20

Colluvial Deposits and Associated Landslides in the Northern San Francisco Bay Area, California, U.S.A.

S.L. Reneau, W.E. Dietrich, C.J. Wilson
Department of Geology and Geophysics, University of California,
Berkeley, California, U.S.A.
J.D. Rogers
Alan Kropp and Associates,
Berkeley, California, U.S.A.

SYNOPSIS

Thick deposits of colluvium that mantle bedrock hollows on hillslopes are important sources of debris flows and constitute a distinct mappable geologic hazard. Typical thickness of the colluvium is 2-4 m. In the northern San Francisco Bay area most deposits underlie topographic concavities, but some have no topographic expression and mapping their distribution is dependent on road cuts or drilling. Spatial variations in both the hydraulic conductivity of the colluvium and the bedrock geometry influence the groundwater concentrations that lead to instability. The hollows may accumulate colluvium for periods greater than 10,000 years, but during this time changes in thickness, density, texture, and permeability can produce a state where an intense rainstorm triggers failure.

INTRODUCTION

On January 4, 1982, thousands of shallow landslides were triggered in the San Francisco Bay area by an intense rainstorm, with precipitation locally exceeding 600 mm in 36 hours. The landslides mobilized as destructive debris flows, reached speeds in excess of 6 m/s, and resulted in 12 deaths and millions of dollars in property damage (Smith & Hart, 1982; Brown, 1983). Throughout this area houses lie along footslopes and in valleys below potential debris flow yielding hillslopes. Much work is now needed to develop means to locate debris flow sources and to explain the factors controlling stability of the colluvium.

It is well understood that shallow groundwater flow is concentrated by topography and that landslides occur in these areas of flow convergence (e.g. Hack and Goodlet, 1960; Swanston, 1967, 1970; Pierson, 1977, 1980; Anderson and Burt, 1978; Tsukamoto et al., 1982). However, comparatively little attention has been given to the variation in thickness of colluvium on hillslopes and its relation to slope stability. Field inspection of many sites from which major destructive debris flows emanated in the northern San Francisco Bay area indicates that the landslides commonly initiated in thick colluvial deposits mantling bedrock hollows. In many areas the deposits are the primary source of debris flows (see Fig. 1, Fig. 2, and Fig. 3). The association of shallow landslides in the Bay area with discrete "pockets" of thicker soil was proposed much earlier by Thomas (1939), although Kesseli (1943) disputed the existence of the "bedrock pockets". The thick colluvial deposits were mapped as "ravine fills" by Schlocker et al. (1958) in San Francisco and southern Marin County. Although they suggested that the deposits are potentially unstable, until the January 1982 storm the geotechnical community had generally regarded the colluvium as relic and not a significant hazard. Geomorphologists, however, have proposed that these features reflect an inherent tendency for colluvium to collect in bedrock depressions or hollows and periodically flush out during intense rainstorms. They have found the colluvial deposits to be numerous in the Bay area and to occur throughout the coastal mountains of the Pacific Northwest (Dietrich & Dunne, 1978; Dietrich et al., 1982; Lehre, 1982; Marron, 1982; Dietrich & Dorn, 1984).

In the San Francisco Bay area the colluvial deposits are typically 2-4 m thick, some reaching 10 m or more in thickness. They are usually located in subtle swales near ridgecrests, as in Fig. 3 and Fig. 4. The deposits are common on hillslopes underlain by bedrock that yields coarse-textured soils. Such bedrock includes sandstone, granite, chert, and greenstone, and the soils are typically SM, GM, or ML in the Unified Soil Classification System. The colluvial origin of the hillslope soils in this region is conceptually

Fig. 1. Landslide scar in Lone Tree Creek basin, Mount Tamalpais, Marin County. Landslide occurred in 1974 (Lehre, 1982), centered along the axis of a colluvial deposit that had a maximum thickness of 4.5 m. The eroded failure plane is visible as a bench within the scar, 2 m deep. The boundary of the deposit is recognized by tonal changes in the grass. Photo taken in 1983 (M. Sloan).

important; the material was transported downslope by slow surficial processes such as soil creep and biogenic transport to its present location. Field criteria, including the sharp contact with bedrock and the presence of foreign clasts, prohibit their origin as residual soils derived from in-situ weathering of the bedrock.

The following paper will discuss some aspects of the colluvium relevant to stability analyses: (1) recognition of the deposits; (2) the effect of bedrock geometry on subsurface flow; (3) vertical variations in strength and permeability of the colluvium; and (4) the history of the deposits.

