Salado River—variable denudation intensity; range: less than 25 percent to 50 percent; most intense denudation appears to be in first- and second-order gullies of upper reaches of the Salado River, and in third-, fourth-, and lower-order tributaries of lower portions of the Salado River (Figure 5.11).

Quequno, Dué, and Dué Grande rivers—variable denudation; range and local distribution similar to that of the Salado River; however, overall denudation for these areas appears to be somewhat less than for the Salado River drainage basin.

Coca River—between the mouths of the Salado River and the Reventador River, denudation is greatest on the left wall of the Coca River valley; downstream from the Reventador River, denudation is about the same on both sides of the Coca River for comparable elevations. Opposite Reventador Volcano, denudation appears greater on the left side of the Coca valley because the ground surface continues to rise toward the crater, whereas the topography flattens at an elevation of 1,500 and 1,700 m on the right side.

The degree of denudation changes with horizontal curvature of slopes. Airphotos show that there is an increase in denudation on the concave portions of the Coca River slopes and a decrease on convex portions, as seen in plan view.

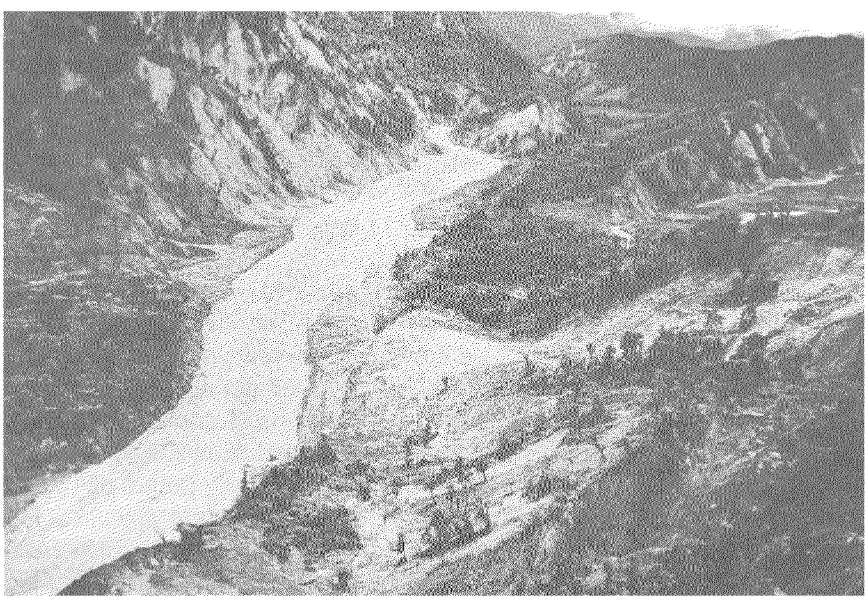

FIGURE 5.11 Upstream view of the Salado River showing remains (center foreground) of a debris flow that entered the river from the right (NE) valley wall. It is probable that this debris flow briefly dammed the river at this point.

Slope Stability—Preliminary Analysis and Interpretation

This discussion is restricted to the Reventador area because it contains by far the greatest concentration of landslides. The slides were shallow (average depth 2 m) and involved residual soil that became very fluid during failure. Stability thresholds as a function of slope angle are 35 to 40° for the main valley walls of the Coca and Salado rivers and 30 to 35° for the upper portions of the ancient Reventador Volcano cone. Field reconnaissance indicated that relatively few failures occurred on slopes flatter than these values and that most of the slopes with steeper angles did fail.

Evaluating the stability of the slopes in the Reventador area under earthquake loading provides insight into the general shear-strength behavior of these soils in particular and of residual soils in general. The stability of thin residual soils overlying high and steep slopes can be analyzed by an infinite-slope model. Further, the earthquake effects can be evaluated roughly by introducing a pseudostatic horizontal force that models the maximum horizontal acceleration. The analysis is carried out in terms of total stresses because evaluating the pore-water pressures at failure is impossible. Thus, the factor of safety can be defined as

$$FS = \frac{c/\cos\alpha + \gamma H(\cos\alpha - k\sin\alpha)\tan\varnothing}{\gamma H(\sin\alpha + k\cos\alpha)}$$

where

$\varnothing$, c = consolidated-undrained shear-strength parameters
H = depth of failure surface
γ = unit weight of soil
α = slope angle
k = seismic factor (maximum horizontal acceleration).

