Ted Melis
'97
1-520-556-7282

Debris-Flow Hazards Mitigation:

Mechanics, Prediction, and Assessment

PROCEEDINGS OF FIRST INTERNATIONAL CONFERENCE

Sponsored by the
Technical Committee on Hydromechanics,
Subcommittee on Mechanics of Non-Newtonian
Fluids Applied to Debris Flows and Mudflows
and the
Technical Committee on Sedimentation of the
Water Resources Engineering Division of the
American Society of Civil Engineers
in cooperation with the
Federal Emergency Management Agency
International Association for Hydraulic Research
International Erosion Control Association
and the
U.S. Geological Survey

Hyatt Regency San Francisco
San Francisco, California
August 7-9, 1997

Edited by Cheng-lung Chen

Published by the
ASCE American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398

DEBRIS FLOWS IN GRAND CANYON NATIONAL PARK: PEAK DISCHARGES, FLOW TRANSFORMATIONS, AND HYDROGRAPHS

Theodore S. Melis,[1] Robert H. Webb,[1] and Peter G. Griffiths [1]

ABSTRACT

Direct measurements of debris-flow hydrograph and flow behavior in remote drainage areas are rare. We infer hydrographs and flow behavior for recent debris flows in bedrock tributaries of the Colorado River from preserved stratigraphic relations, sedimentology and surface morphology of debris fans and evidence of flow-surface elevations. We propose that 3 types of debris-flow hydrographs occur in Grand Canyon: Type I flows have a single debris-flow peak followed by recessional "hyperconcentrated flow" or streamflow; Type II flows have multiple debris-flow peaks with intervening "hyperconcentrated flow" and (or) streamflow phases; and Type III flows begin as either Type I or Type II flows, but late-stage recessional streamflow is higher than the stage(s) of the debris-flow phase(s) and extensively reworks debris-flow deposits or buries them beneath streamflow sand and gravel. Field evidence shows that debris-flow peaks last for seconds to minutes, while recessional flows have durations of several hours to a day.

INTRODUCTION

Debris flows in Grand Canyon National Park, Arizona (fig. 1), transport poorly sorted sediment 1-20 km from initiation points to the Colorado River and form debris fans containing large boulders that commonly exceed the competence of regulated mainstem flows. Before river regulation in 1963, most aggraded debris fans were reworked relatively soon after deposition by the Colorado River (Kieffer 1985; Hereford et al. 1996). Once reworked, these debris fans, which lack fine-grained debris-flow matrix, contain little evidence about debris-flow behavior. Analyses of fresh debris-flow deposits, however, reveal stratigraphic relations, sedimentology, surface morphology ((physical characteristics), and flow-duration evidence that are important clues needed to reconstruct some aspects of debris-flow behavior in these semiarid tributaries, In this paper, we propose hypothetical hydro-

---

[1]Hydrologist, U.S. Geological Survey, Water Resources Division, Desert Laboratory 1675 W. Anklam Road, Tucson, AZ 85745, U.S.A. (Phone: 520-670-6821 Fax: 520-670-6806; email:, tmelis@gces.uc.usbr.gov, rhwebb@usgs.gov, pggriffi@usgs.gov

