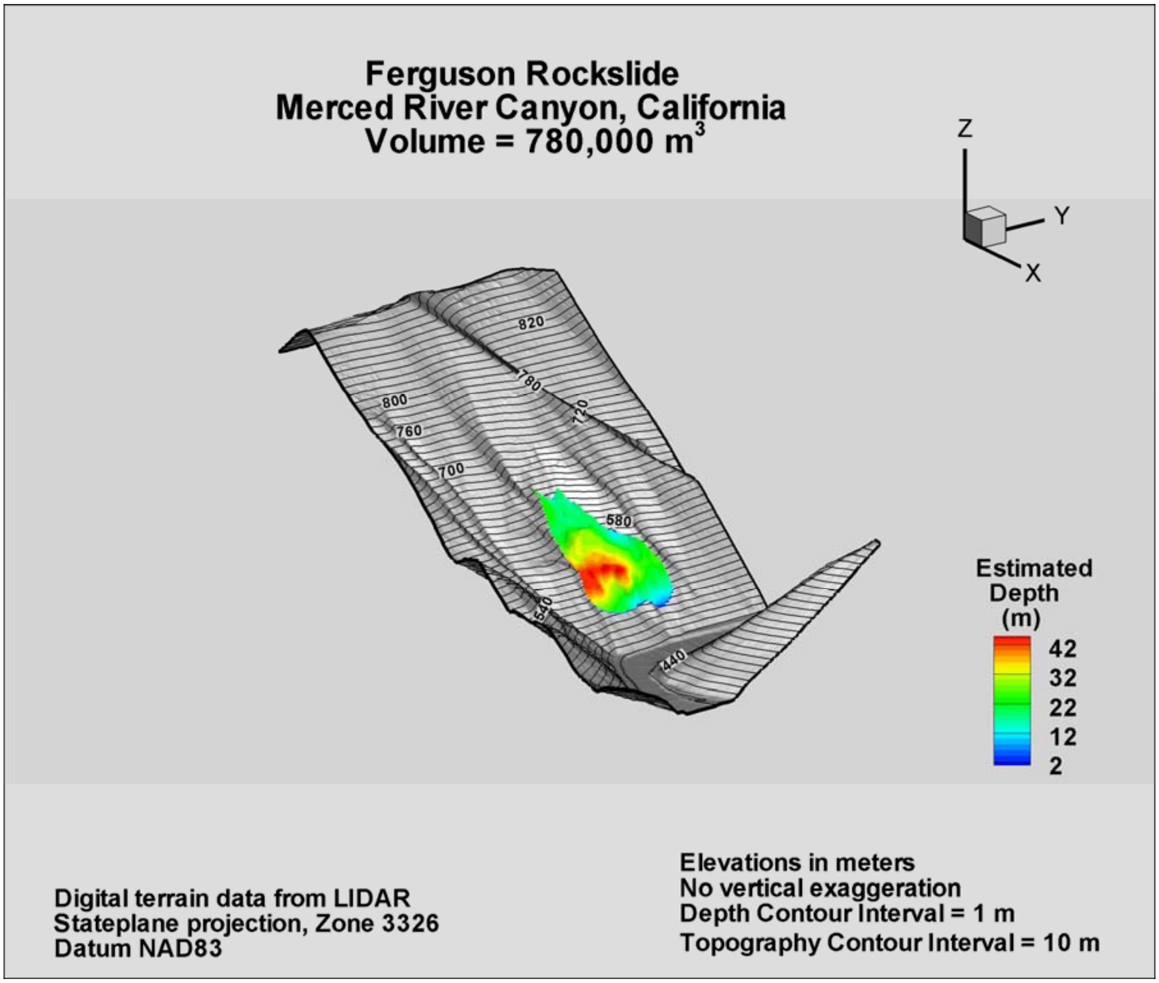

Figure 2. Model of terrain with location and depth (distance from surface to basal slide plane) of the main mass of the Ferguson rockslide estimated from geologic mapping. View looking NW as in Figure 1.