Ishihara and Nakamura (1987) used $c = 0.3$ kg/cm^2 and $\varnothing = 30°$ to calculate a static factor of safety for the 45° slope that failed during the earthquakes and destroyed part of the pumping station on the Trans-Ecuadorian oil pipeline at Salado. The cohesion value was obtained from cone-penetration tests and an assumed reduction factor. The value of $\varnothing_{cu}$ (angle of internal friction based on consolidated-undrained conditions) would appear at first glance to be too high for undrained failure conditions (which we presume were considered by Ishihara and Nakamura), but, as discussed below, may be adequate for these particular failures. Landivar et al. (1986), in their general study of the lateritic soils of Ecuador, performed consolidated-undrained isotropic triaxial tests on soils just outside the Reventador zone. They obtained effective-stress strength parameters ranging from 0.05 to 0.08 kg/cm^2 for c' (cohesion on effective-stress or drained basis) and 32 to

34° for ø' (angle of internal friction on effective-stress or drained basis). We have plotted the total-stress envelopes for these materials and, as expected, the average $\varnothing_{cu}$ values for the stress levels tested are in the range of 5 to 10°. The normal stress levels for 2-m-deep slides are not in excess of 0.5 kg/cm^2; thus, these soils were tested at stress levels several times greater than field conditions at Reventador. A review of the literature on structured soils (loess, residual soils, sensitive clays) in general and of residual-soil case histories in particular shows that at very low stress levels the pore pressures at failure are close to zero or slightly negative (Vargas, 1974; Quigley, 1980; and Lum, 1982). As a consequence, the values of $\varnothing_{cu}$ and ø' are very similar, implying that the total-stress envelope has a strong curvature at low stress levels. For our range of interest, 0 to 0.5 kg/cm^2, ø values typically range from 0 to 35°, and c values are generally less than 0.1 kg/cm^2. Therefore, we fitted curved envelopes on the Landivar data and obtained $\varnothing_{cu}$ values between 30 and 38° and c values between 0.1 and 0.2 kg/cm^2. These values are indeed very similar to the effective-stress parameters for other locations given above. Figure 5.12 shows the variation in the factor of safety as a function of slope angle for static conditions and maximum horizontal accelerations of 150, 250, and 350 gal. A value of $\alpha = 30°$ was used ($\varnothing_{cu} = 30°$ was also used), and the value of c = 0.14 kg/cm^2 agrees well with the c values obtained from Landivar et al. (1986). It is seen that for the range of validity of Eq. (1), or values between 30 and 60° (which also happens to be the range of slope angles in the field), if instability is assumed at $\varnothing_{cu} = 30°$ and k = 0.35, instability will begin at $\alpha = 40°$ for k = 0.25 and at $\alpha = 45°$ for k = 0.15. From our field observations, these values appear to be reasonable for the entire Reventador area, where the range of k probably falls within these limits. For comparison, Figure 5.13 shows a similar family of curves, but one in which $\varnothing_{cu}$ was assumed to be very low (5°), as compared with common assumptions for undrained conditions and a total-stress analysis. Again, c = 0.26 kg/cm^2 was obtained by back calculation assuming FS = 1 and k = 0.35. The use of these strength parameters does not explain failures at angles >45° for k = 0.35 and, more significantly, predicts no slides at lower accelerations.

Furthermore, assuming natural variations in the strength parameters, low $\varnothing_{cu}$ and high c values do not explain our field observations. Figure 5.14 is a comparative plot in which FS was calculated for k = 0.35 and variations in the strength parameters. When $\varnothing_{cu} = 5°$ is assumed, a variation of about ± 0.05 kg/cm^2, or about 20 percent, from the original 0.14 kg/cm^2 value, gives the dashed curves shown in Figure 5.14. In one case, regardless of the slope angle, none of the slopes would fail, whereas in the other case all slopes would fail. However, even in the areas of maximum denudation, there is good correlation between slope angle and failure. On the other hand, when $\varnothing_{cu} = 30°$ is assumed, a variation in slope angle of ± 5°, or

