Characteristic slope angle of V-shaped valleys in humid steep mountains with frequent slope failure

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Abstract—**Characteristic or threshold slope angles with higher frequencies than other angles are related to slope stability determined by soil mechanics, bedrock strength, tectonics and climate. High relief mountains in Japan and Taiwan tend to have a characteristic slope angle of ca. 35°, which corresponds to the typical form of V-shaped valleys. Regolith is usually very thin in these mountains, and differences in bedrock, climate and uplift rates seem to exert little influence on slope angles. Slope histograms are negatively skewed in most parts of mountains where the characteristic slope angle is observed. These results differ from previous observations in other mountains. The angle of 35° corresponds to the angle of repose of dry regolith. Therefore, the angle permits repeated shallow slope failure in almost all parts of the slope even near ridgelines with limited effects of water saturation. This evenly distributed erosion, coupled with the similar production rates of regolith by weathering over a slope with nearly homogeneous bedrock lithology, leads to parallel retreat of the entire slope. Comparisons of hillslopes formed in the post-glacial period with those formed earlier indicate that accelerated erosion in response to climatic change has led to slope incision and locally steepened slope segments, but most of the newer hillslopes still tend to have the characteristic slope angle. The locally steep segments will diminish with upslope migration. These mechanisms combined with gradual river down-cutting can maintain the constant shape of v-shaped valleys for a long period.**

I. INTRODUCTION

The frequency distribution of slope angles has been a geomorphological topic since the classic work by Strahler [1]. Some studies have shown that certain angles appear more frequently than the others. Such characteristic or threshold slope angles received particular attention in the UK and the USA during the 1960s and the 1970s [e.g., 2, 3, 4, 5, 6, 7]. The results point to some characteristic slope angles including ca. 20°, 25° and 35°, and their occurrence was ascribed to soil mechanics. For example, small upper segments of valley-side slopes with dry screes tend to have slope angles around 35°, whereas middle to lower segments under the influence of ground water have angles around 25° [3]. However, in steeper mountains in the USA and the Himalayas, regolith is thin, and bedrock strength, uplift rate, and climate are considered to affect dominant slope angles [e.g. 8, 9, 10]. It is also suggested that the skewness of slope histograms changes from positively skewed to negatively skewed as mean slope increases [11].

This paper analyzes slope angles obtained from DEMs for steep mountains in central Japan and Taiwan with special attention to characteristic slope angles. The results differ from observations by previous studies in that a characteristic slope angle of ca. 35° is widely observed despite the lack of thick scree cover and differences in geology, climate and history of mountain uplift. We investigate the causes of the broad occurrence of similar slope angles.

II. Data analysis and results

The study areas are the three regions of the Japanese Alps (Northern, Central and Southern: NJA, CJA and SJA) and the Taiwan Central Range (TCR). All are typical steep non-volcanic ranges in the two countries. DEMs with a resolution of 40 or 50 m produced from governmental topographic maps, were analyzed to obtain the mean and modal slope angles for each 50-m altitude bin. Based on geologic data, areas covered by Quaternary unconsolidated sediments, such as flat valley bottoms, were excluded before the analysis, although such areas are very limited in the studied mountain ranges. Data for the uppermost and lowermost altitude zones with only a small number of DEM cells were not used.

Fig. 1 shows the relationship between altitude and slope for the NJA. Except for the lowest and highest parts, modal slope angles tend to be constant around 35°. For this altitudinal zone, the mean slope angle is always lower than the modal angle, pointing to a negatively skewed frequency distribution. The altitude–slope relationships for the CJA and SJA are very similar to that of the NJA [12]. Fig. 2 shows the altitude–slope relationship for the TCR [13]. The modal slope values are also around 35° and a negatively skewed frequency distribution of slope except for the lower zone is common to the Japanese Alps. Differences between the mean and modal slopes for the TCR are relatively small indicating that the frequency distribution of slope angles is closer to a normal distribution.

Observation of the topography in the four mountain ranges indicates that the characteristic slope angle of ca. 35° corresponds to the overall inclination of the side slopes of V-shaped valleys. Fig. 3 shows a typical watershed in the TCR, and Fig. 4 shows transverse sections of the watershed, sampled from the lower to upper parts with a regular interval based on the method of Lin and Oguchi [14]. Throughout the watershed, V-shaped valleys with nearly straight side slopes with angles around 35° can be observed.