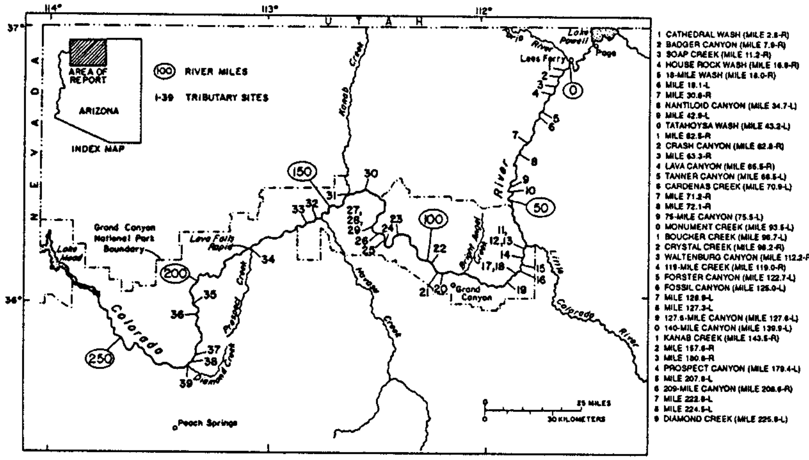

Figure 1. Map of the Colorado River through Grand Canyon National Park and vicinity, Arizona, showing the locations of study sites (from Melis et al. 1994).

graphs of Types I, II, and III debris flows to explain the physical characteristics, hydrology, and geomorphic origin of several recent Grand Canyon debris-flow deposits.

METHODS

We used previously published (Melis et al. 1994) and unpublished sedimentologic and hydrologic data on recent Grand Canyon debris flows (1939 through 1993) to design the hypothetical hydrographs presented in this paper. In addition, we witnessed the recessional phase of a debris flow at Prospect Canyon (fig. 1) in March, 1995 (Webb and Melis 1995; Webb et al. 1996). Flow and sediment data are supplemented by stratigraphic descriptions of recent debris-flow deposits made at many of the study sites (fig. 1). Because the presence of large boulders makes excavation of long trenches through debris fans inherently difficult, our stratigraphic descriptions were drawn from 1-m square by 2-m deep pits and natural exposures within channels incised into deposits. Some of the best stratigraphic profiles were exposed along the distal margins of new debris fans that were partially eroded by the Colorado River. Plan-view maps of debris-fan characteristics were surveyed to produce the illustrations of fan types presented here.

Peak discharges for debris flows that occurred between 1939 and 1993 were mainly estimated on the basis of flow superelevation evidence in channel bends and other channel measurements (Costa 1984) at 18 sites in Grand Canyon (Webb et al. 1989; Melis et al. 1994) using

$$V_s = \left[\frac{g \cdot R_c \cdot \Delta H_s}{W} \right]^{0.5}, \qquad (1)$$

where g = acceleration due to gravity (9.8 m/s^2), R_c = the radius of bend curvature

along the channel's centerline (m), ΔH_s = the difference in cross-channel surface elevation at the point of maximum superelevation (m), and W = the channel's top width at the point of maximum superelevation (m). Use of equation (1) requires the assumption that the flow is steady and uniform, and that all flow lines are parallel as flow proceeds through the bend (Costa 1984). Because debris flows are somewhat similar to highly viscous fluids, these assumptions may be justified.

Iverson et al. (1994) showed experimentally that peak-flow velocities for debris slurries estimated from superelevated mudlines were within 30 percent of directly measured values. Their experiments also showed that velocity estimates varied widely depending on how channel width was measured and input into superelevation equations. Webb et al. (1989) and Melis et al. (1994) also showed that peak-discharge estimates calculated from superelevation evidence varied significantly depending on where cross-sectional areas were measured relative to peak-flow velocities, and that discharges are not clearly related to local channel slope in Grand Canyon tributaries. With these inherent uncertainties, we consider our peak discharges for debris flows to be conservative estimates because they were determined by combining peak-flow velocities with cross-sectional areas measured immediately upstream or downstream from the superelevation bend.

PHYSICAL CHARACTERISTICS OF DEBRIS FLOWS AND FANS

Peak Discharge and Volume

Webb et al. (1989) and Melis et al. (1994) report peak discharges of debris flows ranging from about 100 to 1,000 m^3/s (fig. 2a). The largest debris-flow peak discharge in Grand Canyon since 1890 — about 1,000 m^3/s — was initiated by a tropical cyclone in Prospect Creek (fig. 1) in September 1939 (Webb et al. 1996).