RECOGNITION OF THE DEPOSITS

The colluvial deposits are most easily observed in roadcut exposures where they are found to mantle U- or V-shaped bedrock hollows (see Fig. 5). In the northern San Francisco Bay area these deposits usually do not completely obscure the bedrock topography and a good first approximation of their location can be made by mapping the subtle topographic lows on the hillslopes. At some sites vegetation contrasts in combination with subtle slope changes can be used to delineate the boundaries of a deposit (see Fig. 1, Fig. 2, and Fig. 4). A crude correlation exists between certain vegetation and thick colluvial deposits, probably reflecting a change in moisture availability. There is frequently little or no topographic expression and in this case recognition is difficult without subsurface data, such as from road cuts, drilling, or seismic refraction profiles. Historically, when colluvial deposits were encountered in the field by geotechnical engineers they were not generally identified as potentially unstable or as sources of debris flows. The following is a case in point.

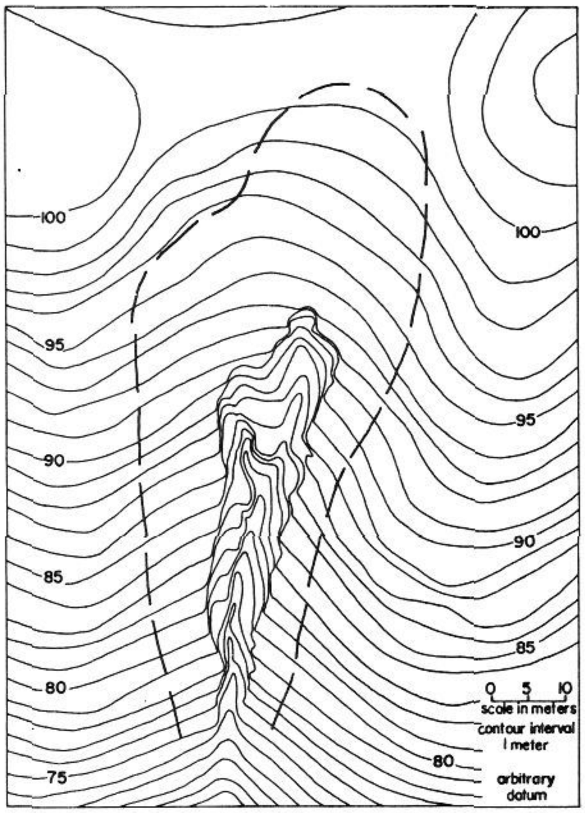

Fig. 2. Topographic map of colluvium-mantled bedrock hollow shown in Fig. 1, with the boundary of the thick deposit approximated by dashed lines. The colluvial deposit extends almost to the ridgecrest and narrows downslope to the head of a drainage channel.

Fig. 3. Ridgecrest at head of Lone Tree Creek showing a series of swales separated by low divides. Each swale is underlain by a thick colluvial deposit and landslide scars are visible in several of them. Lehre (1982) found that the colluvial deposits are the primary source of debris flows in this drainage basin. View south, with entrance to San Francisco Bay in upper left (M. Sloan).

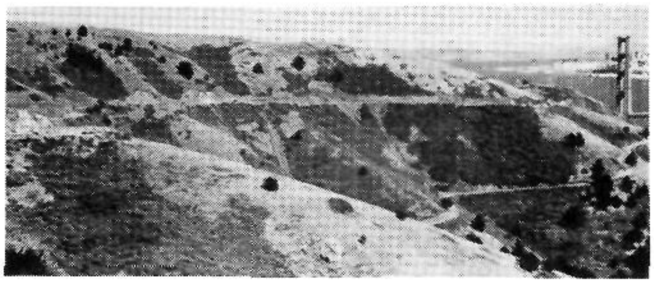

Fig. 4. Southern end of the Marin peninsula in area mapped by Schlocker et al. (1958), with Golden Gate Bridge and San Francisco in upper right. Each swale or basin below the ridgecrest is underlain by a thick deposit of colluvium, well displayed in the road cuts. The areas of darker vegetation crudely correspond with the areas of thick colluvium, while the grassy slopes are underlain by a relatively thin mantle of colluvial soil. Two gullies in the colluvium are visible in the center of the photo where runoff from the road is discharged. The bedrock here is chert and greenstone of the Franciscan assemblage.

