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APPLICATION OF QUANTIFIED TERRAIN DATA TO VEHICLE DESIGN CRITERIA

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Introduction.

Moving critically needed supplies to units operating beyond the existing road nets of a region requires military vehicles with high off-road capability. To build off-road capability into such vehicles the designer needs quantified terrain data -- for example, the size and physical characteristics of terrain extremes, obstacles and barriers, plus the frequency of their occurrence. Potholes, steeply beveled ditches, large boulders--to name but a few of the obstacles that may be encountered--can cripple or overturn a vehicle. If this can happen to one type of vehicle, it can happen, obviously, to others - with disastrous effects on the flow of supplies. Basic to providing the designer with criteria for improving the off-road performance of logistical vehicles is a knowledge of the physical characteristics of off-road terrain in all world environments. The innumerable characteristics of land surfaces in Arctic, desert, tropic, and middle-latitude regions make it impossible to provide a single, simple generalization useful to the designer. It is possible, however, to develop quantitative terrain data with wide application to world regions based on landform types (i.e., sand dune, lava field, alluvial plain, etc.) and it is the purpose of this paper to report a method for doing so, using the alluvial fan as the focus of study.

Parameters of the Problem.

The problem of improving off-road capability can be stated in terms of two major parameters -- the physical characteristics of the terrain and the performance characteristics of present military vehicles. Optimal functional design will have been achieved when engineering improvements provide off-road capability sufficient, within an established risk policy, to meet terrain problems of a pre-selected level of difficulty.

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Microgeometric features of landscapes are of primary importance in developing functional designs for military vehicles, but have been neglected while the emphasis in mobility research has been in the mechanical properties of soils (5, 9, 11). Specifications for required vehicle ground clearance, vertical obstacle clearance, side slope stability, angle of approach, angle of departure, gradability, steering radius, and many other engineering or performance requirements are dependent on applicable evaluation of land surface data (13). To be usable in machine calculations, terrain data must be measured and tabulated quantitatively. Tests for the validity of these data can be made by machine in a point comparison using representative models. Quantified profile data can be programmed, such as inputs to machine evaluation of the suspension systems of existing or prototype vehicles for determining a radius of action as defined by terrain roughness (8).

Determining and measuring the terrain features of concern in establishing design criteria is not without problems. No method exists for studying world environments as an aggregate from which particular constants can be derived. The environments of the world must be interpreted and studied regionally (13). It has long been recognized that military problems in the Arctic, desert, tropic, and middle latitude regions are distinctive. Each of these regions is characterized by interrelated environmental conditions, including climate, vegetation, soils and landforms. Some landforms, such as the Arctic pingo, are found in only one region; others may occur in all regions. Landforms in desert regions generally will reflect the climatic conditions of that region. The same type of landform in humid climates will have different characteristics, due at least in part to different conditions of erosion by running water or drainage.

It is impracticable to measure all of the land areas of the earth by presently used methods or even to remeasure all of the easily accessible areas to derive frequency and areal probability information desired by designers of off-road vehicles. It is possible, however, to make detailed measurements of selected terrain features in the field at carefully selected sites that are representative of major land surface types, and to extrapolate these findings by photogrammetric techniques to adjacent areas. A useful method for land surface classification is the landform approach. It has been shown also that a large percentage of land in each major region of the world is composed only of a few of the major landform types, and by determining the physical characteristics of representative samples from these types, the quantitative nature of the terrain in the greater part of the region can be shown.

In addition to information on the size and physical characteristics of terrain extremes, obstacles and barriers, designers want to know how often these will be encountered, and over how large an area they occur. It is not feasible to design for every possible landform condition that may be found in nature, nor should it be

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assumed that the same scale of logistical operations will be conducted in all environments. Frequency-of-occurrence information is essential in giving dimensions to the problem of design. When the risk policy is determined, the designer can immediately see on the frequency plot the terrain limits that must be met.

Alluvial Fan Investigation

One landform type that reflects regional differences and is found in nearly all regions is the alluvial fan. Alluvial fans are water deposited features that form at the mouths of canyons emptying into wider valleys. They are sector-shaped deposits, consisting of rock debris washed out of the highland in which the parent canyon or wash is located. Alluvial fans occupy 31.4 percent of the land surface of southwest United States deserts (7). In certain smaller areas heavy concentrations of alluvial fans completely dominate the landscape. In Death Valley, California, alluvial fans cover approximately 1,100 square miles, over 73 percent of the main valley floor (2). Because of their relatively gentle slopes, good drainage and sorted composition material, these deposits are frequently used for roads, sites for urban development, and agriculture, especially in desert regions where the mid-valley playa is too soft and saline and the bordering mountains too steep and composed of materials too hard for these purposes. Military operations in desert regions, particularly in folded and faulted terrain, would realize definite transportability and trafficability advantages if alluvial fans were utilized.