Grand Canyon debris flows deliver significant volumes of sediment to the Colorado River. The total volume of sediment appears to be related to drainage-basin area and storm type (fig. 2b). Historic debris flows initiated during winter frontal storms and autumn dissipating tropical cyclones deposited larger volumes of sediment on debris fans than did debris flows triggered by summer convective thunderstorms. However, the total volume of sediment transported to the river is only weakly related to the peak discharge of debris flows (Melis et al. 1994). On most recently aggraded debris fans, the volumes of sediment deposited during debris flows likely depends on factors such as single versus multiple slope failures, tributary size, and storm duration and intensity.

Particle-size Distribution and Water Content

Particle-size distributions for Grand Canyon debris flows are related, in part, to hillslope conditions at initiation source areas as well as to parent bedrock lithology (Melis et al. 1994). Typically, debris-flow deposits contain 15-30 percent sand and more than 30 percent boulders (Melis et al. 1994), but the variability of particle-size distributions among Grand Canyon debris flows is large. Many debris-fan deposits have simple physical characteristics and consist of single, lobate snouts with poorly sorted particle-size distributions that are typical of debris flows (fig. 3a). However, greater variability in particle-size distributions is found within debris fans that display complex physical characteristics that result from multiple-phase sediment-transport processes (fig. 3b). Multiphase flows are also characterized by gen-

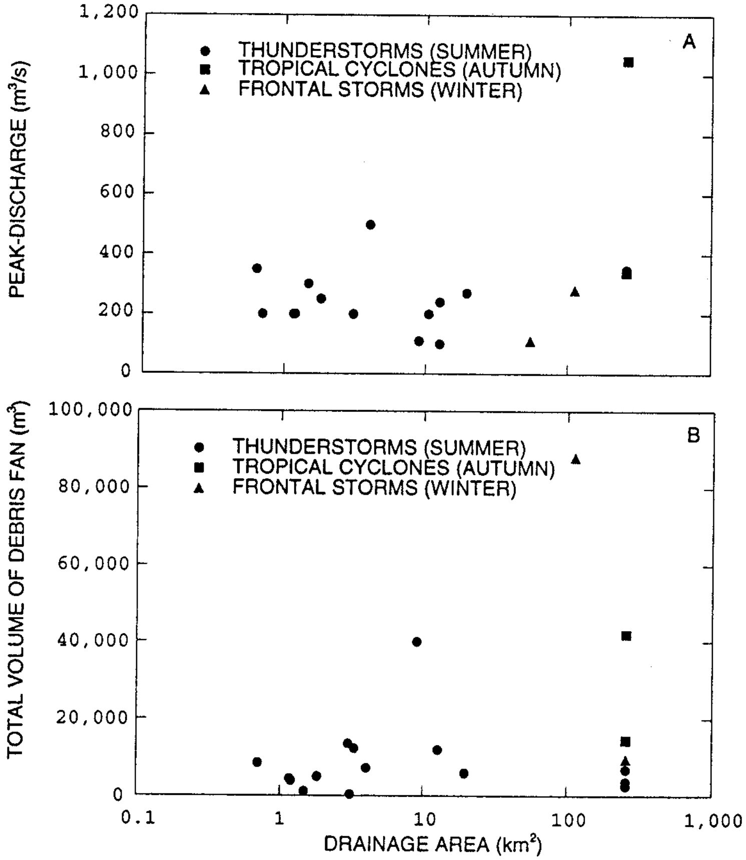

Figure 2. Data on the magnitude of 18 debris flows in Grand Canyon (1939-1993; from Melis et al. 1994). A. Peak discharge. B. Volume of deposit.

eral ranges of water contents (Pierson and Costa 1987). On the basis of reconstitution of dried samples with water, Melis et al. (1994) report that most Grand Canyon debris flows are 10-25 percent water by weight. Grand Canyon fan deposits associated with hyperconcentrated flow and streamflow are assumed to have contained a higher percentage of water, which would have influenced their flow rheologies (Pierson and Costa 1987). Water content and percentage of fine sediments, particularly clay-size particles, are important factors in the ability of sediment slurries to transport large boulders (Costa 1984) to the Colorado River (Melis et al. 1994).