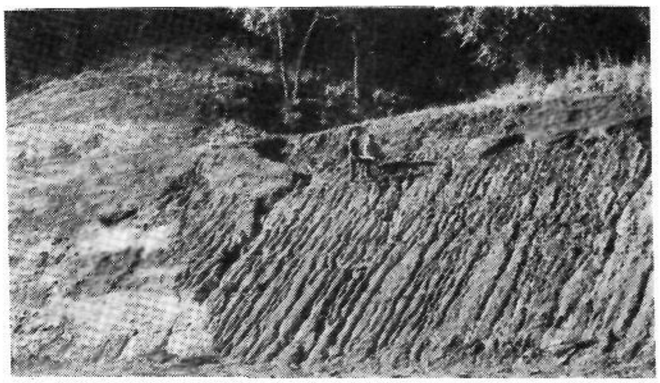

Fig. 5. Colluvium exposed in road cut near Point San Quentin, Marin County. The two people are located at the transition between densely rilled lower colluvium and darker, root-permeated upper colluvium. At the time of the photograph a perched water table had developed above this transition. Bedrock exposed to left along a steep contact with the colluvium is graywacke sandstone of the Franciscan assemblage.

Geotechnical investigations were begun by Alan Kropp and Associates in 1981 at the proposed site of residential development along Grizzly Peak Blvd. in Oakland. The site is near a ridgecrest, within a very broad topographic concavity or basin, with slopes averaging 30 degrees (Fig. 6). Routine drilling revealed an unexpectedly thick mantle of sidecast fill and colluvium, up to 10 m thick, rich in angular chert fragments. This part of the slope was recommended as unsuitable for development but the recommendation was unfavorably accepted by the client and another geotechnical firm was retained. The slope subsequently failed during the January 1982 storm. Gullying and sidewall collapse rapidly enlarged the scar and eroded the poorly consolidated lower colluvium, with headward erosion undercutting Grizzly Peak Blvd. Additional drilling revealed the irregularity of the underlying bedrock surface and the presence of discrete colluvium-filled bedrock hollows (Fig. 7), although there was no indication of colluvial deposits in the adjacent roadcut only 10 m away.

Importantly, discharge of runoff from the road contributed to both the initial failure and to subsequent gullying. The subtle topographic swales often receive additional runoff collected on roads, and post-failure investigations have identified numerous sites where landslides in colluvial deposits were apparently triggered by this alteration of the local hydrology. In addition, landslides and gullies due to the discharge of road drainage onto the deposits can erode large volumes of debris and create sediment problems in downstream channels. The high potential for gullying has also been noted by Schlocker et al. (1958).

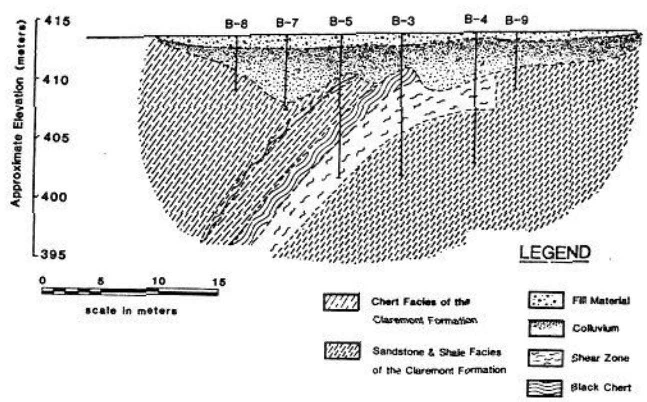

Fig. 7. Cross section of colluvial deposit along Grizzly Peak Blvd. Note the irregularity of the bedrock surface and the discrete colluvium-filled bedrock depressions. The bedrock is well-bedded chert, shale, and sandstone of the Miocene Claremont Formation. The cross-section is based on 6 drill holes and exposures in the scar.