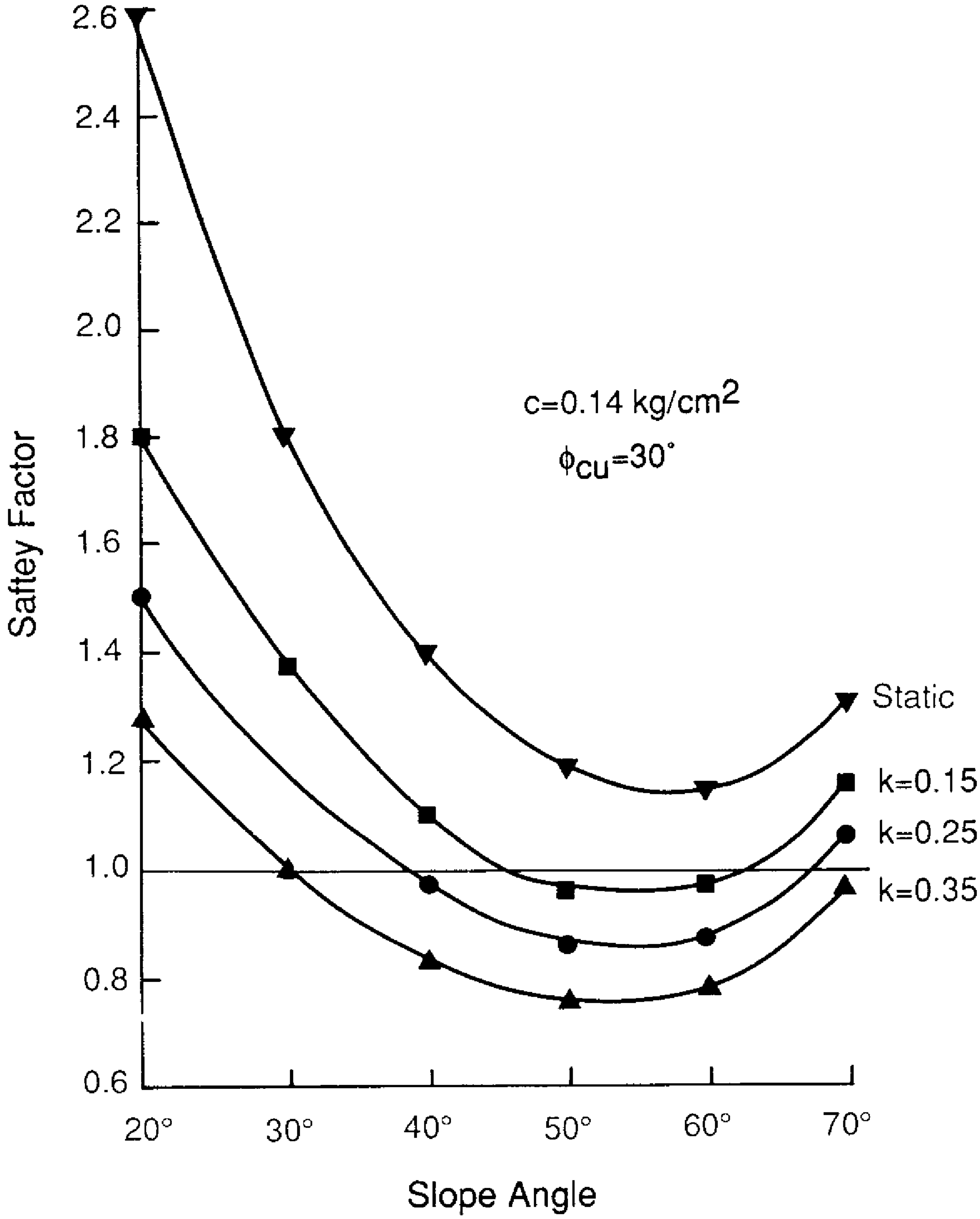

FIGURE 5.12 Pseudostatic and static safety factors vs. slope angle for $\varnothing_{cu}$ = 30° and c = 0.14 kg/cm^2.

about 20 percent from the original 30° value, results in the solid lines in Figure 5.14. These lines indicate that instability for k = 0.35 begins on slopes of 35 and 25°, respectively; these slope-angle values still appear reasonable in light of our field observations.