Areas of similar particle-size distributions representing different flow processes can be mapped across the surfaces of complex deposits if extensive rework-

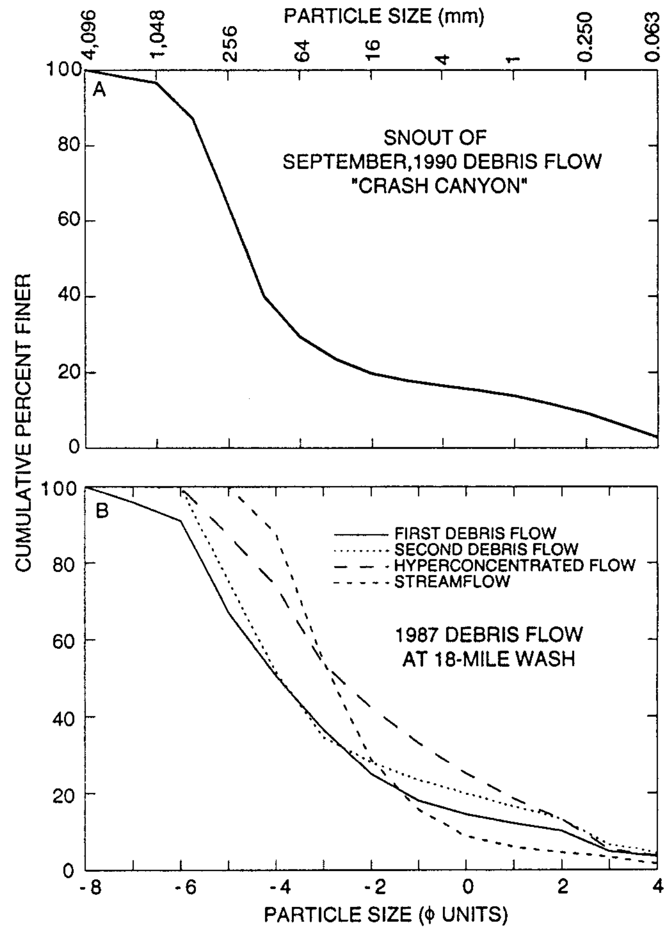

Figure 3. Particle-size distributions of debris flows in Grand Canyon (from Melis et al. 1994). A. Debris-flow deposit from a Type I flow. B. Deposits resulting from a Type II flow.

ing by recessional streamflow has not occurred. These different depositional surfaces may also be present as vertically arranged stratigraphic units deposited near the fan apex. When fan surfaces have been extensively reworked by late stage recessional streamflow, or buried under streamflow gravel deposits, excavation is usually required to reveal stratigraphy that is diagnostic of debris-flow, "hyperconcentrated-flow" (Scott 1988) and streamflow transport and deposition.