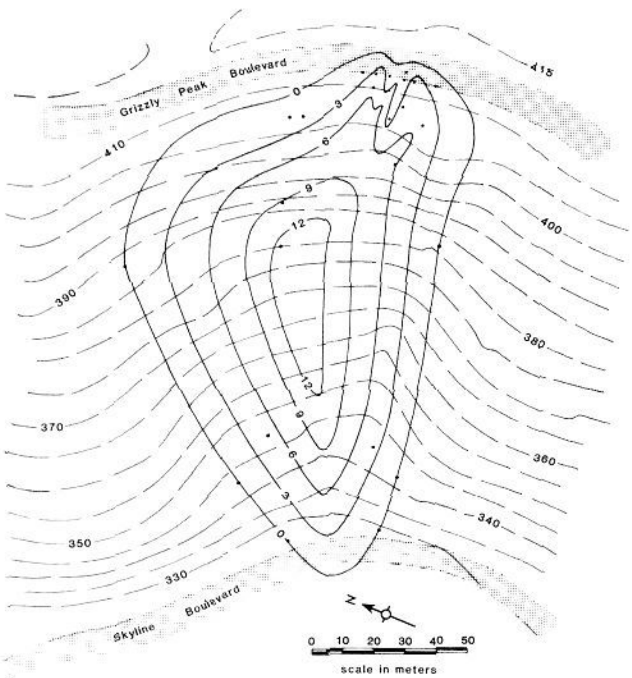

Fig. 6. Map of Grizzly Peak Blvd. site, Oakland, showing pre-failure topography and isopachs of original colluvium thickness. Deposit is centered in a broad topographic concavity and extends nearly to 415 m ridgecrest. Isopachs are based on drill holes and exposures in the scar. The zero isopach shows the boundary of the thick colluvial deposit, with soils outside of this averaging less than 50 cm in thickness.

EFFECT OF BEDROCK GEOMETRY ON SUBSURFACE FLOW

The three dimensional form of the bedrock surface underlying the colluvial deposits is of importance in controlling the magnitude of the downslope rise in the piezometric surface during a rainstorm, and therefore the stability of a slope. Longitudinal profiles of the bedrock axis are often concave, regardless of the slope of the soil surface. For example, the Lone Tree Creek site had a 17 degree surface slope along a 50 m reach, while the underlying bedrock slope decreases downslope from 19 degrees to 12 degrees (Fig. 8). A much more dramatic concavity is present at the Grizzly Peak Blvd. site (Fig. 9). These two examples exhibit characteristics common to many of the colluvial deposits; similar concave profiles beneath the soil mantle are also shown in other studies in California (Dietrich & Dorn, 1984), Oregon (Pierson, 1977), and Japan (Iida & Okunishi, 1983). The concave bedrock profile results in a downslope decrease in both the cross-sectional area of the deposits and the hydraulic gradient; together, these magnify the rise in the piezometric surface that would be produced by the topographic convergence of subsurface flow alone.

A computer model is being developed under the direction of T.N. Narasimhan at U.C. Berkeley to determine the effects of variable three-dimensional bedrock and surface topography on groundwater convergence and the piezometric response to storms in colluvial deposits. A finite element model was previously developed by Humphrey (1982) to predict groundwater flow in a 10 m long, 7 m wide, 1.6 m deep ellipsoidal depression. Although this model showed that convergence doubled the piezometric rise due to the concave profile, excessive computing costs prohibited the examination of a realistic hillslope setting. The model presently being developed uses the integrated finite difference method to solve for transient fluid flow in variably saturated, heterogeneous, deformable media. The FORTRAN program, TRUST, uses an iterative scheme to reduce expensive computer storage requirements and provides the core for a cost-efficient hydrologic model of field scale problems (Narasimhan et al., 1978).

Preliminary modelling of an intensive 4 hour storm at the Lone Tree Creek site predicts that peak fluxes of groundwater flow from the side slopes to the axis of the swale occur within several hours of incipient rainfall, and are maintained for more than 20 hours. The configuration of the side slopes appears to have a major influence on the location of high pore pressure development along the axis.

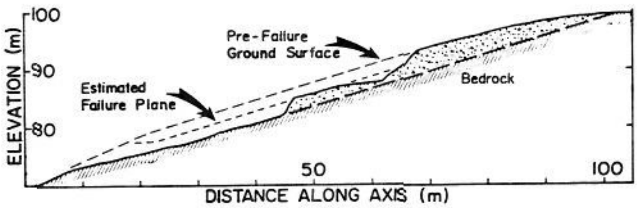

Fig. 8. Longitudinal profile of Lone Tree Creek study site, 1983, showing the eroded landslide scar, the slightly concave bedrock surface, the pre-failure ground surface, and the approximate failure plane. The ground surface was a uniform 17 degrees in the swale, steepening to 24 degrees immediately downslope of the scar. Bedrock is graywacke sandstone of the Franciscan assemblage, Mesozoic age, variably sheared and fractured. Subsurface bedrock contact determined from auger holes.

