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Analyses of Special Hazards and Flooding Problems in Tropical Island Environments

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Abstract

Data and results summarized in this paper show that development of urban projects and design of flood control works in tropical island catchments must consider clear water flooding as well as special hazards such as landslides, flow bulking, high sediment concentrations, mud and debris flows and flow avulsions. The needs for and methods to estimate peak flows, event volumes and the potential extent and depths of flooding during severe storm events in urbanizing tropical environments are described.

Introduction

During the period from 1965 to 1985, floods were the number one cause of deaths and property damage by natural disasters in the United States (Rubin, et al., 1986). Deaths and property losses from floods exceeded those caused by other natural disasters such as earthquakes, hurricanes, tornadoes, tsunamis, landslides and volcanoes. These facts surprise many because floods are not usually thought to be significant causes of destruction and loss of life. This lack of public awareness of the potential dangers of floods is itself a problem. Rapidly urbanizing tropical island communities, such as Honolulu, Hawaii, are especially susceptible to flooding problems because of the rate at which urbanization is occurring, the lack of long-term continuous rainfall and runoff records to document past occurrences and the capability of severe tropical storms to produce high intensity, large volume rainfall events in relatively isolated catchments. Traditional clear water hydraulic design procedures for flood control works can lead to undersizing of debris retention facilities by 10 to 100 times and flood conveyance channels by 3 to 10 times depending on event sequencing, the severity of the storm event and geomorphic characteristics of the basin.

The New Year’s Eve Floods of 1987 in Southeast Oahu are good examples of events that weren’t predicted to be excessively large or damaging. However, within a 24 hour period it caused an estimated $35 million in damages to suburban areas. Flood damages resulted from intense localized rainfall (exceeding 22 inches in some areas). Neither the meteorological

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tracking capabilities nor the present flood control facilities proved adequate to predict or control the flooding. Post flood investigations indicated that excessive runoff was accompanied by landslides and debris flows that all contributed to the failure of the flood control and drainage systems (Dracup, et al, 1991).

Geomorphic Setting

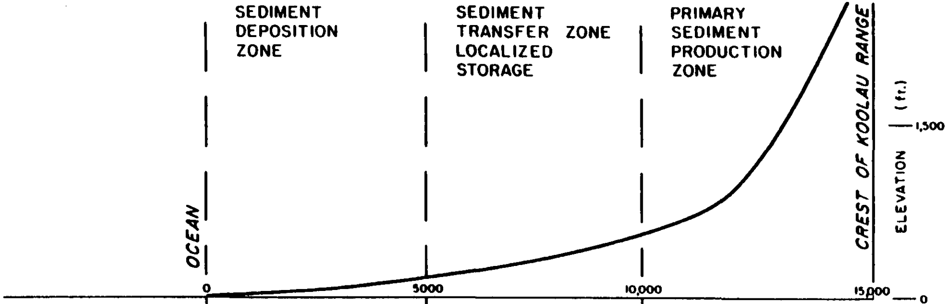
Long linear valleys that characterize catchments on the leeward flank of the Koolau Range on the Island of Oahu can be divided conceptually into 3 physiographic zones as shown schematically in Figure 1 (MacArthur and Harvey, 1991). Zone I represents the headward reaches which are the primary sediment production areas. Zone II represents the intermediate reaches which are characterized as a sediment transfer zone, and Zone III represents the downstream reaches which are sediment deposition areas that also correspond with those areas that have been urbanized. Sediment production from the hillsides is dominated by infrequently occurring shallow landslides triggered by large magnitude and high intensity precipitation events. The distribution of landslides is related to the steep elevation-precipitation gradient, which also controls the clay mineralogy of the soils throughout the valley. Mean annual rainfall in the east and southeastern portion of the Koolau Range varies from 30 inches to about 190 inches per year. Few landslides occur where the annual precipitation is less than 60 inches per year unless the slopes have been modified by cut and fill operations. Landslides appear to be triggered by high intensity storms that occur when the antecedent moisture conditions of the soils are high.

