The relationship between slope gradient and lateritic cobble orientation with respect to shape, northwestern Taiwan

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Abstract In situ investigations of lateritic cobble slopes have demonstrated that where the grain orientation is more uniform, the anisotropy is more obvious. Grain orientation will also affect the slope gradient and slope surface. The slope forms an escarpment when the intersection between the cobble orientation strike and the slope surface ranges between 90 and 180°. By contrast, there is a dip-slope geometry when the angle of intersection is 0°. The slope gradient increases and has an angle of 50 to 80° when the intersected angle ranges from 0 to 180°. The results indicate a positive relationship between these two factors. The slope grade will increase when the disk and bladed grain shape of the cobbles increase their percentage relative to the material composition. On the other hand, the slope gradient decreases when the proportion of equant and roller grain shapes of cobble increase in the composition.

Keywords Cobble · Orientation · Intersected angle of strike · Grain shape · Northwestern Taiwan

Introduction

A particular morphology and sedimentary environment is necessary to form a depositional area for rock fragments.

Rock fragments, such as boulders and cobbles, are transported downstream from higher slopes by debris flows, floods, and turbidity currents (Pettijohn 1975). The thickness of these deposits varies widely because the water volume of each flood and the up-slope material availability varies greatly over time. The deposit will have a matrix supported structure when large boulders are floated within the fine fractions. A grain supported structure will form when a great volume of boulders enters the turbid regime (Nemec and Steel 1984).

The principal sources of sand and cobble are relatively young, unconsolidated superficial deposits accumulated since the onset of the late Pleistocene. Sand, cobbles, and the fine fractions may be spread extensively over the floodplain during flooding. Cobbles are commonly found under a silt cover widely spread over the deposit by flooding. The terrace deposits are commonly cobble-rich below, becoming more silty above.

The western part of Taiwan Island has a series of sedimentary deposits from the late Miocene. Many of these formations have formed from deposited sand and mud. The cobbles and boulders mentioned above appear occasionally in these formations, forming several terraces of that era from the Penglai orogeny after the Pliocene (Ho 1986). Landslides and debris flows often occur on these terraces. Landslide areas total approximately 21.26 ha, representing 10.54% of the total slope area, in the Linkou terrace. They are composed of lateritic soil and flat-lying cobble deposits (Liao and others 1987). Landslides are a serious problem in slopes that are composed predominantly of lateritic soil and cobbles. In this paper, cobbles are considered to be irregular ovoid-shaped materials sized between 4.75 and 300 mm. This definition is taken from the Unified Soil Classification System (Wagner 1957).

Wan and others (1986) point out that the lateritic material is a result of weathering processes on cobbles involving acid pH and varying degrees of wind and precipitation. The iron absorbs the clay fractions and forms a mass that will collapse and decrease dramatically in shear strength when it is immersed (Newill 1962).

Matheson (1986) and Matheson and Parent (1989) point out that when the percentage of cobbles is less than 70%, the shear strength will be governed by matrix support in the lateritic cobble material. Day (1993) demonstrated that with a cobble content of more than 70%, the vertical deformation would be governed by the percentage of cobbles in the lateritic cobble material.

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Laboratory tests have revealed that the major mechanism of slope failure in the Linkou terrace was triggered by heavy precipitation forming a wet zone and creating a shallow failure (Hung and others 1985; Chen 1990). Chen and Chen (1991) used some combined engineering characteristics of lateritic cobble materials in the terraces for comparison. They pointed out that the high proportion of matrix support usually governs the mechanical behavior of slope stability in lateritic cobble formations. These results imply that investigations of the mechanical properties of terraces must consider the percentage of cobbles present. This paper examines slope stability with respect to the orientation of lateritic cobbles and the distribution of slopes in northwestern Taiwan. The aim of this study is to gain an understanding of the relationships between the cobble orientation, cobble shapes, slope gradients, and slope stability. The study was based on the Linkou, Taoyuan, and Tadu terraces in northwestern Taiwan (Fig. 1). All of them are of late Pleistocene age (Ho 1986).

Criteria for outcrop selection

Outcrops were selected according to the following criteria: (1) the slope has not undergone diagenesis and is not part of a rock basement, (2) the slope has no vegetation cover, and (3) the slope has slid into its current fresh slope condition. In this study, 105 sites were selected for analysis. The Linkou terrace had 32 sites, the Taoyuan area had 35 sites, and the Tadu area had 38 sites.