Relatively large populations of terrain measurements are essential for the development of frequency curves. Unless theoretical terrain models are supported with a profound depth of understanding of all terrain conditions, they will not give the same results as those based on a large accumulation of facts from every possible source. In the present study the physical characteristics of 3,876 alluvial fans of all sizes in southwestern United States were analyzed together with 346 in West Pakistan. In these 4,222 samples all major alluvial fan types were represented: the large coalesced fan, secondary fan, etc. Studies of the characteristics of each of these types provide data which may be applied to design problems for similar types in the same environment in other areas of the world.

In making detailed field measurement of alluvial fans, on 25 representative samples, it was found that each of these landforms exhibited significant individual characteristics. Measurement also showed that there is little analogy between landforms in Arizona and those in California. No apparent pattern or areal relationship could be seen until bivariate frequencies (radii and gradient) were computed and tabulated by machine. The population was large enough to determine the actual regional incidence of subtypes of this landform, as well as the spread of possible variations.

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Approximately 70 percent of all alluvial fans included in this study had gradients from 1 to 5 degrees and were from 1 to 5 miles in length (Figures 1 and 2). These gradients closely approximate the slope of the main wash floor on the fan, but not that of the interfluvial surface. The greatest obstacle to foot or vehicular movement on alluvial fans is the steep slope of limited extent. In most instances these slopes are of microgeometric scale.

Military vehicles may overturn or become immobilized in moving over microgeometric obstacles. Large boulders, boulder trains, steeply beveled ditches, potholes at the head of an arroyo, and other micro features on alluvial fans frequently have slopes greater than 60 degrees for short distances. The main wash may have vertical cliff sides from 10 to 50 feet in height, and total local relief of 70 to 100 feet. These slopes are not continuous, and trafficable routes across nearly all parts of the fan can be found. The main alluvial fan wash is a route of easy access from the main canyon to the tributary mountain canyon. Crossfan movement is usually easy on the lower slopes or apron. However, washes with vertical slopes greater than 10 feet may occur at any point along the fan. They are especially prominent near the mountain face where continued erosion has cut deeply into the fan alluvium.

Microgeometry.

Measurements were made of deep distributaries (washes with vertical relief 3 feet or greater) along six 1-mile transects across the face of the upper Avawatz fan (a typical example of the large coalesced fan in California). A great number of these distributaries varied significantly along the transect line. For example, along the second transect (3000 feet downslope from the fan apex) the maximum heights of vertical slopes or cliffs in the distributary washes from east to west ranged from 3 to 25 feet. Over 36 percent of these vertical slopes were between 3 and 5 feet, 37 percent were between 5 and 7 feet in height. These heights are not indicative of total slope conditions, however. Nearly all of these washes have steep sides with piles of debris at their base. In nearly all instances loose material from the upper portions of the wash sides has slumped and slipped down to the base of the nearly vertical middle portion. A gully 5 feet in depth may have a 2 to 3 foot vertical wall on either side above the loose material on the gully floor. A gully 20 feet deep may have vertical walls 10 to 15 feet in height. The older consolidated or cemented fan materials are easily cut into vertical or overhanging forms by stream floods heavily charged with sharp angular material.

Cross fan movement by presently available surface vehicles is impossible in areas of deep distributaries. Concealment, however, is good. Movement up the fan is possible only in the larger gullies because of the general narrowness of the gully floor. The floors of distributary washes vary from 1 to 10 feet in width. The floor of

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the main wash on an alluvial fan may vary from 50 to 3000 feet in width. In most instances these floors are covered by bars of loose sand and gravel, up to 2 feet in height, with an occasional slump of the side walls. At any point upstream from the fan apex talus cones may completely block the valley.

The interfluvial surface between deep washes on the fan is scarred by a maze of minor distributaries (with sides less than 3 feet in vertical height). A random crossfan 1500 foot transect in the lower third of the Stovepipe Wells (California) fan showed that the greatest local relief (a boulder train) in this short distance was 34 inches from plan level. A total of 31 minor distributaries were counted along this transect. The greatest vertical slopes measured were 14.8, 6.5, and 5.4 inches. None of these would stop any of the currently available military vehicles. A problem does exist, however, in crossing boulder trains with individual rock diameters as great as 24 inches. The transect crossed 12 of these trains. These features will break axles, dent transmission housings, and rupture crank cases, even when crossed at crawling speeds.