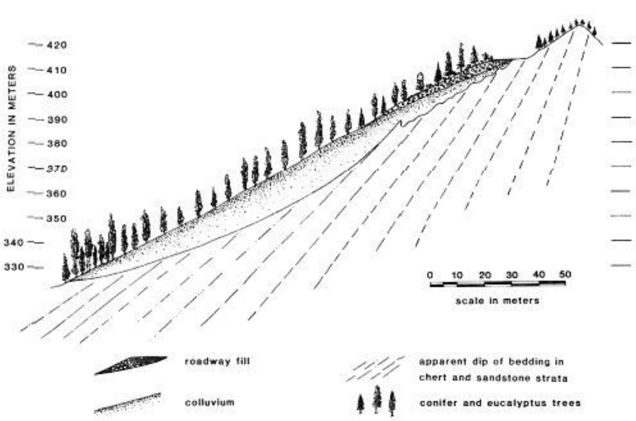

Fig. 9. Reconstructed longitudinal profile of Grizzly Peak Blvd. site, showing the strongly concave bedrock surface and the pre-failure ground surface. Bedrock contact determined from drill holes and post-failure exposures.

VERTICAL VARIATIONS IN STRENGTH AND PERMEABILITY

Vertical variations in the strength and permeability of the colluvium are critical in controlling the location of the initial failure plane and thereby the stability of a slope (Fig. 10). Although the failure surface is sometimes very close to and paralleling the underlying bedrock, in this area the failure plane is more commonly entirely within the deposit. Field evidence suggests that two factors are of primary importance in many of these landslides: the shear strength added by tree roots and permeability contrasts within the colluvium. The role of roots in stabilizing soil-mantled hillslopes has been shown by many workers (see discussion by Gray & Leiser, 1982). In the oak-California laurel forests of the Bay area, major roots rarely extend more than 1 meter below the surface and many landslides in colluvium occur near this depth, where the vegetative contribution to strength rapidly diminishes.

Distinct permeability contrasts within the colluvial deposits were found to be a common occurrence in this area, and are often sufficient to produce perched water tables in the upper soil. This condition was observed both in road cuts and in exploratory borings, with saturated colluvium overlying denser, unsaturated colluvial soil (see Fig. 5). Bulk density data from some landslide scars support this observation. For example, Fig. 11 shows a bulk density profile compiled from a colluvial deposit near San Rafael. A failure surface at 1.25 m depth overlies a dense clay-rich horizon, sharply contrasting in character and sorting with loose, gravelly colluvium in the lower part of the deposit. The dense horizon is probably of pedogenic origin. Clay content increases from 2% of the minus 2 mm fraction at the surface to 17% at 1.5 m depth. Below this, clay content averages 2-4%.

At both the San Rafael site and the Grizzly Peak Blvd. site, loose, highly permeable, stratified gravels in the lower half of the deposits contrast with non-stratified, finer textured upper horizons. Grain size analysis of the upper horizon at San Rafael show 32-45% silt, 45% sand (0.74-4 mm), and 5-10% greater than 4 mm, while the lower horizon contains 30-40% greater than 4 mm and only 10-14% silt and clay. The lower gravels are angular, indicating colluvial rather than fluvial transport.

The colluvium at the Lone Tree Creek site is characteristic of many deposits in this area. Except for a poorly defined gravelly zone near the failure plane, the colluvium is unstratified. The colluvium is a well graded SM soil, with 46-50% sand, 22-29% silt, 14-23% gravel, and 4-11% clay, the clay fraction increasing with depth. Although the texture is relatively uniform, the bulk density increases progressively with depth (Fig. 12), producing a progressively decreasing hydraulic conductivity. Values from field permeability tests range from 0.003 cm/sec near the surface to 0.0003 cm/sec at a depth of 2.5 m.