Geological setting

The island of Taiwan is located on the boundary of the tectonic collision zone arising from the Philippine Sea

plate toward the southeast and the Eurasian Continental plate toward the northwest. The island is 75% mountainous and 25% low-lying hills, alluvial plains, and terraces. The terraces are mostly located in the western half of the island. The mountains are quite steep due to their relatively young age. In general, the eastern part of this island is composed of metamorphic rocks of the Mesozoic to the late Paleozoic age (Ho 1986). The western part is sedimentary rock of Miocene age and the northern part is volcanic rock of Pleistocene age.

Terraces are a major terrain feature in northwestern Taiwan, and are common throughout the island except in the Hengchun area in the south. These terraces from north to south include the Linkou terrace, the Taoyuan terrace, and the Tadu terrace (Yang 1986; Lin 1991). Interlayered gravel, sand, and mud of the late Pleistocene underlie these terraces. There is often a cover of a thin veneer lateritic soil. This sedimentary sequence has been explained in terms of alluvial fan, delta, coastal, and transitional coastal environments (Chen and Teng 1990).

Linkou terrace

The elevation of the Linkou terrace is around 200 to 250 m and creates a triangular area. The predominant lithology of the Linkou terrace comprises loose and uncemented Linkou and Tanawan formations. The thickness of the Linkou Formation is over 300 m and it is mainly composed of conglomerate. This formation is distributed on the eastern part of the Linkou terrace. The Tanawan Formation mainly consists of mud, sand, and conglomerate. This formation is distributed on the western and southern parts of the Linkou terrace (Chen and Teng 1990).

Taoyuan terrace

The elevation of the Taoyuan terrace is approximately 244 m. The stratigraphy of this area includes the Yangmei Formation, the Danmaupu Conglomerate, the Dienzehu Formation, the Chungli Formation, and the Taoyuan

Fig. 1
Location of the study areas (Linkou, Taoyuan, and Tadu terraces) in northwestern Taiwan

Fig. 2

Rose diagrams of cobble orientation showing three categories of high, medium, and low grades

Formation (Tang 1964). The Yangmei Formation is the rock basement in the Taoyuan terrace. The Danmaupu Conglomerate consists of lenticular sandstone, which covers the Yangmei Formation. An unconformity was formed on the contact surface of the upper part of the terrace deposit. The Dienzehu Formation consists of lateritic cobbles. The cobble and boulder diameters range from 10 to 30 cm.

Tadu terrace

The Tadu terrace is distributed northeast to southwest, around 21 km in length at an elevation of around 310 m. The main composition of the Tadu terrace is the Toukoshan Formation, which consists of interbedded sand and

Fig. 3

Diagram of Zingg's (1935) shapes indicating the percentage of various cobble shapes in the study area

conglomerate, lateritic soil, and alluvium (Chiang 1984). The conglomerate formation is mainly composed of weakly cemented quartzite cobbles with diameters that range from 2 to 15 cm. The thickness of the conglomerate is more than 100 m on its northern part but is thinner (approximately 20 m) to the south. The cover of lateritic soil is around 5 m thick.

Field measurements

The field measurements have included: (1) slope attitude and matrix penetration; (2) grain shape and orientation; (3) grain size; and (4) photo counting.

Slope attitude and matrix penetration

A Schmidt lower hemisphere projection was used to analyze the data for slope attitude and cobble orientation. These measures of slope attitude were plotted on the

Table 1

The slope gradient distribution in Linkou terrace

Areas	Cankou	Hungshuishen River	Lenshuken	Kinkou	Denfon
Slope gradient (°)	54–77	60–80	68–76	48–73	54–80
Average (°)	65	71	72	64	67
Total average: 66°					

Table 2

The slope gradient distribution in Taoyuan terrace

Areas	Pushin	Yangmei	Berkonken	Kunshi	Hukou
Slope gradient (°)	54–70	58–74	46–62	44–70	64–70
Average (°)	63	64	55	63	66
Total average: 61°					