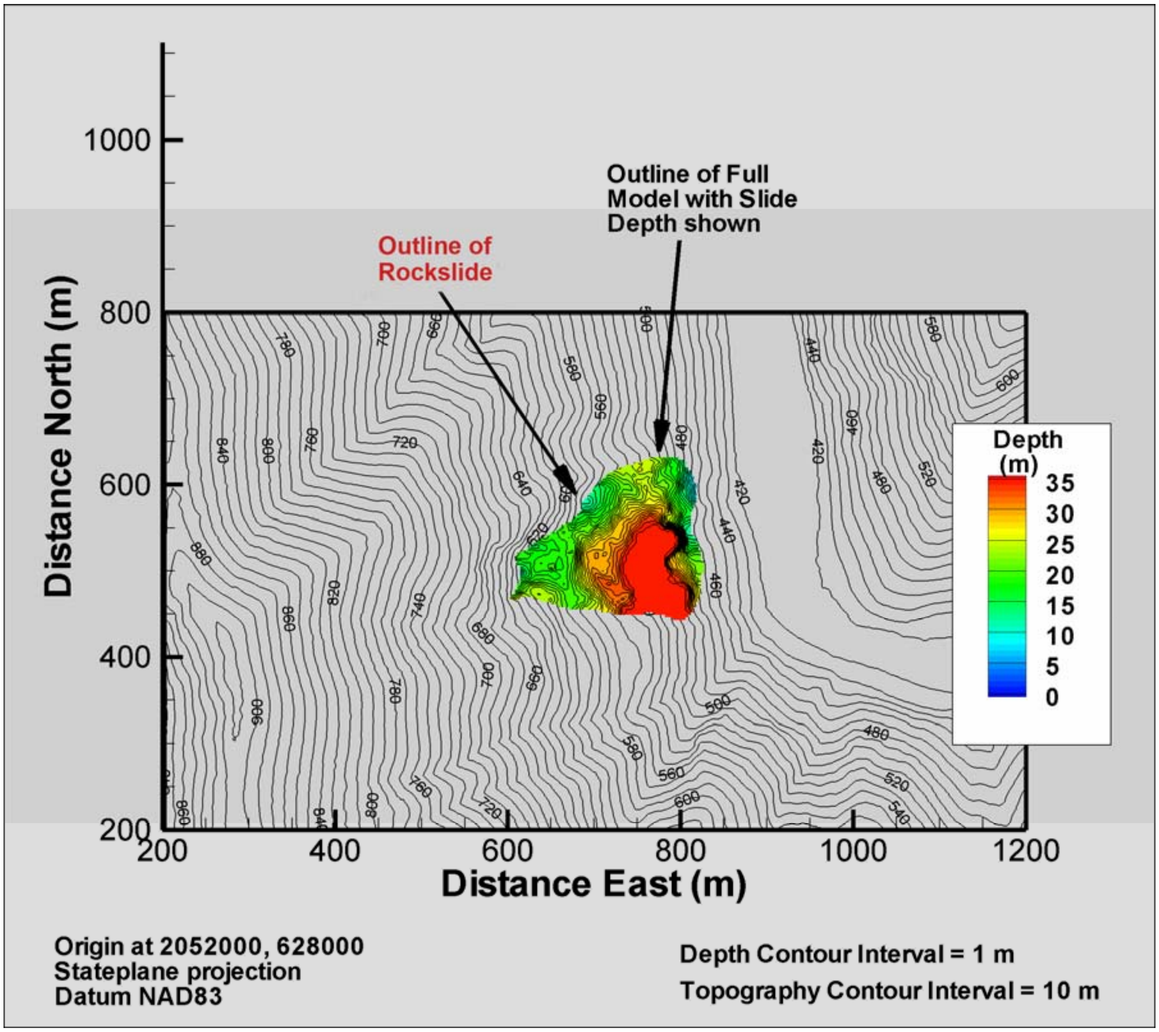

Figure 3. Map view of slide thickness on contoured map of terrain model, where the slide model coincides with the mapped outline of the active 2006 rockslide. Slide thickness is determined by subtracting surface elevation from the elevation of the basal slide plane shown in figure 5.