Because these are such shallow slides, the cohesion value that is assumed

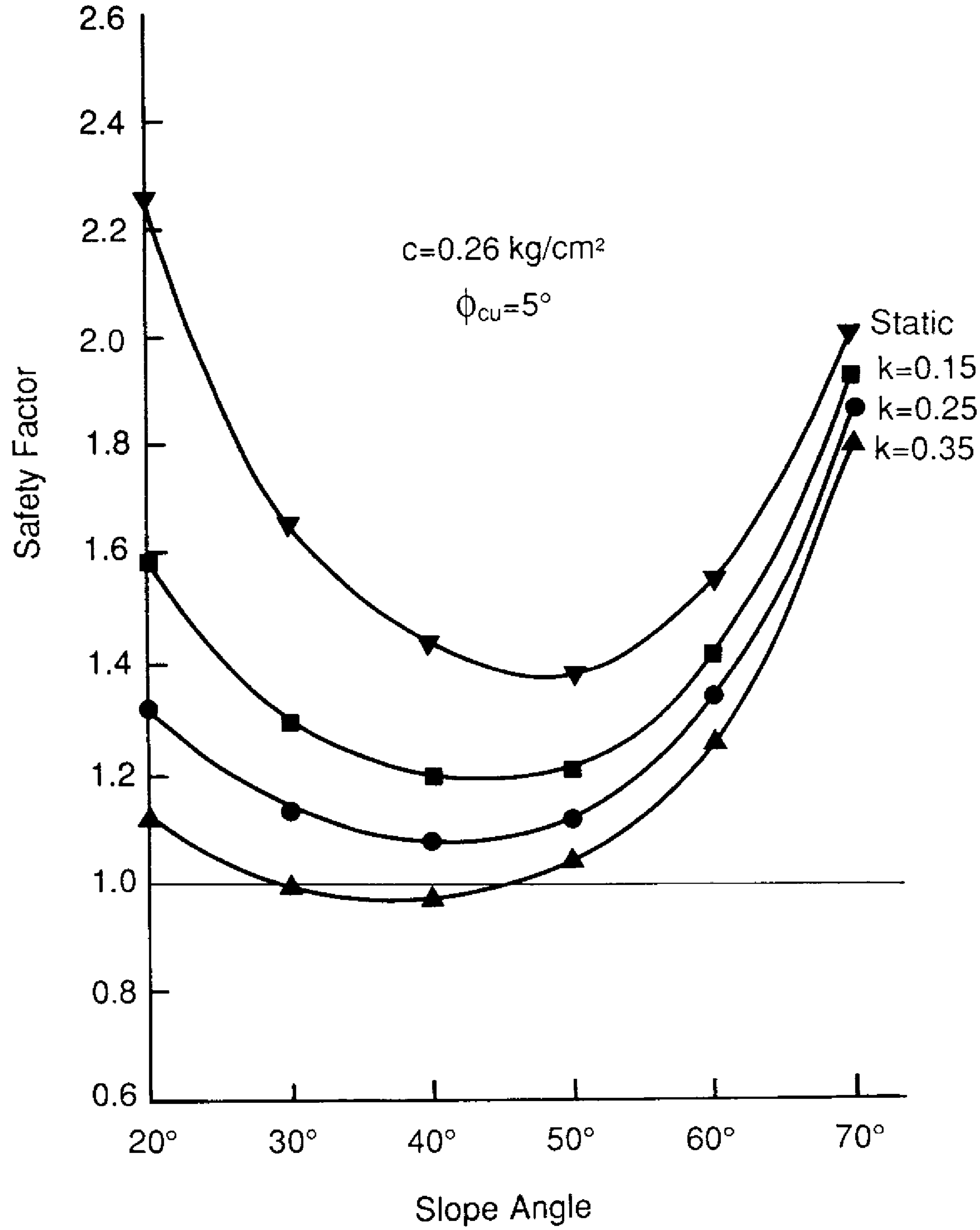

FIGURE 5.13 Pseudostatic and static safety factors vs. slope angle for $\varnothing_{cu} = 5^{\circ}$ and $c = 0.26$ kg/cm^2.

greatly influences the factor of safety even in the case of high $\varnothing_{cu}$. For instance, the value $c = 0.3$ kg/cm^2 used by Ishihara and Nakamura (1987) can explain the 5-m-deep slope failure at the Salado pumping station with a value of $k = 0.35$, but cannot explain the frequent shallower failures (commonly 1 to 2 m deep) observed nearby.