Vehicle Performance.

Vehicles also become immobilized in "V" shaped gullies, many of which have nearly level floors, because of inadequate traction, excessive sinkage in loose materials on the gully floor, or incompatibility of the vehicle configuration with the gully floor geometry. Vehicles with low angles of approach (excessive overhang beyond the track or front wheels) frequently run into the opposite bank when reaching narrow gully floors. Wheeled vehicles cut deep ruts into the loose material on the gully floor and usually had insufficient traction to back up or maneuver. When the vehicle had sufficient momentum or compatible angle of approach to cross the gully, immobilizations were often encountered because it had insufficient traction to climb in the loose material or hard rock on the opposite bank. Their low angle of departure, particularly on wheeled vehicles, would often prevent backing up or maneuvering to another section of the gully.

Occasionally, with insufficient traction on either bank, a vehicle will slip or slide down to the gully floor sideways. When the gully is narrow the track or wheels on one side may not touch the ground, or may be in loose material. In this instance, vehicles with relatively low ground pressure may be immobilized by bearing capacity failure. If the vehicle is not lying on its side, and if its overloaded running gear does not bog down in loose material on the gully floor because of insufficient flotation in relation to soil bearing capacity, it may be possible to recover by moving up or down the gully until a suitable exit is found.

When the gully floor is wide enough to allow the vehicle to sit on the bottom and perhaps make a short run to the opposite

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bank, it may not develop enough momentum to carry itself to the top of the gully bank. Poor traction on the gully floor may prevent the vehicle from developing the required momentum. If the lower portions of the bank are vertical or nearly vertical, and the width of the gully bottom is approximately equal to the length of the vehicle, it becomes trapped, unable to move ahead or to the rear. Every single-unit vehicle will conform to one basic size of ditch of this type (12).

Vehicles with long wheel bases and high breakover angles may become immobilized by reaching "high center". This condition may occur when entering or leaving the gully floor with a low vertical cliff or at the top of the gully bank if the slope makes an abrupt angle with the horizontal. It may be possible for the vehicle to back out of this situation if the vehicle has sufficient traction. A nose-heavy vehicle with a long wheel base will perform better when crossing an obstacle with the rear wheels than when crossing it with the front wheels. There is an optimum of design conditions where both wheels have the same performance and one does not limit the performance of the other (3).

Even minor ditch-like breaks in the landscape can be obstacles. If a large vehicle, such as the M-60 Tank, leaves wide deep ruts in loose or soft soils, or turns crusted soil layers into deep beds of dust, these may cause immobilization of even high performance vehicles, such as the M-116 Personnel Carrier.

The high angle of approach (45°) of the M-116 contributed to its ability to traverse all of the minor distributaries and nearly half of the major distributaries on alluvial fans at Camp Irwin, California (Figure 3). The low angle of approach of the M-113 (25°) and its extremely low angle of departure (15°) contributed to its poor performance (Figure 4). In this instance there has been marked improvement in design without quantified landform data to justify this design. In some instances, such as the GOER, high costs of design changes do not always result in improvement.

In the 25 alluvial fan samples of representative types, a frequency distribution study was made of slopes in several obstacle classes for vehicles such as the M-29 Amphibian, M-35 Truck, M-52 Cargo Vehicle, and M-36 Gun Carrier. Different slope percentages could be computed for such vehicles as the M-113 Personnel Carrier.

Obstacles modifiable only by extensive engineering effort were not considered in this investigation. The following slope conditions are related primarily to individual vehicle equipment or organizational equipment readily available to vehicle crews. The frequency of slope conditions can be determined for various classes of non-trafficable obstacles, and these data may be added to the following table. However, such data are not essential for developing design criteria.

TABLE OF ALLUVIAL FAN OBSTACLE SLOPE FREQUENCY DISTRIBUTION

Class Values (degrees)	*Vehicle-Negotiable (%)	**Vehicle-Negotiable With Winch (%)	***Modifiable by Spade or Dozer Blade (%)
< 20	18	51	48
20-30	6	17	8
30-40	9	17	7
40-50	21	2	11
50-60	15	5	14
> 60	31	8	12
$\bar{x}$	47°	19°	22°
n	100	100	100

* 18 inches or less in height

** 18-36 inches in height

*** 36 inches or greater in height

The relationship of slope angle frequencies to vehicle performance is seen in Figures 3 and 4. Vehicles such as the M-116 are capable of entering the average alluvial fan gully without becoming immobilized, those with characteristics similar to the M-113 can not.