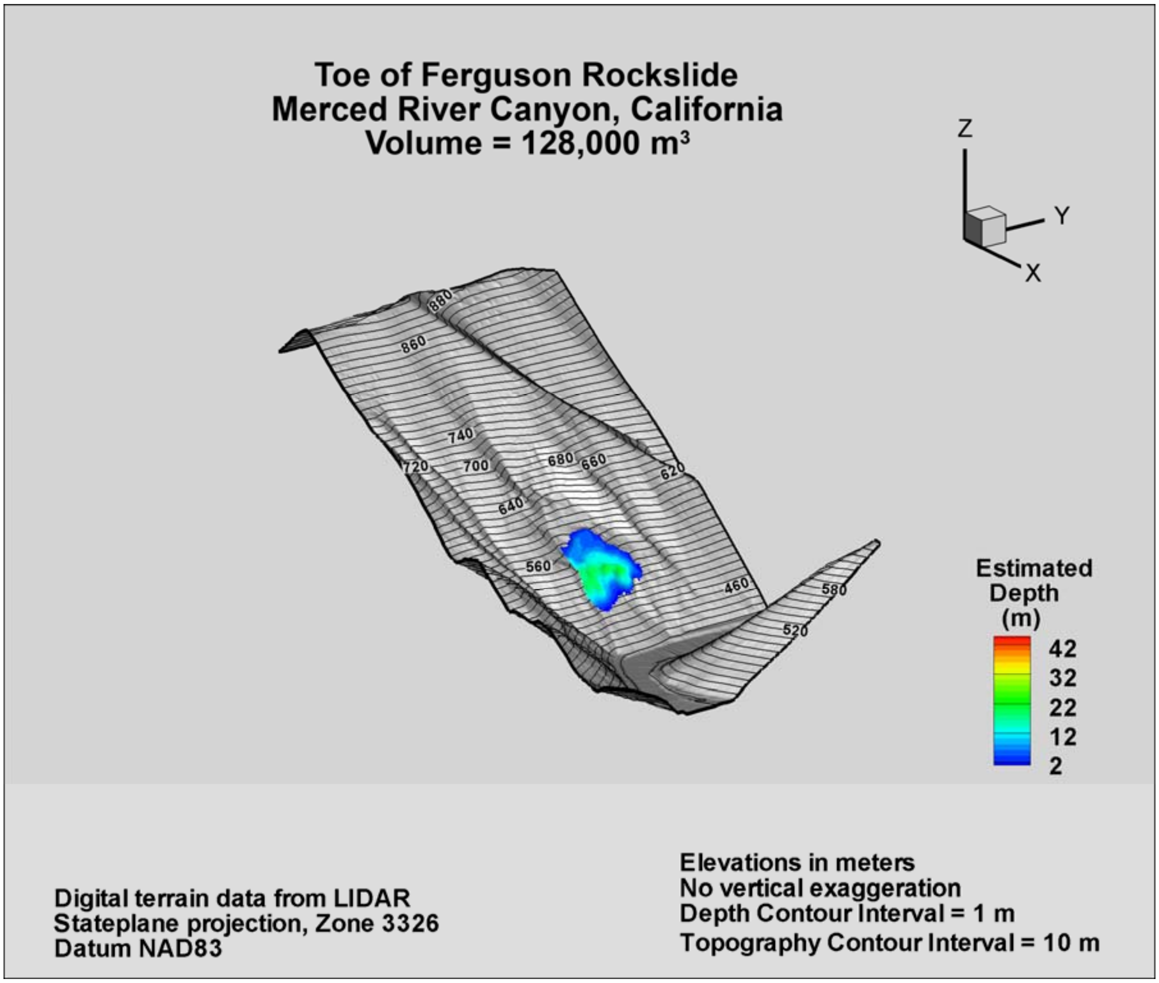

Figure 4. Model of terrain, showing toe portion of Ferguson rockslide used for second scenario.

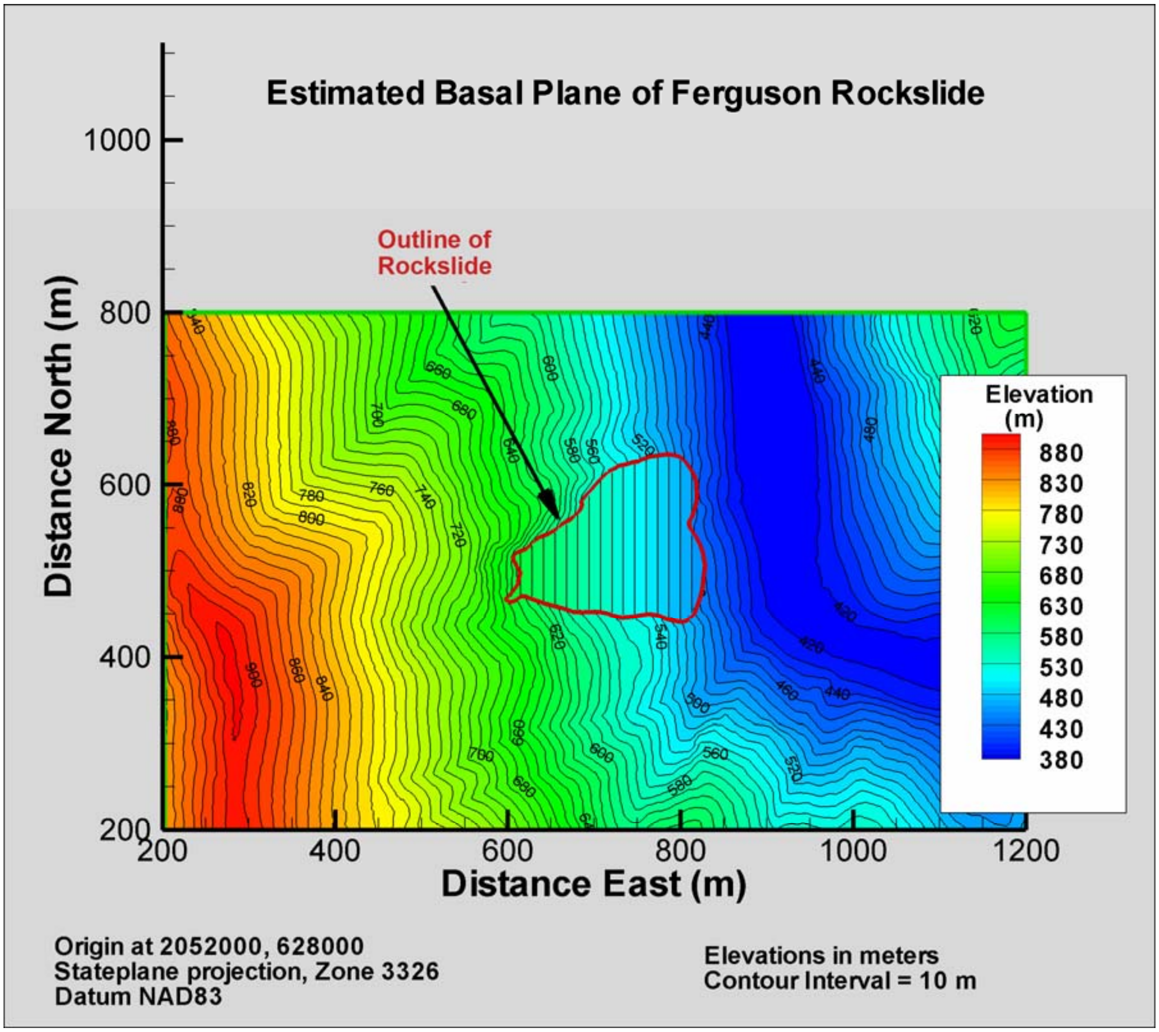

Figure 5. Outline of basal sliding plane elevations for the Ferguson Rockslide. The boundaries and the basal slide plane are estimated from structural mapping of the rockslide (Beck, 2006).