III. Discussion

Hillslopes in the four Japanese and Taiwanese ranges are characterized by thin regolith cover subject to frequent slope failure due to heavy rainfall (and sometimes, earthquakes). In other words, the slope angles of the ranges basically reflect the shape of the bedrock, not the unconsolidated materials. Therefore, in contrast to the studies in the UK and the USA during the 1960s and the 1970s, the observed characteristic slope angle appears unrelated to soil mechanics.

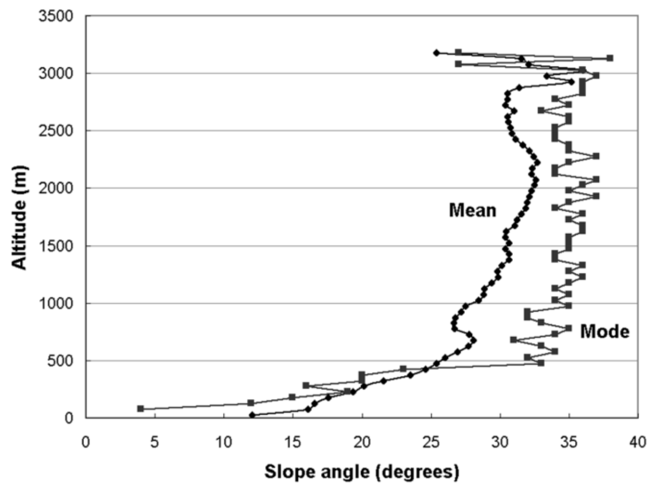

Figure 1. Mean and modal slope angles for 50-m altitude bins in the Northern Japanese Alps (NJA) [12]

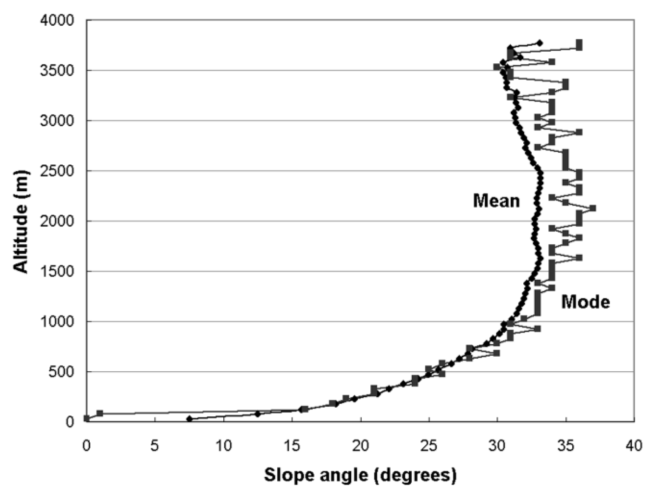

Figure 2. Mean and modal slope angles for 50-m altitude bins in the Taiwan Central Range (TCR) (Modified after [13])

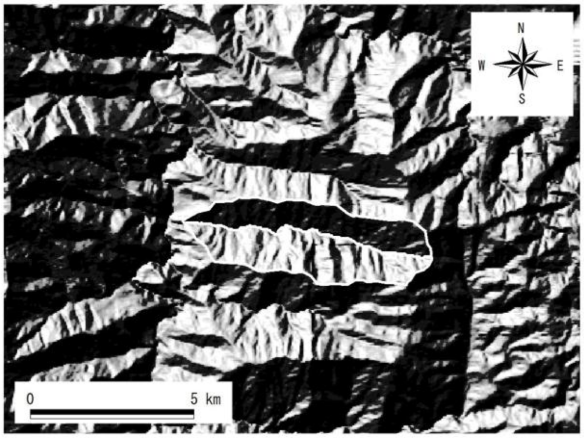

Figure 3. A typical watershed in the Taiwan Central Range (TCR)

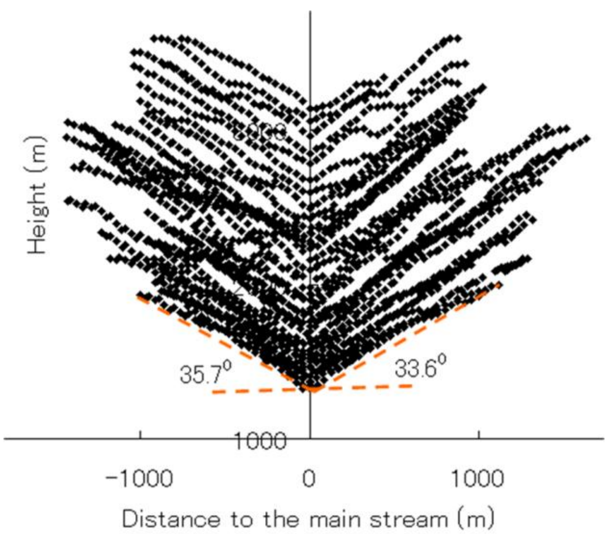

Figure 4. Transverse sections of the watershed in Fig. 3.