Figure 5 illustrates the use of microgeometric profile data together with vehicle performance data in determining required vehicle obstacle clearances. Figures 6 and 7 demonstrate the relationship of given vehicle wheelbase lengths and measured slope entry or exit angles to required vehicle ground clearance heights.

For example, a vehicle such as the M-151 with a wheelbase length of 11 feet and a ground clearance of 11.4 inches would be able to cross an obstacle with a top slope angle of 160 degrees or greater. This vehicle has a very high angle of approach (66 degrees), but this advantage is offset by the low ground clearance of the vehicle. Fortunately, top slope angles of 160 degrees or greater are characteristic of the lower third of the average large alluvial fan, and 70 percent of the entry and exit slopes are less than 66 degrees on gullies in this area. Similar information can be determined for any class of vehicle using the formula in Figure 7 and the slope frequency given above. Also, the required performance characteristics of a vehicle to be designed for movement over 90 or 100 percent of alluvial fan terrain can be determined.

Discussion.

At the present time, vehicle designers merely attempt to improve their previous designs. Standardization objectives give little attention to meeting a particular land surface problem, such as climbing a given slope, because very little information is available on the actual number or areal occurrences of such a slope. If information were available on slope frequencies or on probabilities that given obstacles will be encountered in a given landform complex, the vehicle designer could be guided by facts rather than unsupported estimates or terrain theory.

Quantified terrain descriptors are needed to complement other environmental facts, such as soil strength data, required by vehicle designers. Terrain frequency data can be used to illustrate how many and how often specific obstacles or barriers to movement will be encountered in a given area, information on the probability of occurrence of given slope or profile conditions, or the amount of non-trafficable land for given vehicle types. Frequency data based on photogrammetry and field measurements may be applied directly to revisions of AR 705-15, Military Standards, and specifications for testing military equipment.

Information compiled in this study on the microgeometry of alluvial fans has been used to show specific slope relationships to

essential vehicle performance characteristics, and to aid in making meaningful analyses of vehicle performance data. Alluvial fan data, together with that for other major landforms, may be the basis for vehicle use regions. The close agreement of alluvial fan characteristics in southwestern United States and in West Pakistan (Figure 8) indicates that landforms in similar physiographic regions (in this case, folded and faulted structures) and similar climates (in this case, hot and arid) will have analogous slopes and profiles.

The number of deep distributaries on alluvial fans, those requiring major engineering efforts for trafficability with present vehicles, indicate increased performance requirements for off-road vehicles. The great number of immobilization conditions encountered in minor distributaries, where the "V" shaped ditch may be as much of an obstacle as a vertical wall, indicate a very limited use probability for present vehicles in these areas.

Conclusion.

In order to develop terrain design criteria applicable to increasing off-road capability, it is essential that the microgeometry of the world's landforms be investigated quantitatively, that the data be reduced to frequency curves or similar tabulations, and that comparative analyses be made between these data and present critical vehicle performance characteristics. Inasmuch as a single agency could not catalog all of the world's terrain in the required detail in a reasonable period of time due to normal personnel and funding limitations, it is essential that the task be divided among several agencies. The first step in setting up a cooperative program would be to select representative sample landforms in each major region for detailed study. Investigations of a single landform, alluvial fans, in a single region demonstrate that terrain design criteria can be developed from these data, especially when these data are quantified and their frequencies of occurrence are determined.

TABLE OF FIGURES

Figure 1. Alluvial fan gradient, frequency of incidence. This figure illustrates the frequency of overall slope conditions on large coalesced alluvial fans, and the close agreement of these data in both the United States and West Pakistan. It is an example of the type of diagram which was constructed for each slope category (entrances and exits of gullies, barriers and obstacles) in the 25 representative samples of alluvial fans selected for detailed study.

Figure 2. Alluvian fan radii, frequency of incidence. The radius of each alluvial fan was determined by:

$$S_d = \frac{P_d}{\cos S_a}$$

where S_d is the measured slope distance, P_d is the actual horizontal distance, and S_a is the slope angle. The difference in elevation of the apex and the outer apron termini point divided by the radius (x.01085) gave the overall gradient data shown in Figure 1.