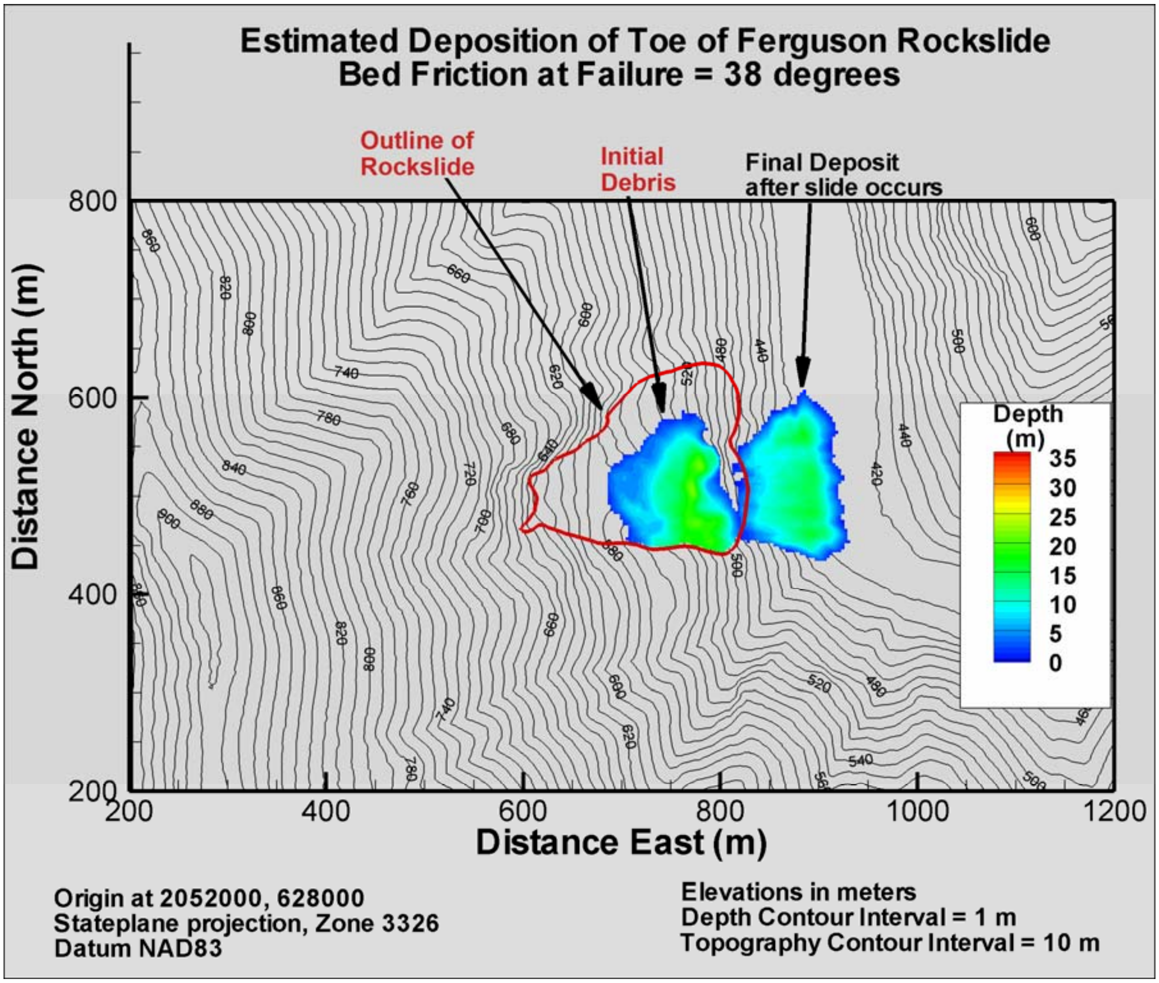

Figure 6. Simulated final deposit for failure of toe volume (128,000 cubic meters) for a bed friction angle of 38 degrees.