Where the annual precipitation exceeds 80 inches per year (Zone I) the clay mineralogy of the soils is dominated by hydrated free oxides of iron and alumina (laterite and gibbsite, respectively) which promote clay particle aggregation and hence high void ratios. High void ratios are associated with the translation of landslides into debris flows which are capable of causing in-channel debris torrents with the ability to entrain very large boulders that would not normally be entrained by clear water flows. Debris torrents are capable of shearing off wide swaths of channel margin vegetation. Once entrained, the large woody organic debris can form debris jams that eventually overtop and fail creating flow pulses or surges during major flood events. Localized damming of the channel during an event and subsequent failure of the dam may also be responsible for fluvial transport of some of the very coarse materials that show evidence of transport under conditions of relatively low sediment concentrations.

In Zone II, the annual precipitation varies between 40 and 80 inches. The clay mineralogy of the soils is dominated by kaolinite which does not promote the development of aggregated clay particles and hence high void ratios. As a consequence, landslides that occur in this zone are less likely to translate into debris flows and are more likely to come to rest on the hillside slopes or on the valley floor with little or no downvalley movement. Valley widening and reduced valley floor slopes promote localized deposition of sediments delivered by debris flows and water floods from Zone I. These localized deposition reaches found within Zone II may be good locations for the construction of debris basins.

Zone III is located in the downstream reach of the valley and is usually in the same location where urbanization is, or has taken place. This is a deposition zone where materials derived from landslides farther up the valley are deposited because the valley floor gradient is flatter and the valley width is greater. Very coarse grained materials can be transported into this zone by debris flows. From a process point of view the valley flows behave as alluvial fans in which channel displacement occurs avulsively rather than as a result of lateral migration.

Organic debris jams often form on the upstream sides of bridges and culverts during flood events and lead to the loss of channel capacity and reinforce the avulsive nature of the channels.



Precipitation (ins)	< 40	40-80	> 80
Clay Mineralogy	Montmorillonite	Kaolinite	Gibbsite/Laterite
Void Ratio of Soils	Low	Moderate	High
(Mass Failures) Landslides-soil slips - rock falls	Deep Seated and slow moving (colluvial aprons)	Landslides deliver sediment to valley floor and rock falls	Landslides directly to channel which is valley floor and rock falls
Debris Flows effects	Sediment deposition; channel avulsion	Sediment storage on bottom floor terraces; flow bulking	In-channel debris flows; mobilization or rock fall delivered boulders
Slope (%)	< 10	10 - 15	> 15
Channel Morphology	Pool-step	Boulder-step	Random stair - step bedrock outcrops
Organic debris	Formation of debris jams	Valley floor source; debris jams	Landslide and valley floor sources
Sediment storage potential	High due to reduced slope and greater valley width	Moderate - local zones of deposition	Low

Figure 1. Schematic of Watershed Dynamics and Physiographic Zones in Tropical Catchments in Hawaii

Debris Flow Hazards

Debris flows are common mass wasting processes in mountainous regions worldwide and are well known for their potential destructiveness and unpredictability. A debris flow is defined as a mass of saturated soil and rock materials of various sizes that moves rapidly downhill typically as a bore. It is usually confined within a channel in the upper reaches of a valley, but may build debris fans where the gradient decreases or where the valley widens and no longer confines the flows laterally. Debris flows are capable of removing and carrying large boulders (as large as 10 feet in diameter) and trees. Debris flows contain such a high percentage of solids that their mechanics differ greatly from normal, turbulent, open channel clear water flow. Debris retention structures are necessary upstream from clear water-designed flood control facilities in order to remove the large debris materials and to ensure that the downstream hydraulic structures perform according to clear water design criteria.