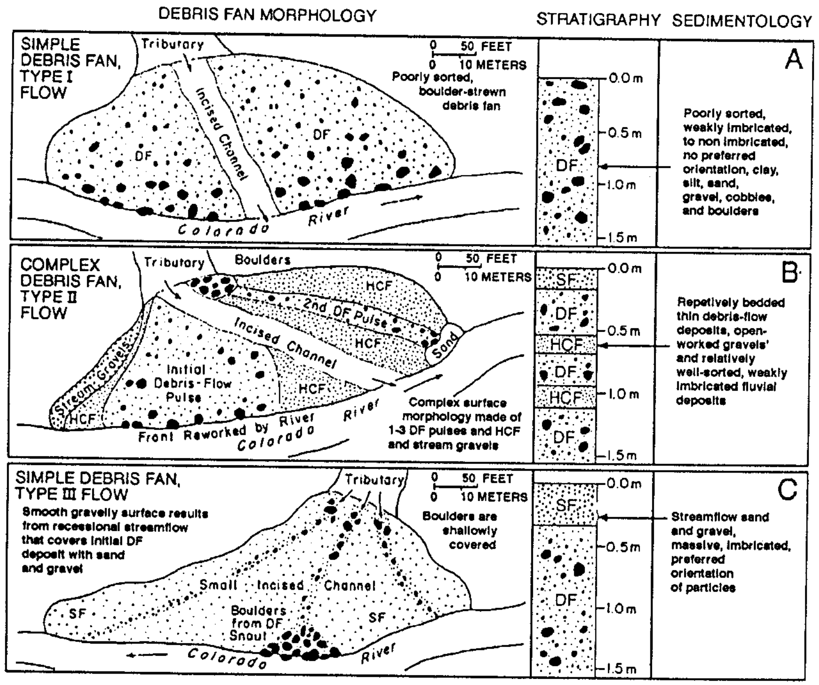

Figure 4. Plan views and typical vertical stratigraphic sequences of three characteristic debris-fan types commonly deposited by recent Grand Canyon debris flows. DF -- debris flow deposits, HCF --"hyperconcentrated flow" deposits, SFG -- streamflow gravel.

FAN MORPHOLOGY AND STRATIGRAPHY

With the most common type of debris flow, debris fans are aggraded by a single pulse debris-flow followed by brief recessional streamflow. Between 1986 and 1997, this type of debris-flow sequence occurred almost annually in Grand Canyon and created simple debris fans characterized by massive debris-flow deposits (fig. 4a). Simple debris fans (Type I; fig. 4a), have variable lobate shapes with low topographic relief, are truncated along their distal edges by the Colorado River, have poorly sorted surface particle-size distributions that include large boulders, and are often immediately incised by small tributary channels during recessional streamflow (fig. 4a).

The stratigraphy of many recently aggraded debris fans in Grand Canyon indicates a hydrograph composed of three sediment-transport processes: debris flow, "hyperconcentrated flow," and streamflow (fig. 4b). Multiple debris-flow pulses are separated by intervening periods of streamflow or "hyperconcentrated flow," and the flow transformations between debris-flow and fluvial processes occur over very short time intervals. On the basis of field observations of debris-flow

deposits in central China and flume experiments (J. Major, U.S. Geological Survey, pers. commun. 1995), mulit-layer debris-flow deposits can result from multiple surges with no intervening flow transformations. However, this surge-behavior hypothesis does not explain the intervening "hyperconcentrated-flow" deposits. Complex debris fans (Type II; fig. 4b) are similar in overall form to the simple fans but have unique physical characteristics, such as multiple debris-flow pushout lobes, streamflow runouts, incised channels, and boulder levees or coarsening-upward stratigraphy that indicate transport and deposition by multiple flow-regimes. Such physical characteristics are most commonly observed on recent Grand Canyon debris fans that aggraded almost annually between 1986 and 1997.

Occasionally, recessional streamflows with higher stages than the initial debris-flow pulse(s) may persist for several hours or up to a day. Such flows rework freshly aggraded simple or complex fans, or bury them under streamflow transported gravel deposits (fig. 4c). These sequences create complex reworked fans of Type III (fig. 4c) where reworking is associated with tributary rather than mainstem flows. Streamflow reworking makes interpretation of flow behavior difficult or impossible by obscuring evidence of the debris-flow process. Large tributary streamflows may also precede some debris flows (Cooley et al. 1977); evidence of these floods usually cannot be distinguished in stratigraphic profiles (Webb et al. 1989).

The initial variability within and among these three types of debris fans results from the combined influences of different types of hydrographs, local mainstem and tributary channel geometries, bedrock lithologies in source areas, and variations in pulse magnitude during the flows related to storm type and the timing of hillslope failures. As a result of pre-dam reworking by Colorado River floods, most debris fans throughout Grand Canyon developed remarkably similar particle-size distributions (Webb et al. 1997) that reflect debris-flow deposition of large boulders in the mainstem. However, the overall physical characteristics of debris fans, including lithologic composition, remain highly variable for the reasons mentioned above, as well as for factors such as variation in the lithology of bedrock source areas.