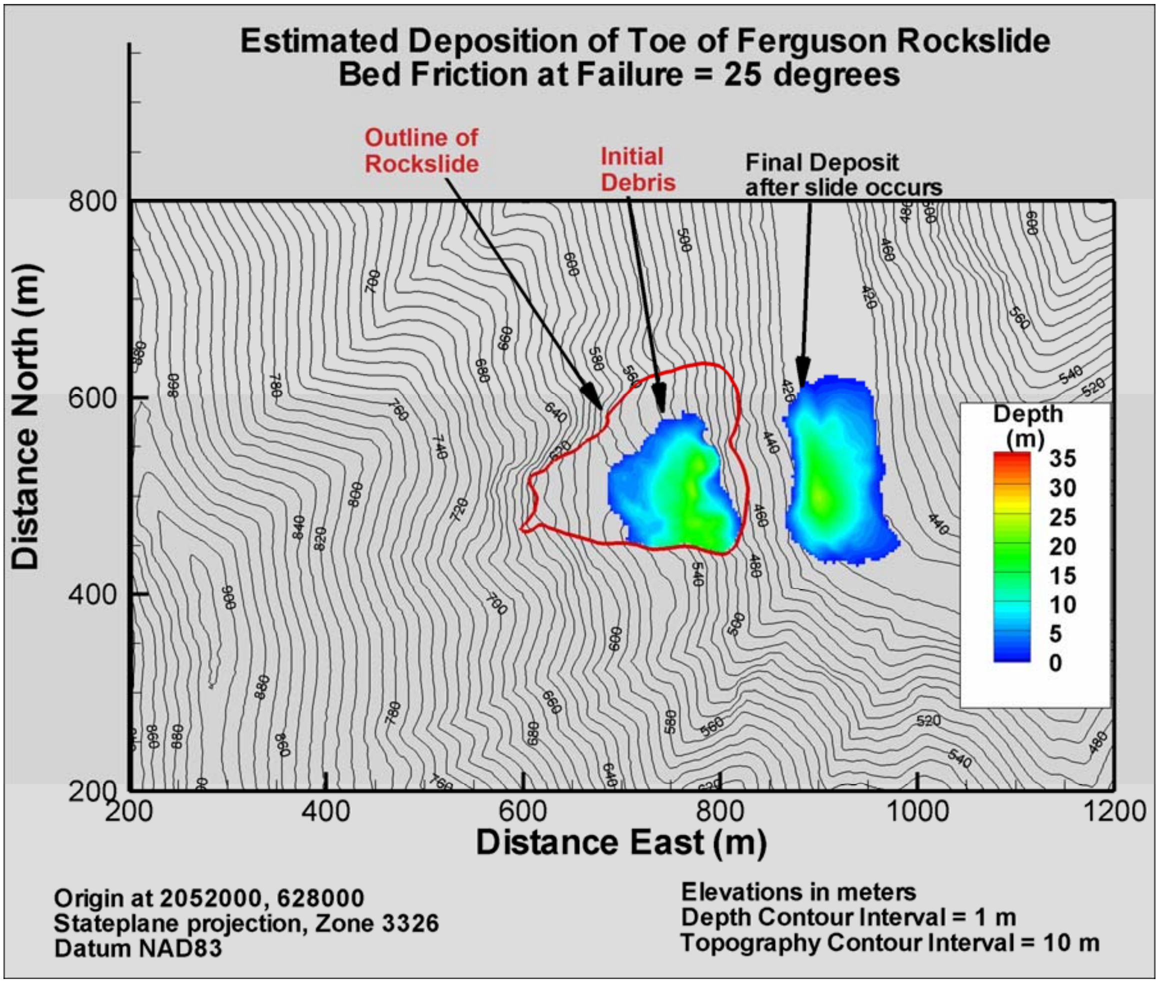

Figure 7. Simulated final deposit for failure of toe volume (128,000 cubic meters) for a bed friction angle of 25 degrees.

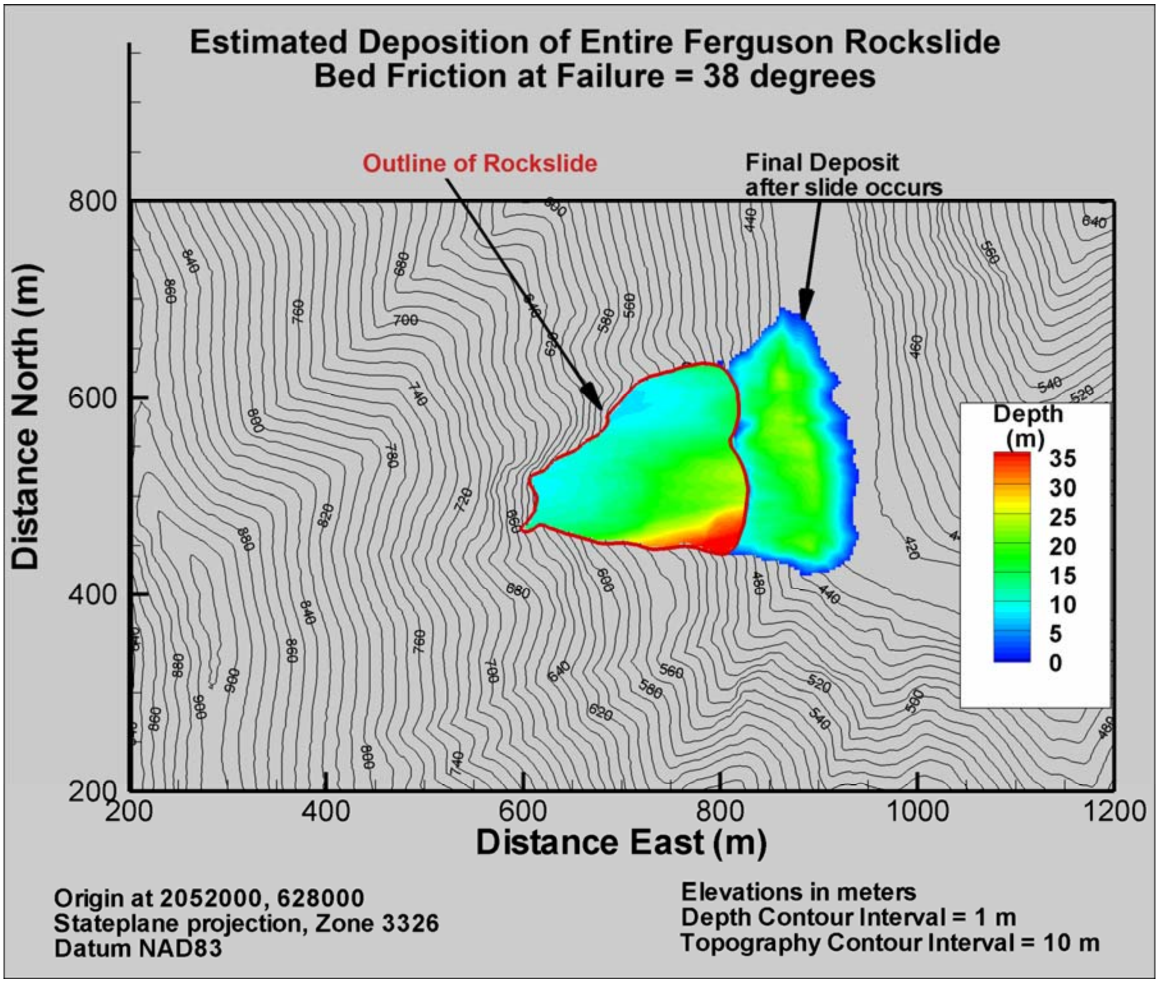

Figure 8. Simulated final deposit of entire Ferguson rockslide (780,000 cubic meters) for a bed friction angle of 38 degrees.