Table 3

The slope gradient distribution in Tadu terrace

Areas	Chinchilla	Shalu	Lonchin	Tadu
Slope gradient (°)	56–76	60–73	56–74	62–82
Average (°)	67	68	65	73
Total average: 68°				

Table 4

The average values of physical properties in the three terrace areas. UCS Unconfined compressive strength

	Linkou terrace	Taoyuan terrace	Tadu terrace
Water content (%)	9.9	12.6	4.7
Specific gravity	2.68	2.69	2.67
pH	5.52	5.22	5.34
>2 mm (%)	69.61	72.24	72.99
2–0.074 mm (%)	16.69	12.01	15.35
<0.074 mm (%)	13.69	15.74	11.64
Liquid limit (%)	28.6	37.3	28.1
Plastic limit (%)	22.4	25.7	20.9
Plasticity index	6.2	11.6	7.2
UCS (kPa)	326.3	336.1	401.8

stereonet using the method of great circle boundaries. Matrix penetration measurements were obtained by using a pocket Schmitz machine.

A rose diagram illustrates the slope attitude projection and cobble orientation (Fig. 2). If the cobble orientation is uniform, the rose diagram will form an equally distributed fan shape. If the cobble orientation is random in its distribution, the rose diagram will be divergent and

A **B****Fig. 4**

Cross sections of the Cankou and the Hungshuishen river areas. The ellipsoid cobble shapes fully underlie the slope and their locations appear to influence slope shapes

include a large area in its fan shape. The diagram categories of cobble orientation could distinctly have high (H), medium (M), or low (L) grades (Pettijohn 1975). In these study areas, the high grade is less than 45° (of a circle) in its major fan shape in the northwest

Fig. 5

Diagram showing the linear trend of the intersected angle of strike on the cobble orientation and slope surface with the slope grade in various terraces

Fig. 6
Diagram displaying the relationship between the slope and the percentage of disk shapes in the three terraces

quadrant of the study area. The medium grade is less than 65° in its major fan shape, mostly in the northeast quadrant (overlapping slightly into the southeast quadrant) of the study area. The low grade is more than 65° from approximately $N45^\circ E$ to $S10^\circ E$ with a very random distribution of the various orientations. In this study, the slope attitudes at the 105 outcrop sites on three terraces were measured. Thirty pocket penetrations were executed on the cobble matrices at each studied outcrop site.

Matrix penetration measurements were obtained by using a pocket Schmitz machine. The matrices were bonded tightly such that they were impossible to dislodge without destroying them in the process. These penetration tests were then executed in the field and correlations were run across all the samples measured.

Grain shape and orientation

The three axes were measured for cobbles within the terraces. These were designated as dL for the longest axis, dI for the middle axis and dS for the shortest axis. These shape measures were undertaken in situ at points randomly chosen from the fresh outcrops of the slopes concerned. The measurements also included the strike and dip of the maximum plane (intersection of dL and dI) in bladed cobbles at fresh slope surfaces. These measurements revealed a strike trend in which the strike consistently intersects a maximum plane of the cobbles on the slope surfaces. Zingg's shape method (1935) was then used to classify the cobble shapes in this study. Four different

cobble shapes were found: disk, bladed, roller, and equant. Measures on the long (dL), middle (dI), and short (dS) cobble axes were further analyzed by considering the ratios of dI/dL and dS/dI. The number and percentage of each of the four cobble shapes could then be deduced. For this study area, the proportion of disk-shaped cobbles was 38%, equant was 24%, bladed was 10%, and roller was 28% (Fig. 3). These results can be used to explain the distributions of cobble shapes.

Grain size

Two separated parts of grain sizes were analyzed for their percentages in the composition. These served as the scaled-down representatives of gravel sizes above 15 mm. One part was on gravel sizes over 15.5 mm. The other part was on gravel sizes under 15.5 mm. The cobble percentage can be calculated by computer analysis from two scaled-down methods of in situ visual counting and photo counting in the laboratory. These two methods provided a comparison of their respective sizes.

Photo counting

In situ photographs were taken of each unique sample. Each image was divided into a grid to enable counting of cobbles. A 17.5-mm-diameter coin was placed on top of the photos for comparing the grain sizes in the photos. The grain sizes greater than 15.5 mm were particularly useful in calculating their percentage. Then the grain sizes smaller than 15.5 mm could be distinguished and counted

Fig. 7
Diagram displaying the relationship between the slope and the percentage of equant shapes in the three terraces

by the computer software when scanned in by a standard scanner with a given scale size included with the photo. These measures were combined for calculation of a final figure representing their particle size distribution as an averaged sum.