HYPOTHETICAL HYDROGRAPHS OF DEBRIS FLOWS

We developed hypothetical hydrographs to explain the three types of debris-fan deposits observed in Grand Canyon (fig. 4). These hydrographs (fig. 5) are based on unique physical characteristics observed on fan surfaces, the duration of peak discharge, and the stratigraphic signature of multi-phase flow processes. Although the hydrograph axes are not labeled with units, data reported by Melis et al. (1994) constrain the discharge from 100 to 1,000 m^3/s and the duration of peak discharge fromseconds to minutes (fig. 5).

Field evidence suggests that Type I flows are single-peak debris flows with minimal recessional flow; an example of this type of debris flow is the 1990 flow at River mile 62.6 ("Crash Canyon"; Melis et al. 1994). These debris flows typically occur in small drainage areas or follow brief but intense storms, and result from limitations in the supply of sediment and (or) water. Type I flows result in simple fan deposits composed of lobate, poorly sorted, structureless sediments (figs. 4a and 5a). Type I flows occur throughout Grand Canyon, typically in summer; however, many Type I flows that occur in larger drainage areas may have insufficient magni-

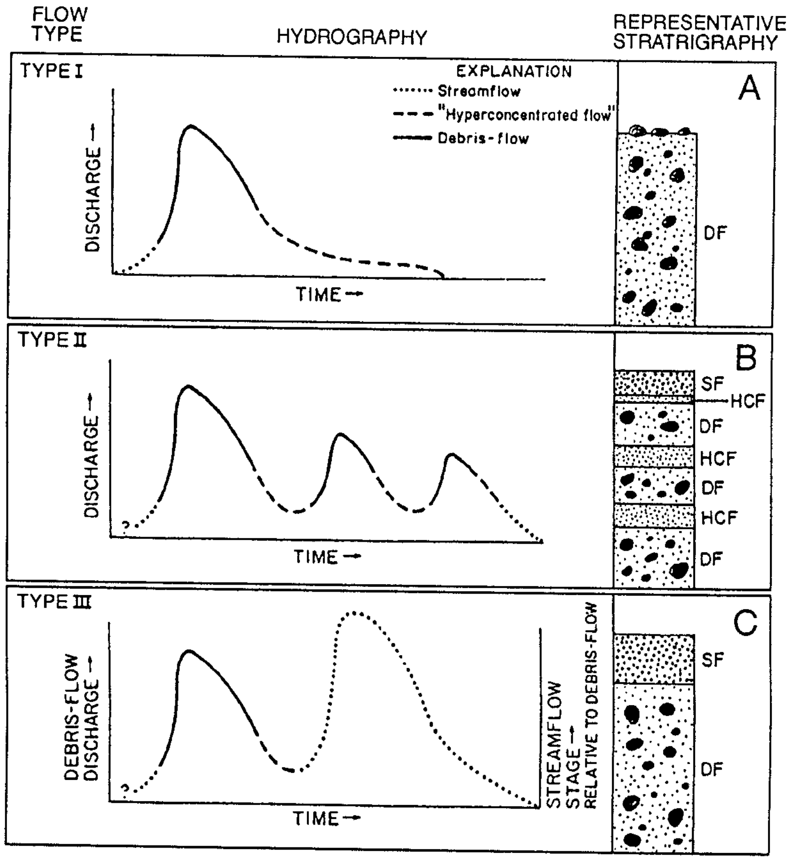

Figure 5. Hydrographs and typical vertical stratigraphic sequences of Type I, II, and III debris flows in tributaries of the Colorado River in Grand Canyon.

tude to reach the Colorado River.