The four ranges each have somewhat different geology: The CJA consist mainly of granite; the SJA and the TCR mainly sedimentary and metamorphic rocks; and the NJA a mixture of the three rock types. The history of uplift also differs: for example, the NJA was already high and steep in the late Tertiary; while the SJA started uplifting in the early Quaternary, and the CJA started uplifting at 0.5 Ma [15]. It is also known that the uplift of the TCR is faster than that of the Japanese ranges.

The climate of the four ranges is basically humid temperate, but there are some differences. For instance, the NJA are near the Japan Sea and receive more snow in winter whereas, the SJA near the Pacific receive more rainfall in summer. The TCR is also characterized by higher temperature than the Japanese ranges.

Despite these differences, the characteristic slope angle and the mode of the skewness of slope angles are similar among the four ranges. Therefore, the Japanese and Taiwanese examples appear different from the previously reported cases in the USA and the Himalayas where lithology, tectonics and climate are considered to play important roles in determining threshold slope angles.

We hypothesize that the characteristic slope angle of ca. 35° is related to soil mechanics in a different way from the classic studies in the UK and the USA. As shown in Fig. 3, the V-shaped valleys in the study area have numerous small channels and hollows. Therefore, most parts of hillslopes have very small upstream areas, and even at the time of heavy rainfall, regolith there does not contain much water. However, a small addition of water into regolith can cause it to fail if the slope angle is close to the angle of repose of dry regolith. This agrees with observations in the four ranges – slope failures can occur on almost all parts of hillslopes including areas near ridges. Not only rainfall-related erosion but also other types of erosion such as earthquake-induced slope failures can occur widely if the slope angle is close to the angle of repose. The resultant evenly distributed slope erosion, combined with the similar production rates of regolith due to weathering over a hillslope with almost homogeneous bedrock lithology, leads to the parallel retreat of the whole hillslope. This mechanism coupled with effective sediment removal and gradual downcutting by a river at the valley bottom can maintain the V-shaped valleys with an angle of ca. 35°. Evans [16] also suggested that the characteristic slope angle observed in the Japanese Alps reflects dynamic equilibrium with landsliding removing fractured rock and river gradient increasing to transport this.

As shown in Fig. 4, local slope segments steeper and gentler than the characteristic slope angle can be created within V-shaped valleys for various reasons. A case widely observed in the Japanese Alps is the effect of post-glacial hillslope incision. Hillslopes there can be classified into two types: smooth and incised slopes. The latter have developed by cutting into the former in response increased storm intensity since the Late Glacial [17, 18]. The boundaries of these two types of slopes tend to form convex slope breaks steeper than the surrounding slopes. However, change in overall hillslope angles due to incision is very small because the depth of incision is limited. Moreover, the locally steep slopes caused by the incision will diminish with their gradual upslope migration [17, 18]. This example suggests that the general shape of V-shaped valleys with the characteristic angle of ca. 35° can be maintained regardless of major changes in climate.

The negatively skewed slope histograms indicate that hillslopes gentler than the characteristic slope angle can survive longer than steeper slopes. Unlike the enhanced erosion and resultant gradient reduction on local steep slopes, it takes longer for gentle slopes to steepen and reach the characteristic angle. The frequency distribution of slopes in the TCR is closer to the normal distribution than that of the Japanese ranges, suggesting that the TCR is closer to typical dynamic equilibrium under faster uplift and erosion. This agrees with an inference from the size and form of alluvial fans and source basins in Taiwan [13].

A modal slope angle around 35° and negatively skewed slope histograms have been observed in some other steep mountain ranges in Japan [19] and in the Southern Alps of New Zealand [20]. Therefore, the reported slope structure seems to be common to humid steep mountains with frequent slope failure. However, the proposed mechanism for the maintenance of the characteristic slope angle in V-shaped valleys is still qualitative and needs further discussion and verification.

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