In Zone I intense precipitation saturates permeable surficial deposits (aggregated soil materials). This causes positive pore-water pressures that trigger slope failures. The failure dewaters adjacent saturated soils and may provide sufficient energy and material volume to develop into a debris flow. Debris flows often grow in volume by entraining underlying saturated hillslope or channel materials. This process where the initial event volume snowballs into a larger net volume downstream is referred to as flow bulking (MacArthur, et al, 1991). Flow bulking may lead to the delivery of 2 to 10 times the initial volume of water and sediment to down valley deposition areas (Zones II, III). Because of the sparse rainfall data in most high mountain areas in tropical catchments, the intensity and duration of precipitation required to mobilize soil slip materials is unknown at the present time. Campbell (1975) determined that 0.25 in/hr rainfall intensity in areas where the total seasonal antecedent rainfall had reached approximately 10 inches are the threshold conditions for the initiation of soil slips and debris flows in the Santa Monica Mountains in Southern California. Dracup, et al (1991) report that landsliding occurred in the Zone I headwaters where the 24-hour rainfall accumulation estimated during in the New Year's Eve 1987 storm exceeded 100-year 24-hour rainfall conditions. Rainfall estimates of 2-4 inches in 1 hour were reported in the same period. Valleys that have recently produced significant debris flows may continue to experience unusually high sediment yields during subsequent storms for several years until the in-channel sediment and debris supply is exhausted or becomes stabilized.

Estimating Debris Flow Frequencies

Assigning a traditional hydrologic frequency to a specific magnitude of debris flow event is not possible at the present time. The probability of occurrence of debris flows is a function of joint probability between the likelihood of occurrence of the specific hydrologic event causing the debris flow and the probability that the drainage basin will have the proper antecedent characteristics (degree of saturation, slope, availability of unstable materials, etc) to generate a debris flow. At this time there are no explicit methods for estimating the coincident frequency of debris flows in tropical catchments because the necessary detailed rainfall and basin conditions data are not available.

Problems with developing coincident frequency relationships are related to the tremendous variability in unit debris yield over a narrow range of rainfall conditions. Comprehensive rain gage networks do not exist in the watersheds where historic debris flows have occurred. Considerable variation in the rainfall distribution occurs within the catchments that cannot be explicitly measured. Most rainfall isohyetal maps (24 hour, 12 hour and 6 hour) assume a reasonably uniform distribution of precipitation over many square miles of drainage area. During the 1987 New Year's Eve event radar images showed that high intensity rainfall was occurring in Waimanalo, Niu, Hahaione and Kuliouou but not in Wailupe Valleys. The high intensity rainfall necessary to trigger significant soil slips and debris flows did not occur in Wailupe Valley even though it did occur in the surrounding valleys.. High intensity rainfall events evidently are very localized and may only occur in small upland portions of the catchments affected by the overall storm system. Therefore, estimating the event frequency is very difficult. More research is necessary to evaluate debris flow triggering mechanisms for these short duration, high intensity rainfall events. Installation of a network of triangulating continuous recording rainfall gages throughout the source zones (Zone I) as well as streamflow gages in Zones II and III is required. Stream gaging should include those areas above the developments as well as the channels near the downstream end of the basin. Geomorphologic field mapping and dendrochronologic methods for dating past debris flows may provide the necessary data to link antecedent basin conditions with hydrologic triggering mechanisms to estimate coincident frequencies for these kinds of special hazard flooding events.

Present design criteria for flood control facilities are typically based on the 24-hour storm event. This may be acceptable for clear water design, but may not be appropriate for debris flow influenced events. International literature shows that soil slips and debris flows occur suddenly as a result of short duration, high intensity rainfall occurring on a saturated basin. The Japanese and Chinese literature suggests that a good indicator of debris flow initiation can be obtained from empirical relationships between the ten minute rainfall intensity I_{10} and the cumulative antecedent rainfall P_a. Recent evidence also shows that "normalized rainfall values" (storm total/mean annual precipitation) above a certain threshold (approximately 0.32 for the San Francisco Bay area) may be another good indicator of the likelihood of debris flows. Therefore, hydrologic forecasting data for debris flows may require new shorter duration rainfall data requirements (10 minute, 1 hour, 6 hour, etc) and other means of examining rainfall data than are presently being used for traditional clear water design. Collection of these kinds of data will be costly and needs to be conducted over a long period of record to improve forecast accuracy.