Type II flows consist of a peak debris-flow pulse followed by successively smaller debris-flow pulses. The pulses are separated by intervening "hyperconcentrated flow." The last debris-flow pulse typically is followed by streamflow. These flows are most common in larger Grand Canyon tributaries and they deposit complex fans with well-defined areas of similar-size sediments that have distinct stratigraphic profiles (figs. 4b and 5b). Type II flows result from protracted summer thunderstorms or warm winter storms and may represent either nonsynchronous timing of runoff in subbasins or pulses that originate from flow transformations induced by formation and breaching of boulder and (or) debris obstructions in the upstream channel. Examples of type II flows include the 1987 debris flow at 18-Mile Wash and the 1989 debris flow at mile 127.6 (Melis et al. 1994).

Type III flows begin as either Type I or II flows and result in complex, reworked deposits. The debris-flow phase is followed by a streamflow flood of a stage sufficient to obliterate most of the evidence of the preceding flows (figs. 4c and 5c). An example of this type of flow is the 1989 debris flow at Fossil Canyon (Melis et al. 1994). Surface particles on Type III debris fans are usually clast supported and composed mainly of sand and gravel. Type III flows deposit fans with surfaces that are interpreted as fluvial, but represent only the recessional streamflow flood. Excavation of Type III fans usually reveals evidence of debris-flow deposition typical of Type I and II debris flows. On some debris fans, the only evidence of the early debris-flow phase may be deposition of large boulders that create and (or) alter rapids in the Colorado River.

DISCUSSION AND CONCLUSIONS

Peak discharges, reconstructed from flow superelevation evidence, suggest that debris flows reaching the Colorado River have a minimum possible peak discharge, and that the maximum peak discharge may be a function of drainage area and (or) sediment supply in source areas. For 18 debris flows that occurred from 1939 through 1993, the range in peak discharge was 100 to 1,000 m^3/s. Debris flows smaller than 100 m^3/s may not have sufficient energy to flow in wide tributary channels; the upper magnitude of debris flows is probably limited by the distribution of stored colluvium and (or) regional flood frequency (Enzel et al. 1993). Comparison of the deposit volumes with peak discharge suggests that the debris-flow phase is usually short, lasting from about 30 seconds to several minutes.

Patterns of debris-fan deposition suggest a relatively consistent order of events following the peak discharge of a debris flow. Secondary pulses of debris flow may follow the initial pulse. Mudlines, levees, and the volume of sediment deposited on the debris fan indicate that the peak discharge of secondary pulses is much lower than the initial surge. Sediments identical to those previously ascribed to "hyperconcentrated flow" are deposited immediately after the peak discharge and between the secondary debris-flow pulses. Rather than resulting from a distinct fluvial process, "hyperconcentrated-flow deposits" may actually result from matrix dewatering, subaqueous debris flows under streamflow, or reworking of runout from bank collapse of freshly incised debris-flow deposits. Streamflow, typically the last phase of the runoff sequence, can cause extensive reworking of fresh debris deposits. Some storms of long duration may cause streamflow discharges that exceed the maximum stage or peak discharge of the initial debris-flow pulse(s). In these situations the entire suite of physical characteristics associated with debris-flow deposition may be altered through reworking.

ACKNOWLEDGMENTS

Funding for the study was granted by David L. Wegner of the Glen Canyon Environmental Studies (Bureau of Reclamation). Chuck Sternberg prepared the illustrations. The manuscript benefitted greatly from reviews by R. Jacobson, E. Wohl, G. Wieczorek, and two anonymous reviewers.