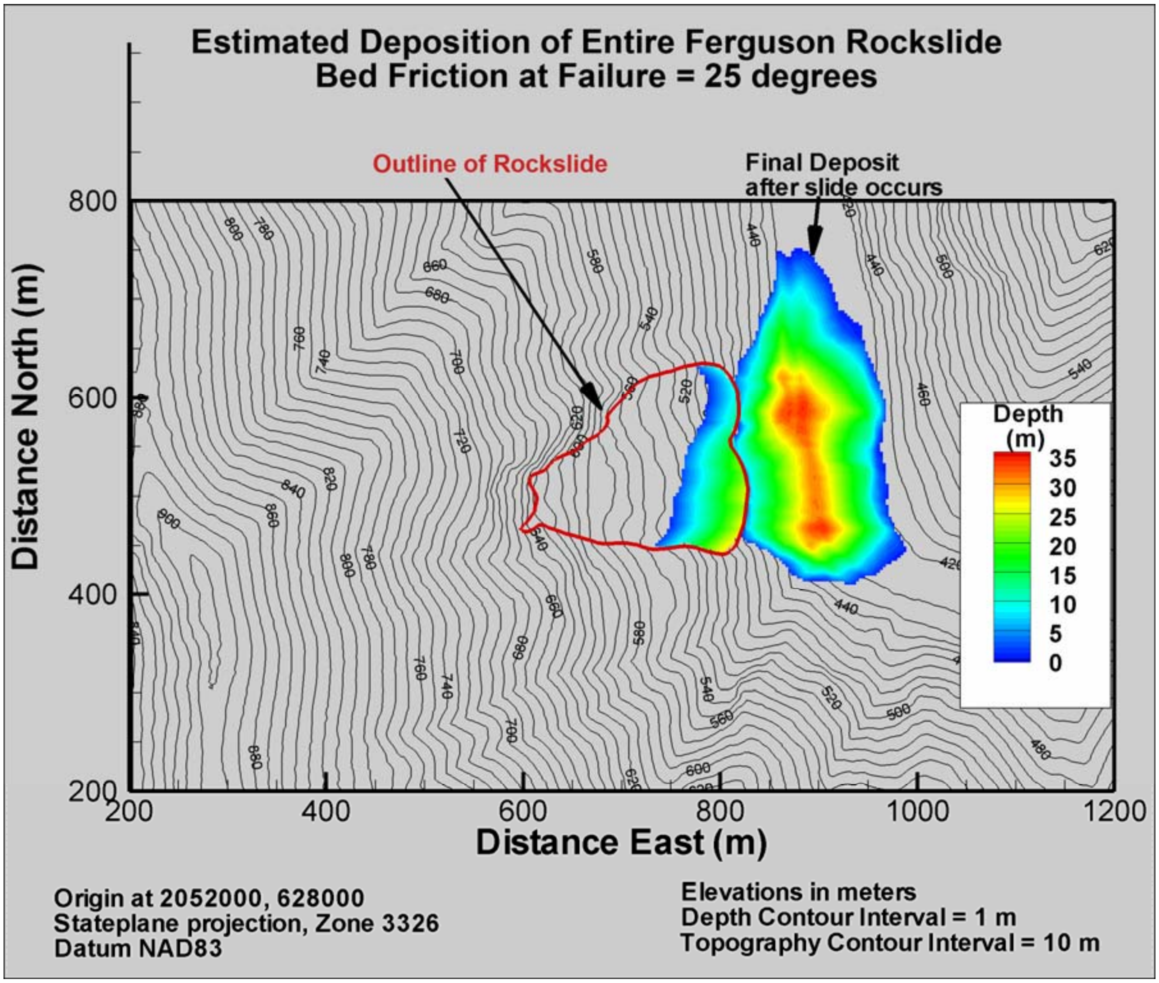

Figure 9. Simulated final deposit of entire Ferguson rockslide (780,000 cubic meters) for a bed friction angle of 25 degrees.