Results

Slope gradient

Measurements of slope gradient are summarized in Tables 1, 2, and 3. These results show that the slope gradient average is around 66° in the Linkou terrace. In the Taoyuan terrace, the slope gradient average is around 61° . In the Tadu terrace, the average slope gradient is around 68° .

Particle size distribution

Particles with a size in excess 2 mm make up around 69.6% of the Linkou terrace. Most of the particles are cobble-sized. The percentage of particles over 2 mm is around 72.24% of the Taoyuan terrace and around 72.99% in the Tadu terrace. Table 4 combines the average results and shows that there is relatively little difference in the above three terraces in terms of particle sizes.

Physical properties

The geotechnical properties of the three study areas are also summarized in Table 4, and show little difference between the three terraces. These results reveal that the major characteristic of the matrices in the Linkou terrace and Tadu terrace is their low plasticity. The Taoyuan terrace has moderate plasticity.

The physical properties of the cobbles on the above terraces do not vary too much from one area to another. Changes in the slope gradient appear to be governed by (1) cobble orientation, (2) cobble shape, and (3) matrix strength.

Morphological characteristics

Two river valleys were selected for a more detailed consideration of the morphology of the Linkou terrace. One site was on the Cankou River, which is orientated in a northwestern to southeastern direction. The second was along the Hungshuishen River, which runs in a south to north direction.

Figure 4 illustrates the cobble orientation relative to the slope gradient for the Cankou River section. The cobble orientation in this area is in a east-west direction, with a dip toward the south (Fig. 4a). The southern part of the section reveals a steep slope at the intersection of the slope surface and the cobble orientation, forming an escarpment. The northern part of the Cankou River section has a gentle slope because the intersection of the slope surface and cobble orientation is a dip-slope type.

Fig. 8
Diagram displaying the relationship between the slope and the percentage of roller shapes in the three terraces

Table 5

The results of the intersected angle of strike on the cobble orientation and the slope surface, the slope gradient, and the percentage of cobble shapes in the constant strength (Qu) 416.5 kPa of matrix material. IA Intersected angle of strike on the cobble orientation and the slope surface

Location	IA (°)	Slope gradient(°)	Disk (%)	Equant (%)	Bladed (%)	Roller (%)
LK9	174	80	43.33	26.67	16.67	13.33
LK11	35	65	26.67	60.00	0.00	13.33
LK14	130	74	50.00	16.67	10.00	23.33
LK14-2	94	73	42.43	24.37	11.25	21.95
LK21	105	72	50.39	21.65	14.36	13.60
LK21-1	129	73	45.37	22.37	17.89	14.38
BK1-3	14	52	21.05	42.11	7.89	28.95
HK5	43	64	46.67	6.67	26.67	20.00
KC9	5	44	26.67	33.33	6.67	33.33
PH1-1	44	70	43.33	16.67	13.33	26.67
TD1-4	173	73	41.67	31.25	8.33	18.75
TD6	154	68	56.25	16.67	6.25	20.83
TD13-1	78	67	47.06	29.41	5.88	17.65
TD16-1	60	70	38.89	13.89	22.22	25.00
TD17-1	37	58	42.42	27.27	12.12	18.18
TD17	94	72	55.26	13.16	7.89	23.68

The cobble orientation of the Hungshuishen River has a northeastern direction and the dip is toward the south (Fig. 4b). The eastern part of the section in the Hungshuishen River reveals an escarpment-slope type at the intersection of the slope surface and cobble orientation (Fig. 4b). The western part of the Hungshuishen River has a gentle slope because the intersection of its slope surface and the cobble orientation is a dip-slope type.

The results of this site investigation demonstrate that changes in the cobble orientation range from irregular to uniform in response to local changes in topography.