REFERENCES CITED

Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic

flood of December, 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.
Costa, J.E., 1984, Physical geomorphology of debris flows, in Costa, J.E., and Fleisher, P.J., editors, Developments and applications of geomorphology: Berlin, Springer-Verlag Publishing, p. 268-317.
Enzel, Yehouda, Ely, L.L., House, P.K., Baker, V.R., and Webb, R.H., 1993, Paleoflood evidence for a natural upper bound to flood magnitudes in the Colorado River basin: Water Resources Research, v. 29, p. 2287-2297.
Hereford, R., Thompson, K.S., Burke, K.J., andFairley, H.C., 1996, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon: GSA Bulletin, v. 108, no.1, p. 3-19.
Kieffer, S.W., 1985, The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon: Journal of Geology, v. 93, p. 385-406.
Iverson, R.M., LaHusen, R.G., Major, J.J., and Zimmerman, C.L.,1994, Debris flow against obstacles and bends: dynamics and deposits [abst.], EOS, Transactions, American Geophysical Union, v. 75, no. 44, p. 274.
Melis, T.S., Webb, R.H., Griffiths, P.G., and Wise, T.W., 1994, Magnitude and freuency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona: U.S. Geological Survey, Water Resources Investigation Report 94-4214, 285 p.
Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, in Costa, J.E., and Wieczorek, G.F., editors, Debris flows / avalanches--Process, recognition, and mitigation: Reviews in Engineering Geology, v. VII, p. 1-12.
Scott, K.M., 1988, Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle-Cowlitz river system: U.S. Geological Survey Professional Paper 1447-A, 74 p.
Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.
Webb, R.H., and Melis, T.S., 1995, The 1995 debris flow at Lava Falls Rapid: Nature Notes, v. 11, p. 1-5.
Webb, R.H., Melis, T.S., and Wise, T.W., 1996, The great cataract: effects of late Holocene debris flows on Lava Falls Rapid, Grand Canyon National Park, and Haulapai Indian Reservation, Arizona: U.S. Geological Survey Open-file Report 96-460, 96 p.
Webb, R.H., Melis, T.S., Griffiths, P.G., and Elliott, J.G., 1997, Reworking of aggraded debris fans by the 1996 controlled flood on the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Open-File. Report 97-16, 36 p.

THE FLOW FIELD AND IMPACT FORCE ON A DEBRIS DAM

Ko-Fei Liu[1], Fong-Chung Lee[2] and Hsiao-Ping Tsai[3]

ABSTRACT

To study the mechanism involved in an impact process of debris flows, we conduct flume tests with natural sand grains. A color coded particle tracking technique is used to measure the velocity field, phase velocity and the density distribution. Bi-directional load cells are used to measure pressure and stress at three different locations. To understand the effect of different mechanisms, the constitutive law proposed by Julien and Lan is used in the momentum equation. The effect of gravity, bottom stress, dynamic pressure and shock are all evaluated according to formula derived with experimental data. The total force calculated is very close to measured.

INTRODUCTION

In many mountainous region with heavy rainfalls, such as Japan, Taiwan and China debris flows occur frequently. Those debris flows cause loss of properties as well as lives. (Ikeya 1976; Yu and Chen, 1987). Aside from soil conservation and disaster alarm systems (Keefer, 1987) the most often used disaster prevention method is constructing detention dams. Nevertheless, there are very few theoretical studies of the impact process of debris flows. It is partly due to the uncertainty of constitutive relation and the complexity of any real problem geometry, partly due to a lack of real data on the impact process. The purpose of this study is to shed some light on the latter.

There are many experimental studies on debris flows aimming at the constitutive law. For example, Hanes and Inman (1982) used a circulating flume in which it is difficult to seperate the centripetal force. Hungr and Morgenstern (1984) used a large stress sensor to measure the total force exerted by granular flow to a 20cm wide 30cm long section. The vertical pressure was not measured.

In this paper, we shall use a flow visualization technique to obtain the flow pattern in order to calculate the impact force. Detailed review of flow visualization techniqueshas been given by Adrian(1991) and Hesselink (1988). The main problem of traditional particle tracking velocimetry (PTV) is to find the

[1] Asso. Prof., Dept. of Civil Engineering, National Taiwan University, No. 1 Sec. 4 Roosevelt Rd. Taipei, Taiwan, R.O.C.
[2] Master, Dept. of Civil Engineering, National Taiwan University.
[3] Graduate student, Dept. of Electric Engineering, National Taiwan University.