Debris Flow Flooding

A unique characteristic of debris flow floods is the shape of the hydrograph. Many debris flow events occur as a series of two or more surges. The individual surges have short durations measured only in seconds or minutes and are commonly associated with a pulse (or bore) of high energy water and debris surging down the channel or over the alluvial fan surface. Debris flow hydrographs often show evidence of flow falling well below the base flow in the channel, followed by a very abrupt spike-shaped high flow for a short period of time. This results from periodic damming and breaching of debris blockages in the channel. A large boulder snout accompanied by a large quantity of floating organic debris easily plugs a narrow constriction in a steep channel. These temporary dams quickly fill, overtop and fail, resulting in a large dam break surge (flow spike) moving downstream as a bore. These bore-like surges are exceedingly destructive. Therefore, the prediction of the peak discharge associated with debris flows occurring in steep confined boulder-step channels with an abundance of organic materials is difficult to estimate. Observed peak flow pulses are often 3 to 6 times that of the estimated clear water peak discharge from a traditional hydrograph. Traditional hydrologic (HEC-1) and hydraulic (DWOPER) routing methods are often unable to duplicate the complex (and severe) hydrodynamic characteristics of debris flow bores moving down valley. It is possible that traditional hydrologic and hydraulic methods can significantly underestimate the peak discharge (and, therefore, the required channel or retention basin capacity) associated with periodic surges and increased (bulked flow) event volumes associated with debris flows. Interaction of the debris flow snout with culverts and road crossing often cause blockages and avulsions thereby diverting flood waters away from the channel. Present hydraulic methods are unable to duplicate this phenomena explicitly.

Application of multidimensional "Debris Flow Routing Models" (see MacArthur, et al, 1987, 1988, and 1991) is recommended during design of flood control projects. Avulsion and flooding depths in flood prone areas are typically based on traditional clear water hydraulics and probably underestimate the possible depths of flow and velocities associated with actual debris flow floods. Avulsions do not constitute "flooding" in the classical sense of the word and the hazards associated with exposure to avulsions are not readily dealt with on the basis of floodplain mapping. Traditional backwater profile computational procedures of floodplain mapping are simply inapplicable, although many agencies continue to use them because there are few easy-to-apply alternatives. Many floodplain maps of fans have been published that give a mistaken impression of a "normal" flooding hazard involving mainly inundation, when in fact the real hazard is related to potential avulsions and high velocity debris flows. Avulsions normally are associated with high current velocities, erosion, and sediment deposition, including very large boulders and organic debris. In almost all instances avulsions are a much more severe hazard than normal flooding. This was the case in Hahaione Valley on Southeastern Oahu during the 1987 flood. Debris blockage at Kahena Street caused an avulsion to occur that resulted in several million dollars of damage to many homes, streets and utilities.

Conclusions

On the Island of Oahu, Hawaii, the combined effects of a geomorphic setting characterized by very steep hillslopes and channels confined within narrow linear valleys, and a tropical climate characterized by localized cells of very high intensity precipitation, lead to the generation of landslide-induced debris flows. The debris flows that are composed of very large boulders and organic debris create a unique set of flooding problems that cannot be readily assessed with traditional clear water-based hydrologic and hydraulic tools. Flood control project design and evaluation should consider flow bulking, high organic and inorganic debris loading and the potential for flow avulsion, all of which are characteristic of alluvial fan flooding problems in arid and semi-arid climates. Non-traditional hydrologic and hydraulic assessment methods are required to evaluate flood hazard potential.

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