Orientation effects

The angle of intersection of the strike of the cobble orientation and the slope surface can be used to analyze the relationship between the cobble orientation and slope

Fig. 9

Diagram exhibiting uniform grain orientation and high grade category of cobble slope. This result shows a significant, positive relationship between the slope grade with the intersected angle of strike on the cobble orientation and the slope surface

Fig. 10

The average results of the relationship between the slope grade and the percentage of disk and roller shapes. The average results were obtained from the slope grade with a 5° measurement interval

surface. When the intersected angle is 0°, the cobble orientation and slope surface forms a dip slope and the slope gradient ranges from 44 to 48°. When the intersected angle is 180°, an escarpment slope is formed and the slope gradient can reach 70 to 80°.

In practical terms, both the Linkou and Taoyuan terraces have statistically significant correlation coefficient ($r=0.74$, 0.77). The Tadu terrace has a lower correlation coefficient of $r=0.44$ (Fig. 5).

The results from the three terraces show that the slope gradient changes according to the changes in the intersection angle of strike on the cobble orientation and slope surface. The slope gradient and the intersected angle of strike on the cobble orientation have a linear trend and a

positive relationship. The combined figure (Fig. 5d) displays a significant correlation ($r=0.61$). This also reveals that the cobble orientation affects the anisotropy characteristics and the slope gradient.

Grain shape relationship

The distribution of disk, equant, bladed, and roller grain shapes in the three terraces were measured for comparison with the slope gradient. The results from the three terraces display a significant positive correlation ($r=0.53$, 0.41 , and 0.55). The figures in the three terraces show a linear trend and a positive relationship (Fig. 6). An increase in the percentage of disk-shaped particles increases the slope gradient results.

The three terraces display a negative correlation between the slope gradient and both equant and roller shapes (Figs. 7 and 8), whereas the slope gradient for blade-shaped particles display positive linear trends. This means that as the percentage of bladed particles increase, the slope gradient will also increase.

As the percentage of bladed and disk-shaped cobbles increase, the slope gradient will increase in the Linkou, Taoyuan, and Tadu terraces. In contrast, as the percentage of roller and equant cobbles increase, the slope gradient will decrease in these terraces.

Matrix strength

Both Matheson and Parent (1989) and Day (1993) point out that when the total cobble content in a terrace is lower than 70%, the shear strength will be transferred from the cobble support to matrix support. To understand the relationship between the cobble orientation and its shapes, some of the slopes in the study areas were selected for study.

The intersection angle of the strike on the cobble orientation appears to influence the slope gradient when the unconfined compressive strength of the matrix is less than 42.5 kPa (Table 5). The results show that the intersected angle of the strike on the cobble orientation ranges from 5 to 174° and the slope gradient ranges from 44 to 80° at the same unconfined compressive strength. They have a relatively high correlation coefficient of $r=0.79$. This means that the cobble orientation can influence the anisotropy characteristics of the geomaterial even when the unconfined compressive strength of the compared matrices is held constant.

Discussion

The rose diagrams show that if the grain orientation is uniform, a relatively high positive correlation ($r=0.98$) exists between grain orientation uniformity and slope gradient (Fig. 9).

These results also demonstrate that the cobble orientation has a higher anisotropy as the slope gradient changes. In contrast, the low-grade grain orientation (L) distribution in the rose diagram has no correlation with slope gradient. Therefore, when the grain orientation is random and rarely uniform, the cobble has more isotropy.

This study sought to minimize or avoid misjudgment in the diagram analysis from the data collected. Therefore, a change was made in the method of data collected. Individual data points within a 5° range on the slope gradient were averaged together and given as one measures for the 5° interval on the slope. Table 5 also shows that the slope gradient ranged from 40 to 84° and divided into nine categories. The results revealed not only a clearly linear relationship in positive and negative directions but also a very significant correlation ($r=0.95$ and 0.86) in disk and roller shapes (Fig. 10). This method could reduce the error impact on the data collection and analysis.

Conclusions

The physical properties of matrices in lateritic cobbles are not different among the three terraces in the Linkou, Taoyuan, and Tadu areas. The cobble orientation will form anisotropy geomaterial and affect the distribution of the slope gradient.

The field results demonstrate that the difference in content percentage of various cobble shapes will affect slope gradient. The correlation of various data in the accompanying diagrams shows that the cobble shape and its orientation still affect slope gradient even when the matrix strength is constant. This means that even when cobble content is under 70% in the matrix support of lateritic cobbles, different cobble shapes and their orientation can still affect the stability of the cobble slope.

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