Figure 3. Angles of approach and departure for the M-116. While this vehicle has better angle of approach characteristics than previous designs, it cannot negotiate all of the off-road conditions found on alluvial fans. A comparison of its angle of approach with angle of entry conditions to be encountered in 18-inch gullies indicates the nature of some of the off-road obstacles for this vehicle.

Figure 4. Angles of approach and departure for the M-113. Comparison of these angles with the average slope for an 18-inch gully on a large coalesced alluvial fan show that this vehicle would become immobilized on entering or leaving this obstacle.

Figure 5. Schematic profile of an alluvial fan gully. In order for a given vehicle to cross a gully wider than its wheelbase length, the required ground clearance of the exit and entrance slope profiles must be computed. Assuming that $180^\circ - B < \phi$, $\phi > 180^\circ - C$, $180^\circ - B < \theta$, and $\theta > 180^\circ - C$,

$$h_1 = \frac{W_v}{2} \tan \left[\frac{180^\circ - A}{2} \right] \quad (1)$$

and

$$h_2 = \frac{W_v}{2} \tan \left[\frac{180^\circ - D}{2} \right] \quad (2)$$

where

- A is angle of entry 1
- B is angle of exit 1
- C is angle of exit 2
- D is angle of entry 2
- W_v is vehicle wheelbase length
- θ is vehicle angle of approach
- ϕ is vehicle angle of departure
- h_1 is required ground clearance exit 1
- h_2 is required ground clearance exit 2

Figure 6. Required ground clearance, top slope angle relationship. Where vehicles have a suitable angle of approach, but a critical ground clearance height, the possible top slope angles of gullies, boulder trains, or other natural obstacles negotiable by this vehicle can be computed. The relationship of these angles to natural terrain frequency distribution show the limitations of use of this vehicle.

Figure 7. Required ground clearance, wheelbase length relationship. For the purpose of vehicle design, the required ground clearance and wheelbase length for each top slope angle can be determined. The slope frequency diagrams for each major landform can be used with these data to determine a reasonable risk policy for design criteria.

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Figure 8. Alluvial fan radii and gradient relationships in random samples in Pakistan and the United States. As a test of analogy, field studies were made of alluvial fans in physically and climatically comparable areas in the two countries. The curves clearly show the close relationship of the landforms in these countries, particularly those with radii of one to two miles (which had the greatest population in Figure 2).

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ALLUVIAL FANS
GRADIENT
FREQUENCY OF INCIDENCE

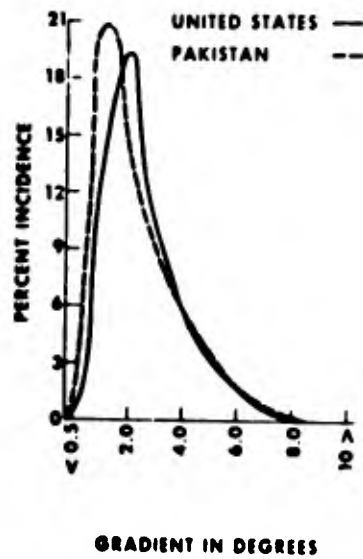


FIGURE 1

ALLUVIAL FANS
RADII FREQUENCY OF INCIDENCE

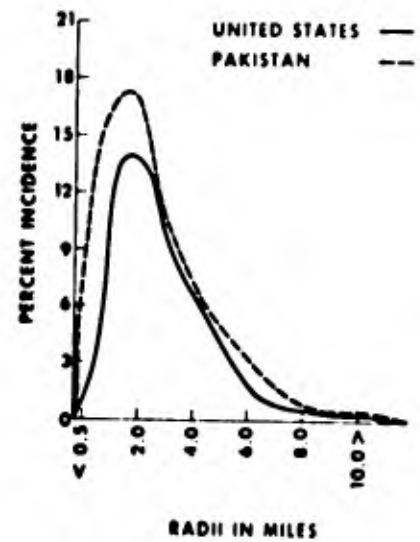
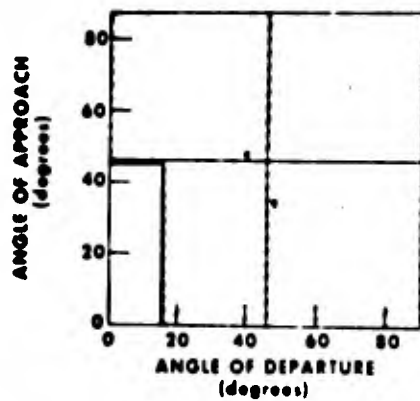