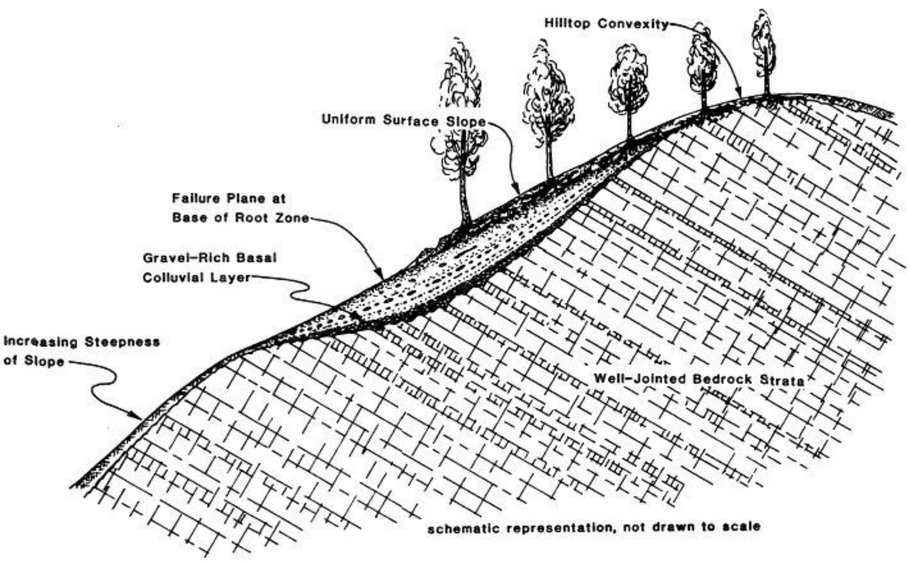

Fig. 10. Schematic longitudinal profile through a colluvial deposit. Shown are: (1) the characteristic concave bedrock surface that develops in these three dimensional spoon-shaped bedrock depressions; (2) a coarse, basal layer of colluvium deposited directly on a clean bedrock surface; (3) a crude stratification subparallel to the bedrock; (4) a convex hilltop above and a steeper slope below the deposit; and (5) a landslide failure plane at the base of the root zone. Strong vertical variations in hydraulic conductivity and shear strength may be associated with changes in root density and texture of the colluvium.

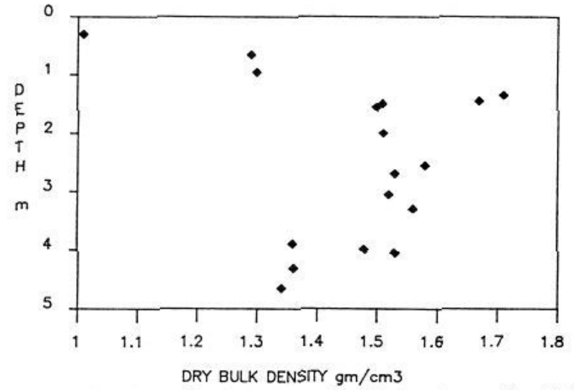

Fig. 11. Bulk density profile through a colluvial deposit near San Rafael, Marin County, sampled in eroded landslide scar. Thin horizon of relatively high density occurs at 1.25 m depth and is associated with a zone of pedogenic clay accumulation; the main failure plane occurred immediately above this. The low density lower horizon is composed of loose, openwork, angular gravel. Bedrock is graywacke sandstone of the Franciscan assemblage.

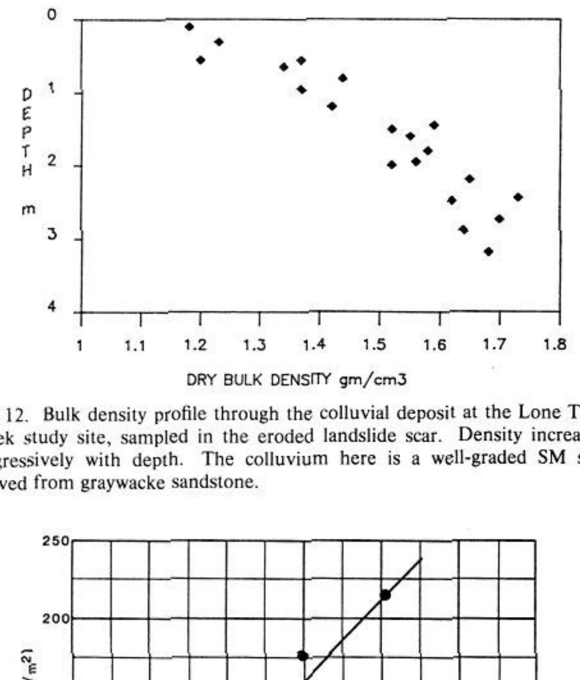

Fig. 12. Bulk density profile through the colluvial deposit at the Lone Tree Creek study site, sampled in the eroded landslide scar. Density increases progressively with depth. The colluvium here is a well-graded SM soil derived from graywacke sandstone.

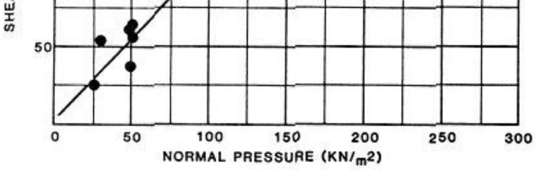

Fig. 13. Combined direct shear test data from colluvial deposit on Grizzly Peak Blvd., derived from chert bedrock, and colluvial deposits near Clear Lake, derived from greenstone of the Franciscan assemblage. The colluvium at each site is cohesionless and has a friction angle of 46 degrees.