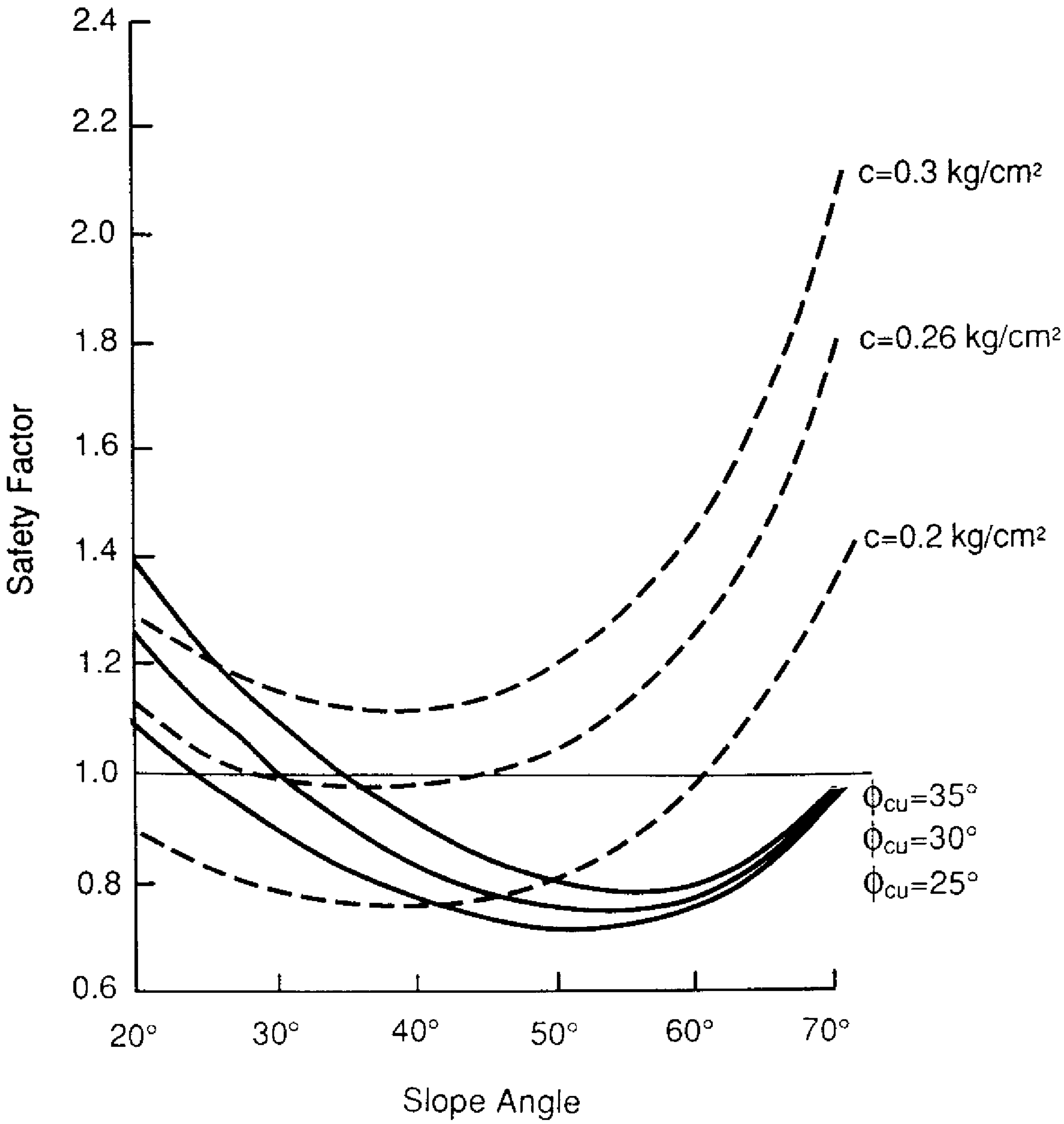

FIGURE 5.14 Comparative plot showing influence of variation in $ø_{cu}$ and c on the factor of safety for k = 0.35.

Relation Between Denudation Intensity and Epicenter

Hakuno et al. (1988) questioned the accuracy of the positions of the epicenters that had been estimated by seismologists because the most severe slope failures occurred about 30 km from the reported epicenters. Ishihara and Nakamura (1987) placed the epicenters at 5 to 10 km from the headwaters of the Malo River and 10 to 15 km from the upper Salado River, presumably on the basis of denudation intensity.

Whereas the position of the epicenters may be open to question, we suggest that the increase in denudation near Reventador Volcano may also be caused by other factors, namely relief, moisture conditions, elevation, and soil composition. The areas of near-total denudation on the SW slope of the ancient cone correspond to an area of deep and dense dissection by parallel gullies. Here, almost all the surfaces have slopes greater than 35 to 40°. Near-total denudation in areas of dissection by gullies also has occurred along the walls of the deep canyons of the Malo River (Figure 5.15), Morales Creek, Dué Grande River, and streams to the N of the Dué Grande. In contrast, the slope on the N side of the ancient cone, which is not deeply dissected, is far less affected by landslides, even though it is closer to the epicenters and is less than a couple of kilometers away from the area of almost total denudation. Along the walls of the Coca, slopes that are concave in profile, and therefore have steeper upper slopes and greater density of steep-sided gullies than slopes that are convex, have far greater concentrations of landslides. The same considerations apply to the Salado valley walls. Thus, it would seem that intensity of denudation is strongly controlled by density and depth of dissection, because these factors determine the percentage of slope surface greater than the threshold values.

Another factor controlling denudation may be local differences in degree of saturation of these residual materials. Degree of saturation greatly influ-

FIGURE 5.15 Aerial view of the NE valley wall of the Malo River showing extreme denudation of slopes due to slips/avalanches/flows and of the valley bottom due to debris flows and flooding. Note the vegetation trimline that indicates the maximum height of the debris flow/flood, about 25 m above the current river level.