FIGURE 2

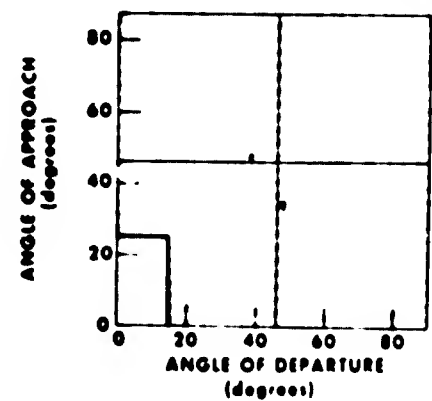
M-116
ANGLES OF APPROACH AND DEPARTURE



- 50% ANGLE OF ENTRY TO OBSTACLE
- 50% ANGLE OF EXIT FROM OBSTACLE
- ANGLES OF APPROACH AND DEPARTURE - M 116
- SLOPE ANGLES GREATER THAN VEHICLE APPROACH OR DEPARTURE ANGLES

FIGURE 3

M-113
ANGLES OF APPROACH AND DEPARTURE



- 50% ANGLE OF ENTRY TO OBSTACLE
- 50% ANGLE OF EXIT FROM OBSTACLE
- ANGLES OF APPROACH AND DEPARTURE - M 113
- SLOPE ANGLES GREATER THAN VEHICLE APPROACH OR DEPARTURE ANGLES

FIGURE 4

ALLUVIAL FAN WASH
SCHEMATIC GULLY PROFILE



FIGURE 5

REQUIRED GROUND CLEARANCE
TOP SLOPE ANGLE RELATIONSHIP

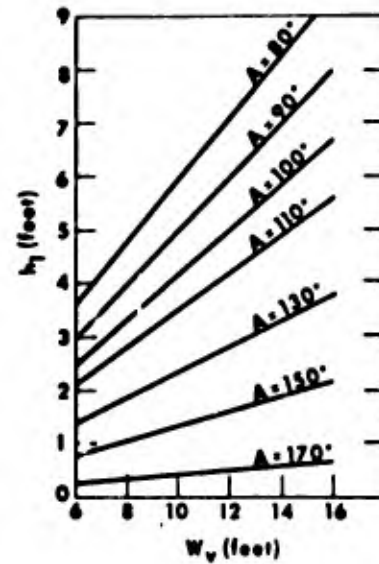


FIGURE 6

REQUIRED GROUND CLEARANCE
WHEELBASE RELATIONSHIP

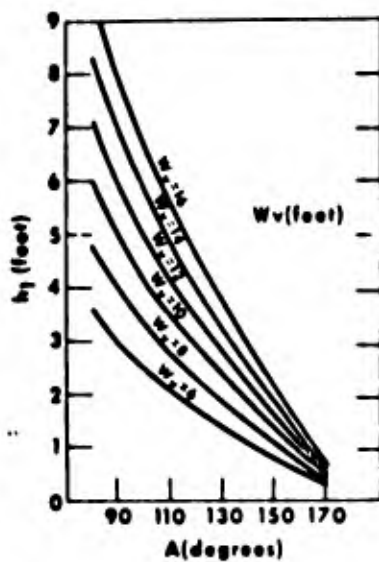


FIGURE 7

RADI AND GRADIENT
RELATIONSHIPS OF ALLUVIAL FANS
IN RANDOM SAMPLES

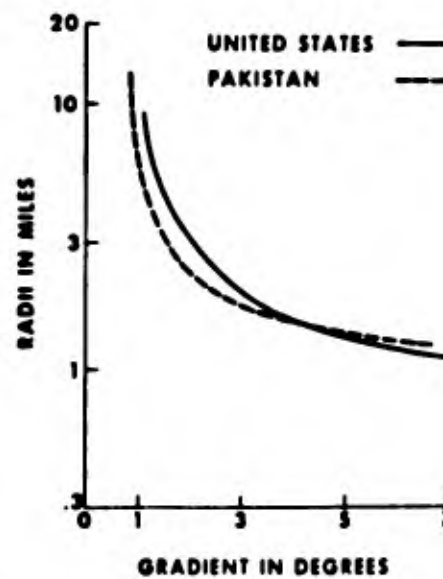


FIGURE 8