Direct shear tests of the colluvium generally reveal cohesionless material and high angles of internal friction. The data in Fig. 13 are characteristic of many deposits. Tests from depths of 1.7 m and 2.4 m at the Lone Tree Creek site also provide friction angles of 45 degrees and no apparent cohesion.

Our observations to date indicate that the location of a failure plane within the colluvium, rather than at the bedrock boundary, results from a general decline in hydraulic conductivity and increase in bulk density with depth, combined with abrupt reductions in apparent cohesion due to roots. Vertical variations in internal friction are not yet well defined but may also be important.

HISTORY OF THE DEPOSITS

On well vegetated soil-mantled hillslopes in the Bay area, overland flow and rill or sheetwash erosion are rare or absent. Surficial debris derived from the underlying bedrock travels downslope and converges towards the axes of the hollows, accumulating as coarse-textured colluvium. Substantial lowering of the hillslopes accompanies these slow transport processes. For example, the basal colluvium at the Lone Tree Creek site has been dated at approximately 13,000 years before present (Dietrich et al., in prep), and the deposit before failure contained roughly 4000 cubic meters of colluvium. This records 1 meter of lowering of the entire source basin at an average rate of 0.08 mm/yr. Dietrich & Dorn (1984) obtained similar rates of lowering for a much larger deposit near Clear Lake, California.

Much of the colluvium in the hollows, after accumulating for millenia, will be abruptly transported out of the basin when a combination of intense rain and changing site conditions produces instability. Site conditions that may change over time include the thickness, density, texture, and permeability of the colluvium. Following a landslide, considerable erosion by gullying and sidewall collapse may evacuate a large portion of the remaining colluvium. Eventually, either through revegetation or armoring with gravel, the surface becomes stabilized and deposition begins again. This cyclic process, a type of geomorphic 'capacitor', was proposed by Dietrich & Dunne (1978) and since accepted by other workers (Lehre, 1982; Marron, 1982; Swanson et al., 1982). A similar cyclic process was suggested earlier by Hack & Goodlet (1960) for "incipient hollows" in the Appalacian Mountains.

The history of deposition and erosion for individual bedrock hollows has yet to be documented in detail, but basal colluvium from several sites in northern California has been dated by radiocarbon methods and pollen stratigraphy at 11,000-19,000 years before present (Dietrich & Dorn, 1984; Dietrich et al., in prep.). These dates may provide maximum recurrence intervals for landsliding at each site, but this interpretation should be used cautiously for several reasons. (1) Landslides can occur within the upper horizons without completely eroding the basal material. (2) The upslope and downslope portions of a deposit may have separate, localized failure histories. (3) The available basal dates partially coincide with a time of global climatic change, suggesting that changes in rainfall patterns may have influenced the frequency of failure. Weathering and cementation of some deposits indicates significantly greater age and therefore stable conditions for much longer duration.

From a practical point of view, an age of 11,000 years for the basal colluvium in no way reduces the potential hazard posed by the thick colluvial deposits. Instead, the potential hazard can only be assessed quantitatively if models that combine rainfall patterns, groundwater flow, and slope stability can be developed. Until such models become available, all colluvial deposits mantling bedrock hollows should be regarded as the most probable sources of destructive debris flows.

CONCLUSION

In the northern San Francisco Bay area, colluvial deposits mantling bedrock hollows on hillslopes are an important source for debris flows and constitute a significant mappable geologic hazard. The distribution of shallow landslides is not random, but is skewed towards the sites of groundwater convergence and long-term accumulation of colluvium. A preliminary evaluation of the most susceptible sites can be easily made by identifying areas of concave slope, both prominent swales and more subtle topographic hollows. Topographic expression may be absent, however, and in such cases identification can be considerably more difficult. Once identified, the probable routes of debris flows derived from the colluvium can be delineated and the most hazardous sites avoided. The stability of specific deposits during a period of intense rain appears to be determined by the perching and convergence of subsurface flow caused by the underlying bedrock boundary and by permeability contrasts within the colluvium. On a geologic time scale, evolution of the colluvial deposits probably controls the timing of failure, but human activity can be significant in triggering failure by concentrating surface runoff collected on roads. In order to minimize the landslide hazard accompanying hillslope development, the colluvial deposits need to be identified and the factors leading to failure more thoroughly understood.