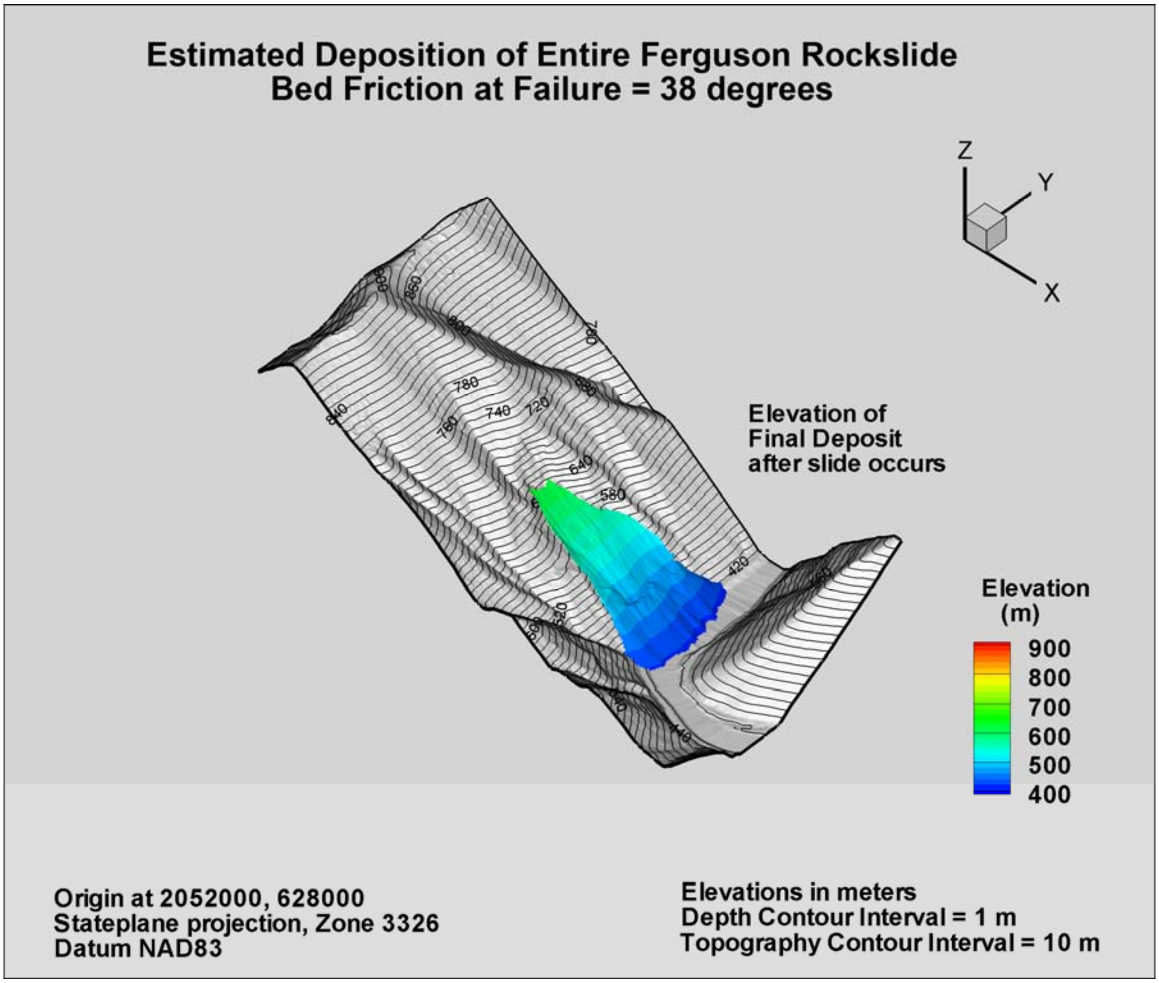

Figure 10. Perspective view of simulated deposition using entire rockslide volume and a bed friction of 38°, comparable to that given by the angle of repose. In this scenario, rock debris builds a steep talus cone that blocks 2/3 of the Merced river channel, diverting but not damming the flow.