REFERENCES

Anderson, M.G. & Burt, T.P. (1978). The role of topography in controlling throughflow generation: Earth Surface Processes (3), 331-344.

Brown, W.R., III (1983). Proceedings of Conference on Landslides and Flooding in the San Francisco Bay Region: Preparing For the Future Using the Lessons of 1982. National Academy of Sciences, Washington, D.C.

Dietrich, W.E. & Dorn, R. (1984). Significance of thick deposits of colluvium on hillslopes: a case study in the coastal mountains of northern California: Jour. Geology (in press).

_____, & Dunne, T. (1978). Sediment budget for a small catchment in mountainous terrain: Zeit. fur Geomorph. Suppl. Bd. 29, 191-206.

_____, _____, Humphrey, N.F. & Reid, L.M. (1982). Construction of sediment budgets for drainage basins. In: Swanson, F.J., Janda, R.J., Dunne, T. & Swanston, D.N. (eds.). Sediment Budgets and Routing in Forested Drainage Basins: U.S. Dept. Argi. For. Ser. Gen. Tech. Rep. PNW-141, Pac. Northwest For. and Range Exp. Sta., Portland, Oregon, 5-23.

Gray, D.H. & Leiser, A.T. (1982). Biotechnical Slope Protection and Erosion Control, 271 pp. Van Nostrand Reinhold Co., New York.

Hack, J.T. & Goodlet, J.C. (1960). Geomorphology and forest ecology of a mountain region in the central Appalacians. U.S. Geol. Survey Prof. Paper 347, 64 pp.

Humphrey, N.F. (1982). Pore Pressures in Debris Failure Initiation. M.S. thesis, Univ. of Washington, Seattle, 169 pp.

Iida, T. & Okunishi, K. (1983). Development of hillslopes due to landslides: Zeit. fur Geomorph. Suppl. Bd. 46, 67-77.

Kesseli, J.E. (1943). Disintegrating soil slips of the Coast Ranges of Central California: Jour. Geology (51), 342-352.

Lehre, A.K. (1982). Sediment Mobilization and Production From a Small Mountain Catchment: Lone Tree Creek, Marin County, California. Ph.D. dissertation, Univ. of California, Berkeley, 187 pp.

Marron, D.C. (1982). Hillslope Evolution and the Genesis of Colluvium in Redwood National Park, Northwestern California: The Use of Soil Development in Their Analysis. Ph.D. dissertation, Univ. of California, Berkeley, 187 pp.

Narasimhan, T.N., Witherspoon, P.A. & Edwards, A.L. (1978). Numerical model for saturated-unsaturated flow in deformable porous media, II: the algorithm: Water Resources Res. (14), 255-261.

Pierson, T.C. (1977). Factors Controlling Debris-Flow Initiation on Forested Hillslopes in the Oregon Coast Range. Ph.D. dissertation, Univ. of Washington, Seattle, 166 pp.

_____, (1980). Piezometric response to rainstorms in forested hillslope drainage depressions: Jour. Hydrology (New Zealand) (19), 1-10.

Schlocker, J., Bonilla, M.G. & Radbruch, D.H. (1958). Geology of the San Francisco North quadrangle, California: U.S. Geol. Survey Misc. Geol. Invest. MAP I-272.

Smith, T.C. & Hart, E.W. (1982). Landslides and related storm damage, January 1982, San Francisco Bay region: California Geology (35), 139-152.

Swanson, F.J., Fredriksen, R.L. & McCorison, F.M. (1982). Material transfer in a western Oregon forested watershed. In: Edmonds, R.L. (ed.). Analysis of Coniferous Forest Ecosystems in the Western United States. Hutchinson Ross Pub. Co., Stroudsburg, Pennsylvania, 233-266.

Swanston, D.N. (1967). Soil-water piezometry in a southeast Alaska landslide area: U.S. Dept. Agri. For. Ser. Res. Note PNW-68, Portland, Oregon, 17 pp.

_____, (1970). Mechanics of debris avalanching in shallow till soils of southeast Alaska: U.S. Dept. Agri. For. Ser. Res. Paper PNW-103, Portland, Oregon, 17 pp.

Thomas, E.S. (1939). Landslide Forms and Their Origin in the Middle Coast Ranges. M.S. thesis, Univ. of California, Berkeley, 65 pp.

Tsukamoto, Y., Ohta, T. & Noguchi, H. (1982). Hydrological studies of debris slides on forested hillslopes in Japan. In: Walling, D.E. (ed.). Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield: Int. Assoc. Hydrol. Sci. Pub. No. 137, 89-98.