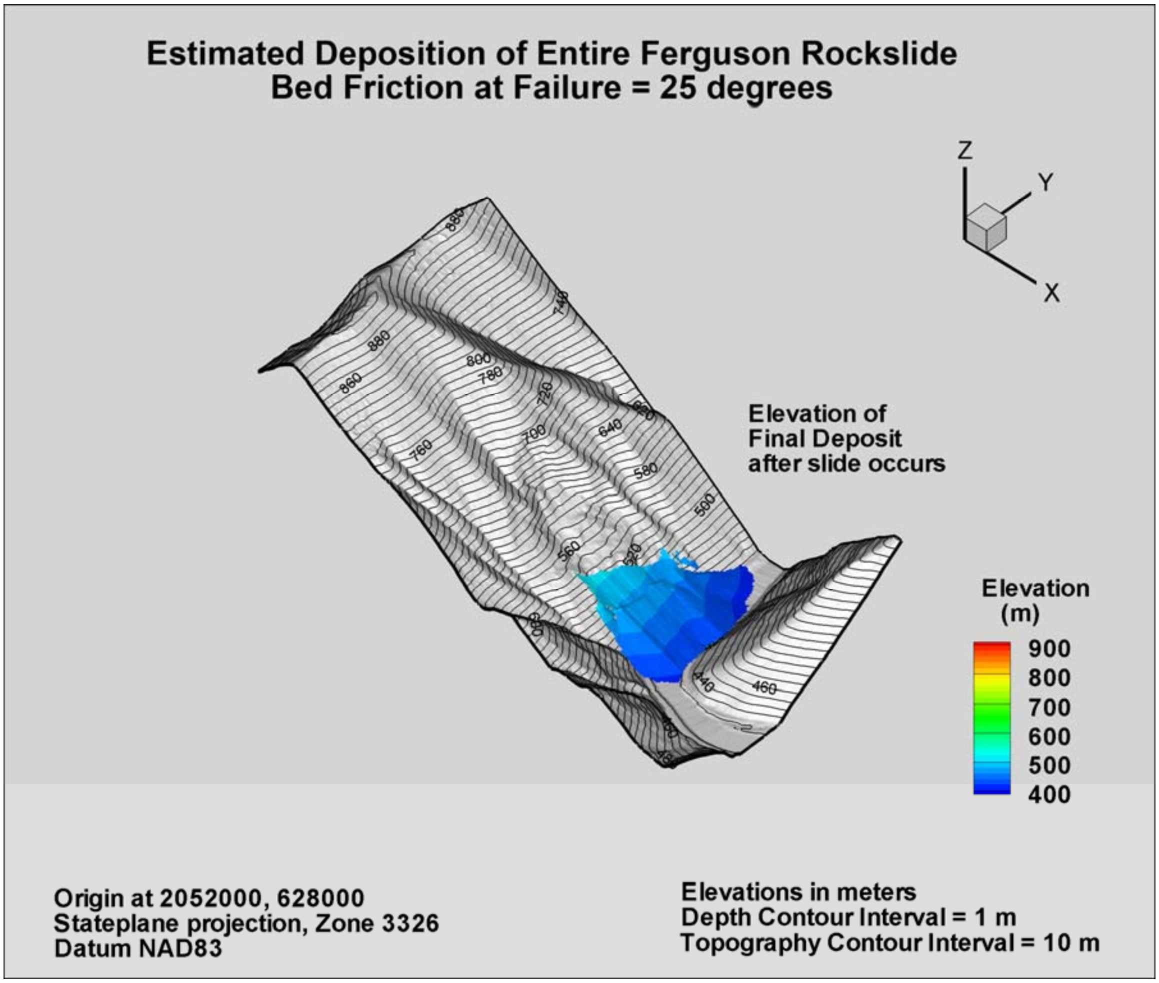

Figure 11. Perspective view of simulated deposition using entire rockslide volume and a low bed friction. In this scenario, rock debris fills the entire valley to a minimum depth of 10 m and a maximum depth of 33 meters.

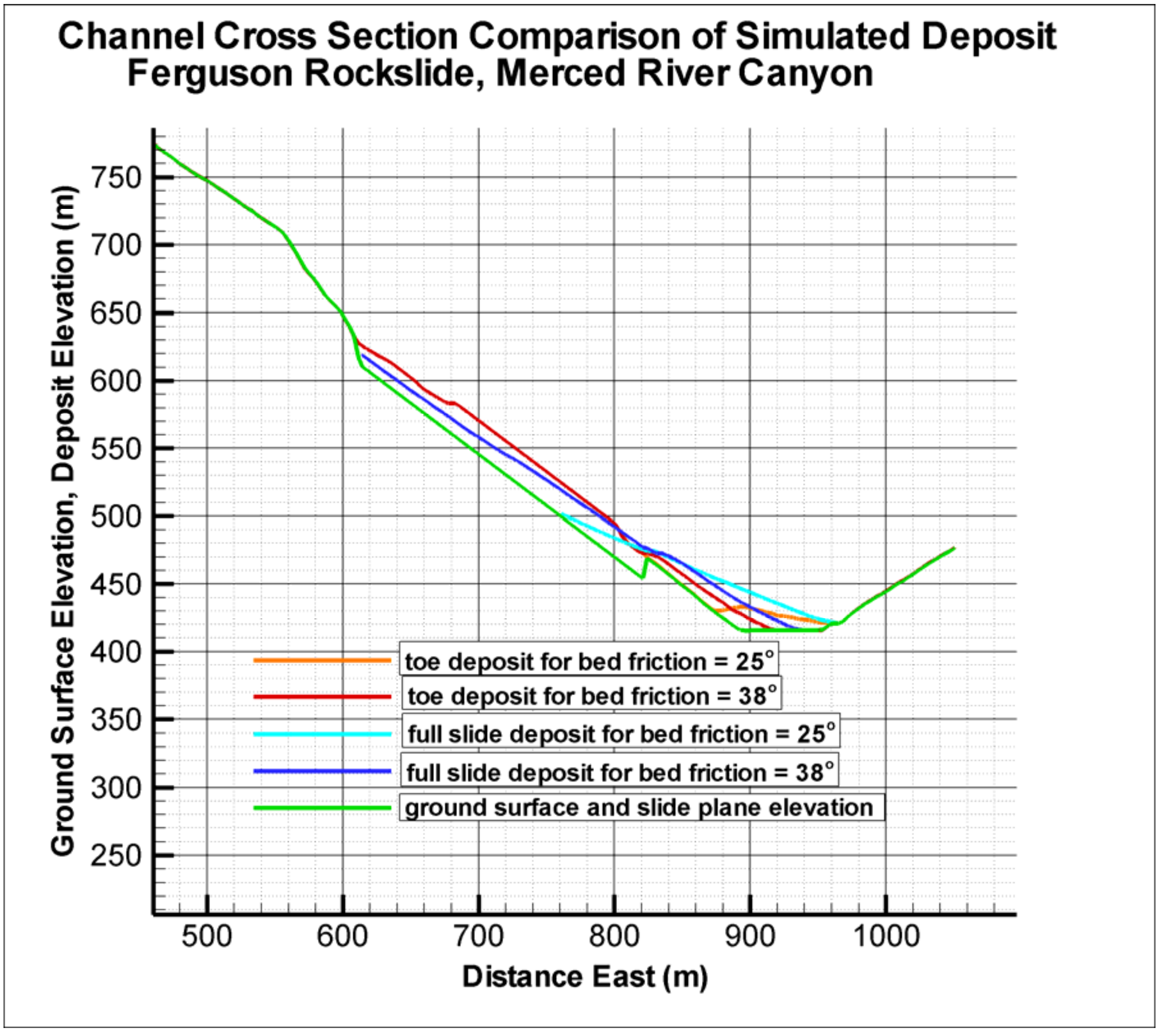

Figure 12. Comparison of the same channel cross section for four different simulated deposits. The combination of existing surface topography and estimated slide plane for the entire rockslide is shown in green. After failure, the profile of the toe deposits are shown in red and orange and the full slide deposits are shown in blue and cyan. In contrast with all of the other simulations, the toe deposit for high bed friction (shown in red) removes just part of the original toe mass from the rockslide and consequently the final ground surface profile overlaps with much of the existing ground surface profile. The toe deposit that is removed is added to the existing talus at the base of the slope (Figure 6).